

The Operator Hierarchy

A chain of closures linking matter,
life and artificial intelligence

Gerard Jagers op Akkerhuis

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Een wetenschappelijke proeve op het gebied van de Natuurwetenschappen,
Wiskunde en Informatica

PROEFSCHRIFT

Ter verkrijging van de graad van doctor
aan de Radboud Universiteit Nijmegen
op gezag van de rector magnificus prof. mr. S.C.J.J. Kortmann,
volgens besluit van het college van decanen
in het openbaar te verdedigen op
maandag 6 september 2010
om 15.30 uur precies

door

Gerhardus Adrianus Johannes Maria Jagers op Akkerhuis

Geboren op 21 maart 1960
Te Hengelo (Overijssel)

Promotor:

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Manuscriptcommissie:

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Paranimfen:

Hans-Peter Koelewijn

Leen G. Moraal

ISBN: 978-90-327-0389-9

Lay-out: Mitekst Service v.o.f.

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Jagers op Akkerhuis, G.A.J.M. (2010) The operator hierarchy: a chain of closures linking matter, life and artificial intelligence. PhD thesis, Radboud University Nijmegen.

The research presented in this PhD thesis was financially supported by the Netherlands Integrated Soil Research Programme, the National Environmental Research Institute (Silkeborg, Denmark), Alterra Wageningen UR and the Radboud University Nijmegen.

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Abstract

Jagers op Akkerhuis, G.A.J.M., (2010). The operator hierarchy: a chain of closures linking matter, life and artificial intelligence
PhD thesis, Radboud University Nijmegen.

Science suffers from a knowledge explosion that is associated with overspecialisation and compartmentalisation. To overcome this crisis, scientists face the challenge of constructing comprehensive and integrating theory. In relation to this challenge, this thesis presents a general theory for recognising hierarchy in the organisation of nature. Novel about this theory is that it unifies in a single, strict ranking the two system types that traditionally are regarded as 'physical particles' and as 'organisms'. This ranking is made possible by focusing on situations in which systems that show cyclical self-organisation create a next system type with this property as the first possibility nature allows. Due to this focus the result is not just a classification but a chain of systems types resulting from and linked by process steps. This chain includes fundamental particles, hadrons, atoms, molecules, prokaryote cells, eukaryote cells, prokaryote and eukaryote multicellulars, and animals. The proposed theory refers, in a general way, to the latter systems as 'operators' and to their hierarchical ranking as the 'operator hierarchy'.

After discussing in detail the construction of the operator hierarchy, it is shown how the operator theory contributes to fundamental unification topics in science. Applications in this field include the definitions of life, the organism and death, the prediction of future operators, a periodic table for periodic tables, the supplementation of evolutionary theory with the opportunity to focus on structural development, and a discussion of the need to redefine the meme concept. In the discussion section the theory's strengths and weaknesses are discussed. It is concluded that the operator theory represents a fundamental contribution to science that offers new roads towards solving integration problems.

Keywords: evolution, operator hierarchy, natural philosophy, major evolutionary transitions, particle hierarchy, closure, memes, arrow of complexity, hierarchy theory, system theory, exobiology, artificial intelligence, periodic table, definition of life, Big History.

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General Introduction

Now, in order to work hard on something, you have to get yourself believing that the answer's over *there*, so you'll dig hard there, right? So you temporarily prejudice or predispose yourself – but all the time, in the back of your mind, you're laughing.

(Richard Feynman)

Read, every day, something no one else is reading.
Think, every day, something no one else is thinking.
Do, every day, something no one else would be silly enough to do.
It is bad for the mind to continually be part of unanimity.

(Christopher Morley)

To all those who have inspired me
Omnia lusus naturae

1 General introduction

Science suffers from a knowledge explosion (e.g., Sagasti, 1999). In the last 30 years more discoveries have been made than ever before (Linowes, 1990). In what could be regarded as a centrifugal vortex of scientific discovery, we have created tools that have helped us to investigate the world we live in, which has increased our understanding of the world, which has been used to create better tools that have helped us to expand our understanding further still. These developments have given us insight into the miniscule and the enormous, as well as the functioning of our own body, brain and behaviour. As a result, science has pervaded every aspect of our existence while the number of scientific disciplines and the knowledge they represent have exploded (Zwart 2010). The rapidly growing amount of information has made communication between disciplines increasingly difficult. Consequently, there is an urgent need for integrating theory that can assist in reconciling scientific knowledge (Gilbert 1983).

The search for theories offering integrating frameworks can be regarded as ‘centripetal’ science. The search for centripetal concepts is not a new phenomenon in science. There are quite a few examples of early attempts to bring order into the chaos of phenomena observed in the world. A well-known example is the *Scala Naturae* (natural ladder) in which the Greek philosopher and naturalist Aristotle ranked natural phenomena by decreasing perfection, from spiritual and divine beings to man, animals, plants and finally rocks and formless matter. The *Scala Naturae* inspired the medieval ‘Great Chain of Being’, at the top of which Christians placed angels and God. More recent examples of centripetal approaches are Mendeleev’s periodic table of the elements and the tree of life that represents an evolutionary viewpoint on the formation of species. Mendeleev’s periodic table of the elements logically arranged atoms and their reactive properties and allowed new elements to be predicted where gaps occurred in the scheme. Darwin’s Theory of Evolution offered a logical mechanism for the processes that cause global biodiversity. Both Mendeleev’s and Darwin’s theories have unified the separate domains of atoms and organisms, respectively. However, an overarching theory that connects domains as different as fundamental particles, atoms, molecules, cell-based organisms and technical ‘organisms’ is still lacking. From the point of view of scientific integration, the absence of such an overarching theory must be considered a gap at the heart of science.

To fill this gap, a theory is needed that explains the hierarchical emergence of increasingly complex system types. The suggestion that system hierarchy represents a knowledge gap may seem strange because the subject has been discussed in literature for decades and there appears to be a fair degree of

consensus about how to rank system types from the small to the large. A typical example of a ranking in the literature is the 'ecological hierarchy'. This hierarchy includes quarks, hadrons, atom nuclei, atoms, molecules, organelles, cells, organs, organisms, populations, colonies, communities, ecosystems, planets, solar systems, galaxies, clusters of galaxies and the universe. The simplicity of this sequence is alluring but camouflages many serious problems concerning both hierarchy rules and the selection of the elements. What makes the problem more complicated is that the above kind of hierarchy is used in different forms as the basis for other studies and this leads to inconsistent reasoning and, thus, sloppy science.

The problem of how to create a strict ranking may be solved by applying evolutionary principles. In evolution, certain things are constructed first and other things later. It is questionable, however, whether invoking evolution will help because Gould's replayed tape metaphor (Gould, 1989) suggests that every hypothetical re-run of the evolutionary process must produce a different outcome. Consequently, it is highly uncertain whether a particular species could emerge twice. Using the same reasoning and broadening it to all systems, it can be stated that every re-run of the universal evolutionary tape could result in a differently organised universe. The idea that re-running the evolutionary tape results in unpredictable new situations seems to be inspired by chaos theory. Chaos theory states that certain dynamic processes cannot be predicted in advance because the nonlinear development of their future states critically depends on initial conditions. Lorenz popularised this critical dependence as the butterfly-effect: a wing beat of a butterfly on one continent may create a thunderstorm on another.

If the butterfly-effect were the only rule shaping the universe's evolution, the process would be utterly unpredictable. But, if it is true, how can we explain that spectral analyses of remote stars show that these stars harbour the same physical particles, e.g., atoms and molecules, as the earth? And how can we explain that the cell holds such a central position as the basal building block of all organisms on Earth? The general existence of atoms, molecules and cells -- at least on earth -- is intriguing because it hints at the existence of a fundamental and universal structuring process.

The major question of this thesis is whether it is possible to find rules guiding the above mentioned universal structuring process. To answer this question, the work focuses on circular self-organisation processes because such processes clearly stand out from their environment as individual entities. A cycle of interactions in a system is also regarded as a 'closure'. Of special interest for this thesis are closures based on thermodynamic-driven self-organisation. A system based on this type of closure may show a next closure and in this way produce the next closed system. By repeating this process a long sequence of

closure-based systems can be built. Using a specific type of closure, a long series of closure steps can now be recognised in the emergence of increasingly complex particles and organisms in the universe. The proton, the atom, the molecule, the cell (prokaryotic and eukaryotic), the multicellular organism and the animal are examples of increasingly complex closed systems. Every one of these systems can be considered an individual entity showing its own system dynamics in the environment in which it 'operates' (i.e., functions). For this reason, these systems are labelled 'operators' in this thesis.

The search for hierarchic order described in this thesis originated in an ecotoxicology study aimed at integrating toxicant effects on terrestrial organisms and ecosystem functioning. To properly integrate these effects, all targets for change in ecosystems needed to be arranged strictly and hierarchically. This action initiated the quest for a strict hierarchy of levels of complexity in nature. In turn, this quest for levels led to a search for a general particle hierarchy, as this was considered the backbone for all other hierarchies. As is described in the next paragraph, the major ideas that were developed during this ecotoxicology study became the starting point of the present theory.

As an introduction to particle hierarchy, this thesis will present an overview of the field of system studies and the role of particle hierarchy therein. The introduction is divided into two parts: a summary of system science and a synopsis of particle-related discoveries in physics and biology. After this general introduction, the work of Teilhard de Chardin (1881-1955) is discussed. Teilhard de Chardin was one of the first scientists to develop the idea of a general particle hierarchy that included physical particles and organisms. The introduction is followed by a process-based analysis of all the individual closure steps in the operator hierarchy. Finally, two topics are discussed that are of general importance to this study's context. The first topic examines whether the operator hierarchy can be regarded as a falsifiable methodology. The second discusses thermodynamics as a necessary basis for all systems. The introduction ends with an outline of the subjects discussed in chapters 2 to 9 of this thesis.

Problems with hierarchy

The realisation that quite a few things were wrong with existing system hierarchies came in 1992. In that year I was involved in an ecotoxicology study aimed at integrating the findings of roughly two dozen PhD projects dealing with separate aspects of the Netherlands Integrated Soil Research Programme (NISRP). The PhD candidates had investigated different aspects of soil ecotoxicology. Their topics ranged from the availability of toxicants in the soil, through absorption-desorption balances between soil and the surface of roots, cuticle or skin, to toxicant uptake with food and the complex dynamic balance of the internal concentration in organisms, followed by the effects on targets in organisms and the impacts on individuals and their functioning in ecosystems. The integration study covered many levels of ecological organisation and needed a framework for ecological hierarchy that could act as a backbone for the integration process.

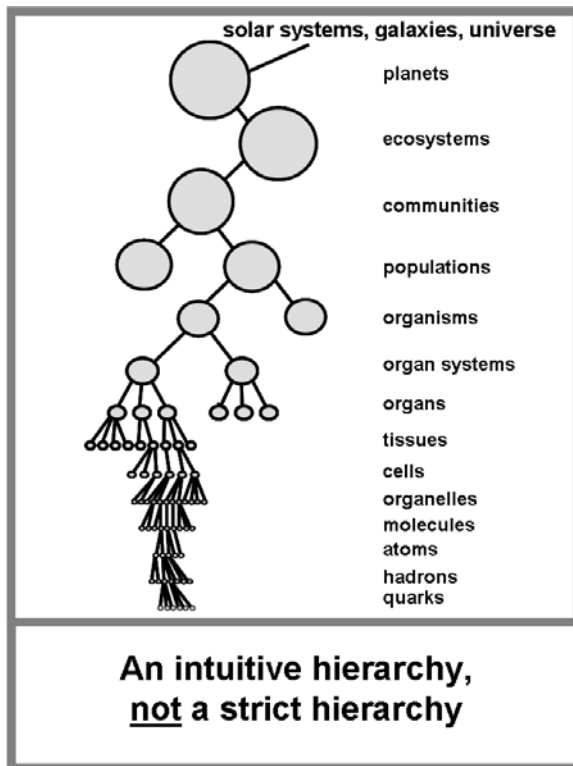


Figure 1.1. A system hierarchy that rests on the intuition of lower level elements taking part in the organisation of higher level elements

A literature search produced a fascinating plethora of ecological hierarchies, most of which were variations on the following themes: atom, molecule, organelle, cell, organ, organism, population, community, ecosystem, planet, etc

(e.g., Miller, 1978; Koestler, 1978; Sheehan, 1984; Naveh and Lieberman, 1994; Laszlo, 1996; Newman and Jagoe, 1996; Nederbragt, 1997; Høegh-Jensen, 1998; Korn, 2002) (Fig. 1.1). The logic behind these rankings seemed to rest on the intuitive notion that lower level objects are 'taking part' in the organisation of higher level objects; that is, atoms take part in the organisation of molecules, which take part in organelles, which take part in cells, and so forth.

Upon closer look, however, the latter examples of rankings were generally found to be inconsistent. To begin with, their hierarchy seemed in many aspects to be constructed specifically from the point of view of multicellular organisms because unicellular organisms do not consist of cells and do not have organs. In fact, some hierarchies seemed to ignore that organisms may differ in complexity, from bacteria and eukaryotic cells, through bacterial and eukaryotic multicellulars to animals. Another interesting observation was that the hierarchies generally could not be considered as representing a historical sequence. For example, while atoms integrate to create molecules, molecules do not first integrate to create organelles, which then integrate to form cells. The reason for this is that as long as nature has not constructed a cell, neither the context nor the means exist for organelle evolution. The same reasoning applies to organs in multicellular organisms. Furthermore, it may seem confusing that the ranking was based on two different types of transitions. The first transition type involved particles creating next particles, for example, the step from the atom to the molecule and from the unicellular organism to the multicellular organism. The second transition type involved the interaction of particles in systems that were not particles themselves. With respect to the latter transition it is suggested that organisms take part in populations, which take part in communities, which take part in ecosystems. Yet it is hard to imagine how organisms are first integrated into populations, then into communities and then into the ecosystem. As Schultz (1967) has indicated, a community, for example, is not a subsystem but a conceptual part of an ecosystem. Consequently, organisms directly contribute to the ecosystem while a focus on one specific interaction can be used to group the organisms without such grouping representing a physical object. For example, focusing on reproduction leads to recognising clones or populations, focusing on feeding relationships leads to food chains, focusing on engineering relationships leads to a 'who-uses-the-construction-of-who' chain and focusing on interactions between organisms of different species leads to a community viewpoint.

Based on the above considerations, it was decided that the generally used ecological hierarchies did not offer a strict enough basis for the integration study because their logic needed to be improved. Consequently, a stricter analysis of ecological hierarchy had to be developed. To keep things as simple as possible, the individual organism was used as the foundation of the new hierarchy. A focus on individuals would allow the association of toxicant effects with:

- interactions between individuals in ecosystems (e.g., populations, food chains)
- complexity levels of individuals (e.g., bacteria, protozoa, plants and animals)
- targets in the internal organisation of individuals (e.g., atoms, molecules, organelles, cells, organs)

These three aspects can be regarded as separate 'directions' for discussing hierarchy. If hierarchy is discussed in one of these directions, then the aspects of other directions cannot be included without developing mixed reasoning and an inconsistent hierarchy. For example, transitions from bacteria to eukaryotes, and from eukaryotes to multicellulars, can be discussed, but this ranking cannot be continued with populations as the next step because multicellulars are not the only organisms that form populations. Prokaryote cells, eukaryote cells and multicellulars also form populations. Similarly, prokaryote cells have an internal organisation, eukaryote cells have an internal organisation and multicellulars have an internal organisation. Because all three directions for analysing hierarchy are accessible from every organism, these directions involve independent hierarchies and should not be mixed. Moreover, because of their independence, these directions can be considered separate *dimensions* for analysing hierarchy (Fig. 1.2).

The search for a strict hierarchy in ecotoxicology started with the ranking of organisms of different complexity levels, from bacteria to eukaryote unicellulars to multicellular organisms. These levels were subsequently applied when analysing the internal organisation of multicellular organisms because the cell level is again found in a multicellular organism. To further extend this logic to the cell's interior, the levels of abiotic particles also had to be included because the cell's interior harbours many elements smaller than cells, such as molecules, atoms, etc.

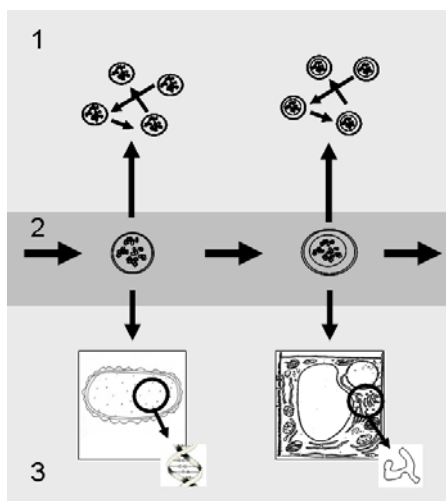


Figure 1.2. Hierarchy dimensions in nature's organisation: (1) hierarchy of how organisms form complex systems of interacting particles and/or organisms, (2) hierarchy of how organisms self-organise to form higher level physical particles and organisms, (3) hierarchy of the internal organisation of organisms. The same logic can be extended to physical particles as well as multicellular organisms.

It was decided to analyse the complexity of organisms as if this complexity resulted from a range of construction steps, for example, from prokaryotic to eukaryotic and from unicellular to multicellular. After every step, a new system emerged that showed new properties typical for its complexity level. Every new property represented a new target for stressors. Consequently, the ranking of new organism properties also offered a ranking of targets in an organism. The following example illustrates this target ranking.

When looking at a unicellular life form, such as a bacterium, its membrane and internal autocatalytic chemistry are the main system properties. These properties simultaneously represent the major targets for stressors. New targets arise as soon as a bacterium gains internal membranes and becomes eukaryotic. The nuclear membrane, the processes in both compartments, and the exchange of information between nucleus and cytoplasm form new targets for stress. Going from eukaryotic cells to eukaryotic multicellulars, new stressor targets develop in the structural binding of the cells and in the chemical communication between the cells that make it a multicellular life form.

While analysing complexity levels of stressor targets in organisms, the question emerged whether the ranking method that was developed could be applied to non-living systems as well. In other words, would it, for example, be possible to distinguish between atoms and molecules in the same way as between unicellular and multicellular organisms? If this were possible, a general

framework for complexity levels of both organisms and particles could be created that would implicitly offer a rationale for organising *all* targets for toxicant action. This promising vista was the reason that the major subject of study turned towards developing a uniform method to rank all complexity levels including both the non-living particles (e.g., atoms, molecules) and the organisms (e.g., bacteria/archaea, eukaryotes, multicellulars).

Before examining the construction of a strict ranking for the complexity of abiotic and biotic particles, the next paragraph presents an overview of hierarchy theoretic ideas and the discovery of complexity levels of particles and organisms. This information establishes a context for the general 'particle'-hierarchy developed in this study.

Hierarchy theory: a selection of major ideas

In the mid-20th century, Von Bertalanffy (1950, 1968) envisioned a kind of general systems theory that would one day connect a broad range of scientific disciplines. A strict approach to hierarchy can be regarded as a prerequisite for any general systems theory. An early review by Feibleman (1954) shows that many general hierarchy rules had already been identified in the 1950s, including:

- *Each level organises the level or levels below it plus one emergent quality.*
- *Complexity of levels increases upward.*
- *In any organisation the higher level depends on the lower.*
- *For an organisation at any given level, its mechanism lies at the level below and its purpose at the level above.*
- *Time required for a change in organisation shortens as we ascend the levels.*
- *The higher the level, the smaller its population of instances.*
- *It is impossible to reduce the higher level to the lower.*

But what exactly is hierarchy? Hierarchy is generally regarded as a relationship that follows two simple rules: transitivity and irreflexivity (Bunge, 1969; Simon, 1973; Webster, 1979):

- *Transitivity* implies that as long as A has a lower hierarchical position than B, which, in turn, has a lower position than C, the hierarchical position of A is automatically lower than C.
- *Irreflexivity* means that A can never hold a hierarchical position below or above itself.

From these rules *antisymmetry* follows because if we suppose a symmetrical relationship in which A is lower than B, and B lower than A, then, by transitivity, A would be lower than A, which is forbidden because of irreflexivity.

Examples of hierarchical relations are 'is larger than', 'is older than' and 'is a part of'.

The simplicity of the above definition does not mean that applying hierarchy to real world systems is always straightforward. First of all, problems arise if levels depend on different hierarchy rules, resulting in what can be considered a mixed hierarchy. Secondly, the demand of transitivity (if A is hierarchically below B and B is below C, then A is below C) creates a hierarchy, but does not forbid inserting an element into a hierarchy or taking an element from it. For example, for any situation where a system A is hierarchically lower than B, a system A* may be inserted into the hierarchy as long as A* is hierarchically above A and below B. Yet, such 'flexibility' or 'generality' precludes constructing a strict hierarchy in which the elements remain at fixed levels. To solve this problem, the elements must show a non-transitive hierarchical relationship. This implies that when A is hierarchically below B, and B is hierarchically below C then A is not hierarchically below C. The difference between a transitive and non-transitive relationship is comparable to the difference between using ancestry or parenthood as a ranking rule. Using ancestry, both the grandparent C and the parent B are ancestors of A. Using parenthood (and excluding the possibility of incest), the situation is different because when A is child of B, and B is child of C, then A cannot be a child of C.

Finally, there is the question of how to deal hierarchically with a circular relationship? In fact, a circular relationship no longer represents a hierarchy because it has lost transitivity, non-transitivity and irreflexivity. Consequently, there is no way of determining which interaction is first or last. Heylighen (2010) used this aspect to indicate that a circular system must also be regarded as a new unit for defining time. Therefore, when circularity occurs, a refocusing of hierarchy analysis is implied. Before circularity, the analysis of hierarchy focused on relationships between the elements that create the circularity. When the circularity is present, a new focus is required that ranks the holistic properties of the circularity in comparison to the holistic properties of other circularities.

The above peculiarities may well be the reason that a generally accepted analysis for hierarchy in natural systems has not been found. Yet, Von Bertalanffy (1968) has indicated that when it is found, a '*...general theory of hierarchic order obviously will be a mainstay of general systems theory*'.

Not everyone considers the subject of hierarchy equally important (e.g., Guttman, 1976). One reason for this may be that the early theories suffer from an overly general attitude. They consider everything a system that is based on lower level elements and that is affected by its environment. Given this viewpoint, the theory becomes so abstract that all contact with specific real world examples is lost. Another reason may be that general system theorists have sometimes considered one-dimensional representations a sufficient basis for generalisation. An instructive example is the idea that energy is the aspect that rules an ecosystem's organisation (e.g., Odum's systems ecology, 1994).

Despite the advantage of simplicity, any low-dimensional representation always neglects aspects. For example, an energy-based approach to the ecosystem neglects the structural effects of ecosystem engineers, the genetic effects of selection and the role of dispersal, which according to the DICE approach (Dispersal, Information, Construction and Energy, see Jagers op Akkerhuis, 2008) are the required inputs for minimal models of ecosystems.

Another reason why everyone does not consider hierarchy equally important may be that the reductionism-versus-holism debate has troubled the objective hierarchical analysis of systems. This debate started with Aristotle, who in his *Metaphysics* (Book, H, 1045: 8-10), coined the phrase: "*The whole is something over and above its parts, and not just the sum of them all*".

Reductionists generally disagree with Aristotle's statement because they consider that a system with all its properties, including emergent properties, can be completely explained as the result of the interactions between the constituent parts. According to their viewpoint, a thorough understanding of a system's parts, their properties and interactions allows a full understanding of a system's functioning, at least in principle. Consequently, a system cannot be more than its interacting parts. This reductionist viewpoint has led to a search in systems for constituting parts and their functional properties, the parts of the parts and their properties, etc. For this reason reductionist theory shows a close link with a hierarchical analysis of a system's construction. Examples of hierarchical approaches are the 'worlds within worlds' approach and abstract simplifications of it represented by Chinese boxes or Russian babushkas (e.g., Simon, 1962; Koestler, 1967; Lazslo, 1972, 1996).

In comparison to the reductionist viewpoint, a holistic viewpoint strongly emphasizes the system's emergent properties and the way these affect the functioning of its parts. Illustrative examples of how a whole system affects its parts are the presence of genes and organelles in the cell, the presence of castes in social insect colonies, and the presence of organs and the brain in multicellular animals. These and similar phenomena are fully explained by physical laws (reductionist point of view) while at the same time their typical realisation cannot be explained in a purely 'bottom up' way; they can only develop in an environment where the higher level of organisation (cell, colony, animal) is exposed to selection (e.g. Turchin 1977, Witting 1997, Wilson & Wilson 2007). In addition, the holists stress that the cooperating parts may show emergent properties that, in their typical realisation, are extremely hard to predict. For example, the thought of a muffin may give a person a hungry feeling and even make his mouth water. However, it is virtually impossible to predict deterministically, from the level of the interacting nerves, why that person thought of a muffin and not a slice of ham. What makes predicting a thought even more difficult is that the thought may be guided by a continuous flow of

internal and external causes, such as reading a story in a cooking magazine and the way the reader's eyes process the magazine's perception.

Another aspect of emergent properties that reductionists sometimes question is the acclaimed discontinuity between two system states at the moment of emergence. The idea is that emergence can be regarded as a gradual trajectory (in time and/or space) along which it is not possible to say exactly when an emergent property is present. This idea is sometimes used to argue that it is useless to focus on emergent properties in relation to the analysis of organisational transitions. Indeed, if we look closely at the moment of its occurrence, the presence of an emergent property, such as a closure, may not be easily recognizable; during the transition phase, a closure may switch between being present and being lost. This switching can be compared with a person who walks between two rooms. When going through the door, the person is not entirely in the first room and not entirely in the second room. Yet, such presence/absence dynamics during a transition state offer no arguments for denying a transition. At a certain point a person has fully passed the door and has entered the second room. What may trouble this discussion is that in non-closed self-organised systems, such as a tornado, the transition is indeed absent because the emergent property, the whirl, is based on a gradient and does not involve a closed topology acting as a system limit. In the case of a tornado, there is no 'door' to walk through; there are only two parts of the same room directly connected by a long winding hallway.

The above discussion shows that both the deterministic and the holistic viewpoints have their virtues and that they supplement each other when it comes to understanding the functioning of a system.

In addition to holism and determinism, another relevant viewpoint for particle hierarchy is the evolutionary viewpoint. The evolutionary viewpoint focuses on the way in which small particles create more complex particles, which, in turn, create even more complex particles, etc. in a long hierarchy of particle complexity. Because this viewpoint considers the *construction* of increasingly complex particles, it would be logical to call it constructivism. The concept of constructivism, however, already has various scientific uses two of which are particularly relevant to particle hierarchy. One use relates to constructivist epistemology. Constructivist epistemology is an epistemological perspective in philosophy asserting that scientific knowledge is constructed by scientists and not discovered from the world. The other use relates to a constructivist viewpoint in mathematics that originated in a 1938 paper by Gödel (Gödel, 1938). In this paper, Gödel states that only those mathematical objects that can be constructed from certain primitive objects in a finite number of steps can exist. Gödel's mathematical constructivism offers a useful analogy to real world

systems, if it is assumed that reality emerges as a large hierarchy from primitive elements constructing more complex elements.

Whether it is wise to call it a constructivist viewpoint or not, the emergence of higher level particles on the basis of lower level ones is considered in this thesis the most logical perspective for analysing particle evolution. Two general observations support this assumption. The first is that scientific measurements solidly support that the universe shows a long history of more or less globular expansion. When looking back in time, any globular expansion implies some sort of origin at its centre. The second is that the concentration in a small origin of all matter in the universe implies that material is heated. Heating generally decomposes complex structures to lower level elements. The combination of these two points strongly suggests that the universe once started as a small volume with a high energy density (high temperature) in which only low complexity particles existed. The latter shows that evolutionary particle hierarchy is a likely candidate for a major organising principle in science. The following historical overview presents a selection of authors that have substantially contributed to a hierarchical construction theory of particles.

Whitehead (1929) presents a system of process metaphysics that defines the world as a process of becoming of actual entities. These entities are both process and outcome because they are both the subject (as the process of becoming) and the superject (as the result of the process). Whitehead reasons that processes are the basis of all entities: *'... we are faced with the question as to whether there are not primary organisms which are incapable of further analysis. It seems very unlikely that there should be any infinite regress in nature. Accordingly, a theory of science which discards materialism must answer the question as to the character of these primary entities. There can be only one answer on this basis. We must start with the events as the ultimate unit of natural occurrence.'* (Whitehead, 1925). Whitehead refers to the events representing the ultimate units of occurrence (the lowest possible level) as *actual entities* or *actual occasions*, while *"whatever things there are in any sense of 'existence', are derived by abstraction from actual occasions"* (Whitehead, 1929). When actual occasions interact and integrate into macroscopic objects, they form a *nexus* (plural: *nexūs*). All macroscopic things we see are *nexūs*: a tree, a table, a human being, a star, etc. The composition of the actual entities contributing to a nexus can change. Whitehead also refers to individual actual entities as *creatures* because they are the product of self-creation. He uses the concept of the *organism* for actual entities as well as for *nexūs* of actual entities.

The work of Teilhard de Chardin (1959, 1969) focuses on physical and biological particles. He identifies particles on the basis of organisational properties that he describes as *formedness* and *centeredness*. He ranks the identified particles in

order of emergence. His hierarchy includes abiotic particles, single-celled and multicellular organisms and a future holistic state for society, *Point Omega*. Because his ideas about the organisation of systems are still relevant, his work will be discussed in more detail later in this introductory chapter.

Simon (1962) focuses on the role of *modularity* in the evolution of complexity. He convincingly argues that it is much more efficient for nature to work with assembled modules than to start every assembly process from scratch. In a quantitative example, he introduces the watchmakers Hora and Tempus, assembling watches consisting of 100 parts. Hora and Tempus are regularly disturbed in their work. Each time they are disturbed, they lose the unit they are working on. Hora then starts to assemble units in pieces of 10 and then puts these modules together in a final assembly. When disturbed, he only loses the last 10-piece module. Tempus continues to build his watches from 100 individual elements. Every time he is disturbed, he has to start again. Simon shows that it is easy to calculate how unsuccessful Tempus will be and demonstrates the advantage of modularity in the evolution of system types.

Koestler (1967, p.301) introduces the *holon* for the elements at the nodes of hierarchical relations and states that '*The holons which constitute an organismic or social hierarchy are Janus-faced entities: facing upward, toward the apex, they function as dependent parts of a larger whole; facing downwards, as autonomous wholes in their own right*'.

Turchin (1977) introduces the concept of the *metasystem transition* (MST) to describe structural and functional aspects of evolutionary steps from one level to the next, from system S_1 to system S_2 , that occur when, given two or more systems S_1 (S_{11} to S_{1N}) that may or may not show variations, the highest control level of the individual systems S_{11} to S_{1N} becomes itself controlled. Turchin also considers every metasystem transition a *quantum of evolution* and furthermore introduces the *law of the branching growth of the penultimate level*. The law states that only after the formation of a control system S will it become possible for the subsystems S_i to multiply and differentiate.

Varela (1979) introduces the concept of *autopoiesis* (Greek for "self-making") for a system in which the parts, including a boundary, support dynamics that recreate every aspect of the system. He defines autopoiesis as follows: "An *autopoietic machine* is a machine organised (defined as a unity) as a network of processes of production (transformation and destruction) of components which: (i) through their interactions and transformations continuously regenerate and realise the network of processes (relations) that produced them; and (ii) constitute it (the machine) as a concrete unity in space in which they (the components) exist by specifying the topological domain of its realisation as such a network." Including the concepts of 'regeneration', 'production' and the

‘concrete unity in space’ in the definition creates a natural association with the dissipative catalytic processes and membrane as a subset of the cell’s properties but makes autopoiesis unfit for describing the brain.

Eigen and Schuster (1979) introduce the *hypercyclic* theory. A hypercyclic process is created when catalysts that can individually perform a cyclic catalytic process interact. Their interaction results in a second-order cyclic process: a hypercycle. Eigen and Schuster (1977, 1978a, 1978b, 1979) and Kauffman (1993) have worked out in detail aspects of the catalytic hypercycle.

Gánti (1971, 2003a, 2003b) has developed the *chemoton* theory. Gánti takes the cell as the building block of life. The chemoton is constructed as a minimum complexity representation of the cell, and thus ‘minimal life’. The chemoton theory is based on networks of chemical reactions in which cyclic reactions fluidly represent the information required to produce the system. RNA or DNA are not required at this level of simplicity. The chemoton theory is supported by *cycle stoichiometry*, a theoretical framework. *Stoichiometry* refers to quantitative calculations for describing the number of reactants and products before and after a reaction. A chemoton consists of three compartments: (1) a chemical motor system, (2) a chemical boundary system and (3) a chemical information system. Chemotons have been suggested as an appropriate model for the cell and, as such, for the origin of life. Gánti recognises absolute and potential criteria for living organisms. The absolute criteria are (1) individuality, (2) metabolism, (3) inherent stability, (4) the presence of a subsystem that carries information for the system, and (5) the regulation and control of processes. The potential criteria are (1) growth and reproduction, (2) hereditary change, and (3) mortality. According to Gánti’s definition, any technical intelligence (e.g., an intelligent robot) cannot be regarded as life. Moreover, too narrow a focus on minimal life does not allow the definition of life, in general, because even the most excellent definition of a least complex cell has little to say about the rules that define multicellularity.

Jaros and Cloete (1987) propose a *biomatrix* of interacting *doublets*. They regard these as comparable to Koestler’s holons. Every doublet combines an *endopole*, representing its internal organisation, and an *exopole*, representing interactions with the environment. As an example of three levels of interacting doublets, Jaros and Cloete choose the cellular level, the organism level and the societal level.

Heylighen is one of the advocates of the importance of *closure* in system science. Closure has a long history. Early references to closure can be found, for example, in Wilson (1969). Wilson points out that natural boundaries may result from minimum interactions or ‘*some form of closure, either topological or temporal*’. In its most general form, closure indicates the invariance of a set

under an algebra of transformation. Thus, when an operation is performed on the elements of a set, the operation's products are still elements of the set. Closure thus indicates "*the internal invariance of a distinction (or distinction system) defining the system*" (Heylighen, 1989a). As a variation on this theme, in cybernetics a system is said to be organisationally closed if its internal processes produce its own organization (Heylighen 1990). A well known example of such organisational closure is autopoiesis (Varela 1979). Heylighen proposed *relational closure* as a means to deal with systems that do not show a primitive level because every element is defined relative to other elements (Heylighen, 1990). Circular closure relationships break a system from any pre-existing temporal hierarchy; all relationships lose temporal order and must be considered as occurring simultaneously (Heylighen 2010). Heylighen also analyzed the role of a manager as an agent causing organisational closure in *mediator evolution* (Heylighen, 2006). Heylighen (1989a, 1989b) furthermore discusses how a broad range of closed structures can be defined by differently combining four basic closure types: (1) transitive closure (or recursivity), (2) cyclic closure, (3) surjective closure, and (4) inverse surjective closure. *Transitivity* implies that if A is lower than B and B is lower than C, then A is lower than C. *Cyclicity* implies the existence of inverse transformations. *Surjectivity* implies the many-to-one relationships, while *inverse-surjectivity* implies one-to-many relationships. In addition, any of the relationships in the four classes can be negated e.g., non-transitive or non-cyclic.

Alvarez de Lorenzana (in Salthe, 1993) sketches a straightforward application of a construction sequence to describe the development of the universe. He states that the universe (U) can be understood and explained assuming that '*...variety and complexity can be obtained only by processes of manipulation and combination, operated on and by the initial, given, U*'. Using this reasoning, he describes a general hierarchical model in which '*the elements of each new level are made out of combinations of elements of the previous level*'. Alvarez de Lorenzana further states that "*Evolution of and within U takes the form of a constructible "metahierarchy" (Alvarez de Lorenzana and Ward, 1987) – a chain of evolutionary cycles with, ideally, no missing links*'. That a construction sequence should not have missing links was recognised earlier by Guttman (1976). Although de Lorenzana's approach leads to a strict series of construction steps (no missing links), the requirement that interactions between preceding level elements have to form the next level is too rigid to accept, for example, the eukaryote nucleus or the brain as a next level.

Maynard Smith and Szathmáry (1995, 1999) propose another constructivist example in the sense of lower level systems constructing higher level systems. They focus on *major evolutionary transitions*, including the following examples:

- A. From replicating molecules to populations of molecules in protocells
- B. From independent replicators to chromosomes

- C. From RNA as gene-and-enzyme to DNA genes and protein enzymes
- D. From bacterial cells (prokaryote) to cells with nuclei and organelles
- E. From asexual clones to sexual populations
- F. From single-celled organisms to animals, plants and fungi
- G. From solitary individuals to colonies with non-reproductive castes (e.g., ants, bees and termites)
- H. From primate societies to human societies and language

The rules for identifying and ranking the latter major evolutionary transitions still need to be discussed. This need becomes clear if we analyse the points A to H with help of the three dimensions for hierarchy that were introduced in the first paragraph of this introduction (interactive complexity, individual complexity and internal complexity). These three dimensions show that the ranking of the major evolutionary transitions is based on different types of hierarchy. For example, the transition from RNA to DNA in cells relates to the internal hierarchy, the transition from unicellular to multicellular relates to the formation of a new operator, and the transition from asexual to sexual and from individuals to colonies relate to interactions in ecosystems.

So far, the above and other theoretical developments have not resulted in a detailed, strict, evolutionary particle theory. Going back to basics, the following paragraphs, therefore, review historical developments that have helped to give insight into the evolutionary construction of 'particles', both in physics and biology. The aim is to offer the reader these insights as a context for discussing a comprehensive particle hierarchy in later chapters.

Hierarchy in particle physics

Particle physics has generally followed a reductionist approach because it explains the functioning of a higher level -- for example, molecules -- from the properties of smaller components, which in the case of molecules are the atoms (for historical overviews, see, for example, Close 1983; Perl 1987; Walker 2009). This methodology has strongly increased our understanding of the construction of matter and has resulted in a long sequence of increasingly small particles, down to the level of the quarks.

Although particles have shown a disquieting tendency not to be fundamental, a consistent application of the reductionist approach may eventually lead to the discovery of the smallest, truly fundamental kinds of particles, i.e., 'the building blocks of the cosmos'. If truly fundamental particles exist and a single logical theory can describe the laws determining their properties and interactions, science will then have found a 'Theory of Everything' (TOE) or 'Grand Unifying Theory' (GUT). These labels were originally used as ironic connotations of overgeneralised theories, but they have gained some acceptance in writing

about particle physics (e.g., Wilczek, 1998). As Laszlo (1994) has emphasised, a little prudence with naming such theories may be wise because the mechanisms described by the TOE or GUT do not reach further than particle physics and, for this reason, will fail to explain the emergence and functioning of more complex entities, for example, atoms, molecules and organisms. 't Hooft (1992) has also pointed this out when he stated that 'We are not at all capable of deducing the properties of a saw-bug from the standard model, and this will never happen, too'.

The history of particle physics dates back to the Greek philosopher Democritus (585 BC), who proposed that every kind of matter is constructed of small, indivisible particles, or atoms ('that which cannot be cut' is called *ατομος* in Greek). According to Democritus, many types of atoms exist and they make up all forms of matter. This atomist point of view goes back to Leucippus, Democritus's master. In 1808, the ideas of Leucippus and Democritus were revived by the English chemist, John Dalton. Dalton proposed a theory in which different chemicals were assumed to consist of indivisible particles, the atoms.

The idea of the indivisibility of atoms lasted until 1902 when Rutherford and Soddy discovered that some large atoms could disintegrate spontaneously into smaller atoms. About this time, Pierre Curie and his wife Marie Sklodowska discovered that the disintegration of uranium also formed new, smaller atoms, namely radium and polonium. In both cases, the disintegration of large atoms into smaller ones indicated that atoms were not indivisible. Yet, the divisibility of atoms did not immediately give further information about a precise substructure.

A few years later, in 1909, Ernest Marsden carried out experiments in which he bombarded a thin layer of gold with alpha particles (consisting, as we now know, of two protons and two neutrons) (Geiger and Marsden, 1913). His finding that only 1 particle in 10000 bounced back suggested that atoms mostly consisted of empty space, and that their mass was concentrated in a minute sub-volume. In 1911, Marsden's work and other experiments led Rutherford to conclude that the positive charge and the mass of atoms were located at the centre of an atom in a compact nucleus orbited at a large distance by electrons.

At the same time several factors indicated that nuclei were composed of still smaller elements. One was the regularity of Mendeleev's periodic table of the elements (1896). Another was Rutherford and Chadwick's observation that the bombardment of nitrogen nuclei with alpha particles formed hydrogen nuclei. In 1932, Chadwick discovered the neutron, and in 1935, Yukawa postulated that the proton(s) and neutron(s) in the nucleus were held together by the exchange of a small particle, which he called a pion. This particle was discovered in 1947 by Powell (Occhialini and Powell, 1947).

Later, it was demonstrated that every pion consists of two minute particles, and protons and neutrons consist of three. Gell-Mann named these particles quarks. Quarks were never found alone but always in pairs or triplets. That quarks were never found alone was explained by a theoretical model. The model states that the force that holds quarks together becomes stronger when the distance between the quarks increases. When the distance becomes large enough, sufficient energy is accumulated to form a pair of new quarks in the middle. Accordingly, separating a pair of quarks always results in two pairs of quarks. The grouping of quarks in pairs or triplets was explained by assuming that every quark carries a kind of charge, called its 'color', and that nature allows only neutral combinations of color charge, represented either by a color and an anti-color or by the combination of three different colors.

Current theoretical studies try to describe quarks, leptons and bosons as special configurations of hypothetical objects called 'superstrings'. Alternative descriptions of fundamental particles explore dressed or undressed manifestations of bare quarks (Greeb 2010) or relationships with bifurcation dynamics of self-organising dissipating force fields (Manasson, 2008). So far, no evidence has been found for particles smaller than quarks.

Hierarchy in the construction of organisms

One of the most exciting events in early biology was the discovery of the cell (e.g., Wolpert, 1995; Mazzarello, 1999). Until Antony van Leeuwenhoek (1632-1723) had invented the microscope, the cellular world was closed to investigation. With access to this new tool, van Leeuwenhoek made many observations that revealed the wonderful diversity of the small creatures that he described as 'animalcules'. His discoveries included many unicellular organisms, such as protozoa in water drops, his own semen and bacteria in dental plaque.

In 1665, Hooke described structures in cork as 'cellular' and concluded that these were channels for conducting fluid. However, he did not suggest that such cells could be the basal units of life. It took many more observations and some 200 years before Schleiden (1838) and Schwann (1839) coined the idea that all life was based on cells as the basal modules. Schleiden (1838) wrote that *'Each cell leads a double life; an independent one, pertaining to its own development alone; and another incidental, as far as it has become an integral part of a plant'*. Compared to plant cells, animal cells have much thinner membranes. This was probably the reason why it took until 1895 before Overton showed that the animal tissue also consists of cells with a proper membrane.

Around this time, scientists also started to investigate the cell's interior. Important cellular discoveries in this respect were those of the internal 'vesicles'

represented by the chloroplasts and mitochondria. Because they are large and green, chloroplasts in plant cells were observed by early microscopists, including Anthony van Leeuwenhoek. In 1682, Nehemiah Grew described green precipitates in leaves. His description is considered the first report of chloroplasts. Although the earliest descriptions of mitochondria date back to 1840, Richard Altmann was the first to specifically address these organelles, calling them bioblasts. When studying spermatogenesis in 1898, Carl-Benda introduced the name mitochondrion from the Greek words *mitos*, which means thread, and *chondros*, which means granule.

Meanwhile, Louis Pasteur (1822-1895) had shown that a culture medium remained sterile after heating. Pasteur's observations indicated two things. Firstly, a sterile culture medium had to be exposed to air currents before organisms present on dust particles could colonise the medium and propagate. Secondly, the chance that the chemicals in a given culture medium would spontaneously combine to form living cells (*'generatio spontanae'*) was apparently small or non-existent. In relation to these types of experiments, Virchow (1855) stated that all cellular life is derived from parental cellular life (*'omnis cellula e cellula'*).

The cell became a basic concept in biology, and in 1892, Wilson (Wilson, 1892) wrote that *'no other biological generalisation, save only the theory of organic evolution, has brought so many new points of view or has accomplished more for the unification of knowledge'*.

However important the cell had become, the idea that all cells originated from cells did not last. Regardless of how small the chance, when thinking about the emergence of life on earth, two possible explanations arise: one is forced either to accept a chemical origin for life on earth or to speculate that extraterrestrial life colonised the planet. Since the latter speculation contains the question of how these earth-colonising organisms came to be, both lines of explanation imply that a solution is required for the emergence of living cells from a chemical environment.

A range of theories has been proposed that have helped to understand the conditions that may be required for the emergence of life and to understand what constructions may be typical for the first cell (Oparin, 1957; Wächtershäuser, 2000; Eigen, 1977; Kauffman, 1993). In order not to invoke Dennett's 'skyhooks' (Dennett, 1995), his metaphor for the impossibility of top down constructions, scaffolding is required by which simple elements can pull themselves up by their bootstraps while creating the cell's complex ensemble, including the maintenance of its individuality on the basis of catalytic chemistry and a membrane (Conrad, 1982; Martin and Müller, 1998; Gánti, 1971; Hengeveld and Fedonkin, 2007). Although no approach has yet led to a *de novo*

construction of cells, the first cells must have had autocatalytic chemistry and a rather simple construction, while more complex structures, such as DNA and organelles, gradually evolved afterwards.

To define the cell's basic properties, the artificial life community frequently uses the concept of autopoiesis (Maturana and Varela, 1980). Interestingly, problems have arisen because the original definition of autopoiesis refers to a network of component production processes that continuously constitute the system as a concrete unity in space. Yet, the cell is an open system that depends on a continuous influx of substrates and efflux of waste. Some scholars now reason that, for example, in the case of spider venom, bacterial excretes and intestinal digestion fluids, the external digestion enzymes actually form part of the network of processes reconstructing the cell and that, for this reason, the membrane of the cell is not the limit for the autopoietic dynamics. This controversy indicates that autopoiesis should perhaps be more strictly interpreted, namely that the membrane should be considered a closed interface only for its mediating role in maintaining sufficient internal concentrations of those catalytic molecules that are directly involved in the cyclic basis of the autocatalytic process. This restricted interpretation of autopoiesis would sharpen Maturana and Varela's definition; it would more clearly explain that only the placing of the basic catalytic molecules outside the membrane would break up the cell's catalytic closure and place it outside the autopoietic domain.

Just as van Leeuwenhoek's invention of the microscope caused a revolution in biology because it made cells visible, the invention of the electron microscope in 1931 (Knoll and Ruska, 1932a, 1932b, Ruska, 1986) greatly enhanced our vision of the much smaller world hidden in the cell's interior. By 1935, an electron microscope had been built that had twice the resolution of a light microscope. In later years, electron microscopes would allow detailed study of the cell's broad range of structures, including the endoplasmic reticulum (named by Garnier in 1897), the Golgi apparatus (discovered by Golgi in 1898), mitochondria (named by Benda in 1898), and spindles and the nuclear envelope.

An exciting development with respect to mitochondria and chloroplasts was Margulis' hypothesis (1970, 1981) that these organelles evolved from bacteria that had invaded host bacteria and continued to live in it as endosymbionts (see also Schwartz and Dayhoff, 1978; Gray, 1992; Knoll, 1992). There is currently broad support for this theory, based on evidence that the endosymbionts have their own genetic material, produce their own cell membranes and multiply by cell fission. Nevertheless, questions still remain about how the symbiosis was established. In a recent publication Blackstone (1995) has asked attention for a units-of-evolution approach that simultaneously accounts for the gains and losses that the interacting cell types experience when living together compared

to when living separately in the environment. The approach also focuses on the difficulties both partners may encounter to communicate and, to a certain extent, to control the other. Recent discussions on an anoxibiontic origin of mitochondria can be found in Martin and Müller (1998), Doolittle (1998), Martin et al. (2001) and Martin and Russel (2003). These publications propose that a strictly anaerobic archaeobacterial host, that initially was not capable of digesting larger organic molecules, and a facultative anaerobic α -proteobacterium, that could digest organic molecules, may have been the first to establish endosymbiosis on the basis of H₂ and CO₂ production by the α -proteobacterium. The Archaeal host then metabolised the H₂ and CO₂ to methane. The latter theory also assumes that the development of a karyos took place after transfer of genes for the production of eubacterial membrane lipids to the Archaeal host.

Forms of endosymbiosis have recently been discovered that are even more complex than the mitochondria and chloroplasts in eukaryote cells. The complexity of such cell-in-a-cell relationships can be understood by focusing on the number of internal membrane layers. For example, all compartments in the eukaryote cell are surrounded by a single membrane whilst mitochondria show two internal membrane layers and chloroplast even have three. This method can also be used to analyse other remarkable endosymbiotic relationships. For example, in phototrophic cryptophytes, a red alga is contained in the rough endoplasmatic reticulum of the host. This means that four additional internal membrane layers can be found within the membrane of the endoplasmatic reticulum of the host. The first is the outer membrane of the endosymbiotic red algae. The second and third originate from the double membrane of the endo-endosymbiotic phototrophic bacteria, the thylakoid membranes of which form the fourth internal membrane layer. Another example is the alga *Peridinium balticum*. This heterotrophic dinoflagellate contains a phototrophic chrysoflagellate. A total of six membrane layers of the endosymbiont can be found within the host cell. The first is the cell membrane of the endosymbiont, and the second and third are from an extension of the nuclear envelope that surrounds the chloroplast. The fourth and fifth are the outer and inner membrane of the chloroplast, and the sixth is the membrane of the thylakoid vesicles. (Bardele, 1997).

According to the evolutionary viewpoint, the organisational complexity of organisms can be arranged in a large tree. The branching pattern of this 'tree of life' generally offers no explicit information about the structural complexity of the species involved, such as the presence of endosymbionts, a nucleus or the development of multicellularity. However, this problem can be solved by specifically highlighting the various complexity levels. Figure 1.3 (Alberts et al., 1989) shows how the 'tree of life' can be enriched with information about important levels of structural organisation. The figure shows the following levels: the cell, the eukaryote cell and the multicellular organism. The figure also

illustrates that the brain is regarded as an organ and not as a separate level of organisation.

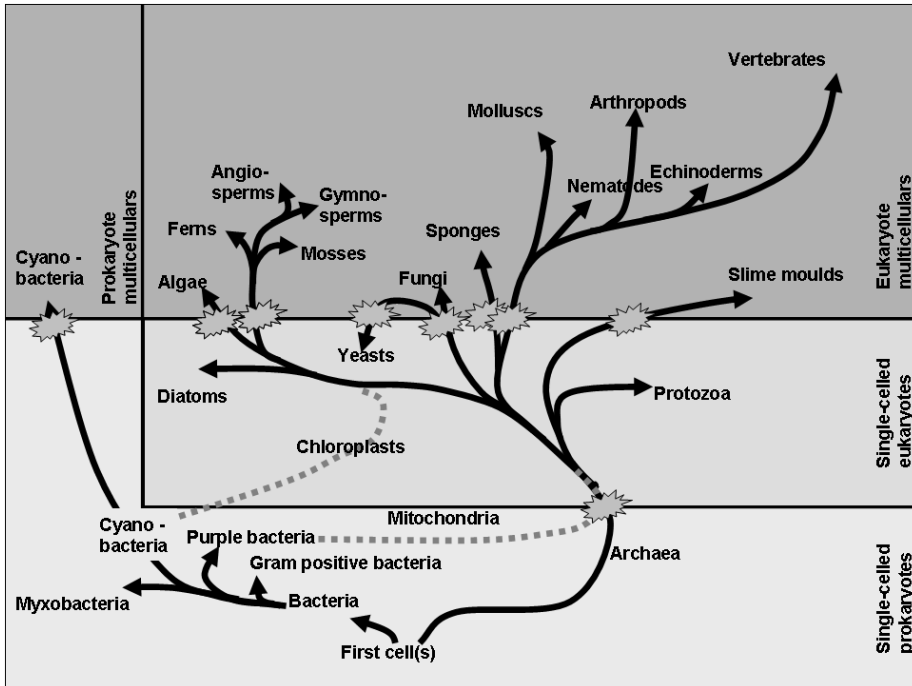


Figure 1.3. Representation of the 'tree of life' showing the historical speciation processes, the occurrence of endosymbiosis and the closure levels of the first cells, the eukaryote cells and the multicellular life forms (modified from Alberts et al., 1989).

A pioneer of particle hierarchy: Pierre Teilhard de Chardin

Teilhard de Chardin was one of the first scientists to combine a construction viewpoint with a focus on particles to create a worldview that incorporated physical particles as well as organisms in one large evolutionary hierarchy.

As a palaeontologist, Teilhard de Chardin studied the evolutionary processes of organisms, including the human race. His studies in China included early work on the Peking man, *Sinanthropus pekinensis* (presently classified as *Homo erectus pekinensis*). Teilhard de Chardin would probably be less known if he had not broadened his paleontological viewpoint to incorporate major aspects of the evolution of abiotic systems. Using his 'law' of complexity-consciousness as a central heuristic principle, Teilhard de Chardin created a unique all-embracing representation of the evolution of complexity in the universe. His extrapolations of evolution's course beyond the present allowed him to speculate about humanity's future. His approach was unique because it was predominantly based on particles, which he described as systems that were both 'formed' and

‘centered’. Due to this focus on particles, he could integrate evolutionary transitions between physical and biological particles into one large sequence. He thought this sequence showed a direct link with the chronology of the emergence of complexity and, therefore, with the genesis of the universe (ES VIII, p. 36; 1949).

Teilhard de Chardin called the core of his theory ‘complexification intériorisante’, or inward complexification, defining complexity as the result of relationships of elements amongst themselves. Following this reasoning, he arrived at two insights that are still relevant for particle-based evolution:

First, in the multitude of things comprising the world, an examination of their degree of complexity enables us to distinguish and separate those which may be called ‘true natural units’, the ones that really matter, from the accidental pseudo-units, which are unimportant. The atom, the molecule, the cell and the living being are true units because they are both formed and centered, whereas a drop of water, a heap of sand, the earth, the sun, the stars in general, whatever their multiplicity or elaborateness of their structure, seem to possess no organisation, no ‘centricity’. However imposing their extent they are false units, aggregates arranged more or less in order of density.

Secondly, the coefficient of complexity further enables us to establish, among the natural units which it has helped us to ‘identify’ and isolate, a system of classification that is no less natural and universal (ES V, p. 137; 1946).

These two points have remained relevant because they highlight some fundamental principles for identifying particles, distinguishing them from other systems and ranking them in a general hierarchy. Teilhard de Chardin’s work includes some personal points of view, of which the following are presumably the most relevant in the context of particle hierarchy. Firstly, he assumed a full correspondence between complexity and consciousness. For this reason, it made no difference to him to discuss the complexity or the consciousness of an atom. Next, he regarded evolution as ascending to consciousness and thus assumed that evolution would reach its zenith in some sort of highest consciousness (Teilhard de Chardin 1959). Subsequently, he predicted that all individuals in society would evolve to an integrated organisation/consciousness, which he called Omega.

The use of consciousness as a synonym for complexity merges a constructional and a functional property of multicellular animals. Unless we assume that consciousness is an esoteric phenomenon requiring no physical basis, consciousness is a mental process that is caused by interactions between brain cells, and, for this reason, functionally depends on a multicellular construction. Consequently, Teilhard de Chardin’s equating complexity with consciousness

implies the presence of multicellularity at all complexity levels, including, for example, the levels of unicellular organisms and atoms. The latter example shows that Teilhard de Chardin's viewpoint suffers from overextending the term consciousness, as Ulrich (1972) has also indicated

In principle, when extrapolating his particle hierarchy, Teilhard de Chardin used a scientifically acceptable heuristic procedure. The integration of multiple personalities into a single organism would be analogous in this context to the integration of atoms that create molecules, or cells that create a multicellular. However, as will be made clear in this thesis, there are serious problems with using the human phenotype as the basis for such integration. Furthermore, it is hard to defend Teilhard de Chardin's suggestion that Point Omega represents some final evolutionary unity because every historical step in the evolution of particle hierarchy has been succeeded by a next step. As a result, the claim that Omega suddenly would represent a *final* situation must be considered illogical and hence improbable, even though, strictly speaking, the successful occurrence of past steps does not guarantee the possibility of future steps.

Even though certain aspects of Teilhard de Chardin's philosophy can be improved, his ideas of inward complexification and true and false units as well as his comprehensive hierarchical ranking, including abiotic and biotic particles, are demonstrations of his visionary insight into the abstract nature of system hierarchy and into the universality of the evolutionary process.

Introducing first-next possible closure

The concept of closure, in particular that of first-next possible structuro-functional closure, is essential to the operator hierarchy. The next paragraphs introduce this concept.

What is closure? One of the oldest visualisations of closure is perhaps the ancient symbol of the Ouroboros, the snake that swallows its own tail and by doing so creates a closed structure: a circle. In more general terms, closure relates to the situation in which a set is closed for the performance of an operation on its elements. This leaves room for different closure types. For example, the set of integers {...-2, -1, 0, 1, 2, 3,...} is said to be closed under the operation of subtraction because the outcome of every subtraction is a member of the set. The set of natural numbers {1, 2, 3,...}, however, is not closed for subtraction because 2 minus 7 is -5, which is not a natural number.

The application of closure to system dynamics plays a major role in Heylighen's work (e.g., Heylighen, 1989a, 1989b, 1990). Closure adds a special property to a system because the state space of a closed system has become invariant (i.e., it does not change) under the internal dynamics (e.g., Heylighen, 1990).

Moreover, closed dynamics allow one to distinguish between the system and its surrounding world.

In the context of the operator theory, closure refers both to the closing process and to the closed (dynamic) state that results from it. Consequently, a closure is intimately linked to underlying mechanisms through the functionalities of the elements causing the closure. Once present, the closed system with its emergent dynamics gains mechanistic importance because it allows for discussion about the system's accountability as a unity, about novel dimensions for entropy production and about the sensitivity to novel selective forces. If there is no closure, there is no new unit that can simultaneously be the object and the subject in interactions.

In line with other publications (e.g., Heylighen, 1995), the operator theory distinguishes between functional and structural closure. Functional closure is defined as a group of elements that show a closed cycle of interactions that do not involve a physical mediating layer. Examples of functional closure are the autocatalytic set, the pion exchange between protons and neutrons in the atom nucleus, and the plasma strands connecting the cells of multicellulars. In contrast, the definition of structural closure demands that interactions create a physically closed topology. In the operator hierarchy, the focus is on a special form of structural closure, namely the structural closure that creates a physical boundary mediating a contained, first-next possible, hypercyclic process. Specific examples of structural closure in the operator hierarchy are the electron shell around the atom nucleus, the cell membrane of a single cell, and the connected cell membranes of multicellular organisms. Structural closure is important because the presence of a physical mediating layer is essential to defining a system as a 'unit' or as an 'individual'. For example, without the structural closure of a cell membrane, the catalytic molecules of an autocatalytic set would float freely in their chemical soup. They would drift apart, dilute or mix with other sets. As long as they can mix, it is impossible to identify the catalytic molecules as members of any autocatalytic set in particular.

While constructing the operator hierarchy, I aimed at a strict ranking of all elements involved because only a strict hierarchy can be used as a reference or 'yardstick' for complexity. Here strictness indicates situations in which it is impossible to include an element in a hierarchy or exclude an element from it without disrupting the ranking's logic. A consequence of a strict construction sequence is that all elements build directly upon each other (Fig. 1.4). Thus, all system types in a strict construction hierarchy can be seen as belonging to one large family tree.

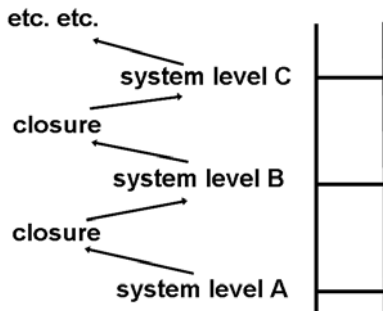


Figure 1.4. This figure illustrates closures creating a strict hierarchy of levels. The levels are only strict as long as every closure represents the shortest route to the next level system type.

Given the demand for strictness, the operator hierarchy has to be based on a rule that always produces the next particle -- nothing more and nothing less. To deal with the latter demand, the notion of closure has become the basic principle in all publications about the operator hierarchy. As seen from the publications in this thesis, the closure concept has been more precisely defined over the years. In the first publication on this subject (Jagers op Akkerhuis and Van Straalen, 1999), the rules defining the transitions were described as '*hypercycle formation*' and '*compartmentation*'. In the next paper (Jagers op Akkerhuis, 2001), the focus was on major and minor transitions. Major transitions were described as always relating to an emergent hypercyclic dynamic and an interface, while minor transitions '*reflect the emergent properties of major transitions occurring earlier*'. Still later, the aspect of first-next possible closure was introduced. In Jagers op Akkerhuis (2007), first-next possible closure is defined as follows: '*According to the operator viewpoint, an operator of type x creates a next operator of type $x+1$ by means of a first-next possible closure. ... The adjective 'first-next possible' refers to the demand that the closure must be the first possibility for a new type of closure in system $x+1$ after the preceding closure created the operator of type x .*'

First-next possible closure always indicates a new type of structural and/or functional closure. Using the combination of these closures as a means for identifying complexity levels has worked well for constructing the operator hierarchy. First of all, many steps in the operator hierarchy involve closures that leave little room for discussion, such as the construction of the hadron, the atom, the molecule and the cell. Concerning these closures, no relevant alternative closure states exist that could be inserted between the atom and the molecule or between the molecule and the cell. In addition, the use of structuro-functional closure also offers a simple and robust rule for recognising higher level closure steps. There is hardly a chance that the transition from unicellular to multicellular will not be identified because the cells show recurrent physical bonds (structural closure) and physiologically depend on each other (functional closure). The same holds for the transition from a prokaryotic to a eukaryotic cell, where the

endosymbionts/nucleus form internal compartments (structural closure) allowing for recurrent interactions between the new internal levels (functional closure).

First-next possible closure is not just a structural state and the operator hierarchy is not just a ranking of states. As stated earlier, closure stands for the closed states as well as for the self-organisation processes causing closure. This implies that for every transition in the operator hierarchy, the closure/closing process is intimately linked to underlying mechanisms. However, because every operator resides at a specific level in the operator hierarchy, it is an illusion to expect that a single underlying mechanism could explain all these transitions. Instead, the new properties created by the closure of an operator at level X have to allow for the dynamics that enable the closure of the operator at level $X+1$. Because every closure, in principle, is based on its proper mechanisms, an overarching mechanism can only be recognised at a higher level of abstraction. A good candidate for such an overarching 'mechanism' would be the process of first-next possible closure.

As a practical rationale that identifies the lowest complexity boundary of every closure type, first-next possible closure has allowed identifying the operators without major problems.

Processes, closures and operators

This chapter discusses the functional and structural aspects of all the individual transitions that formed all the different operators and/or intermediate closure states that were required for their formation. The individual transitions are discussed as part of the introductory chapter because the other thesis chapters mainly discuss the higher-order logic of the operator hierarchy and focus on the properties that certain types of operators have in common.

Because the operator hierarchy results from a construction process, a low level of organisation is required as a start. At this moment, the fundamental particles (the particles included in the standard model) represent the most fundamental level of organisation known. For this reason, fundamental particles are used in the following text as the starting point for analysing how closures create operators. This choice, however, implies no *a priori* assumptions about whether fundamental particles represent the lowest level in an absolute sense.

The sequence of first-next possible closures listed below includes situations in which the emergence of a next-level operator is analysed as consisting of two seemingly separate closures: one functional and one structural. The theoretical 'addition' of these closures must, in practice, be seen as functionally unifying both closures into one emergent process. For example, the formation of a

prokaryotic unicellular operator represents not just the addition of an interface to an autocatalytic set, but implies a functional merger as well, making both aspects fully dependent on each other.

As the following paragraphs focus on the construction of a type-hierarchy, the examples deliberately represent the simplest representations of their kind. Consequently, any real examples of these systems will generally involve more complex hypercycles and/or interfaces.

Fundamental particles: a first-order cycle

Fundamental particles split off and reabsorb virtual particles, such as virtual photons, in a process called self-interaction. Likewise, quarks show a continuous emission and re-absorption of gluons. In a Feynman diagram, the emission and re-absorption of a virtual photon by an electron or a gluon by a quark results in a straight line for the electron or quark, with the virtual photon or gluon line splitting off and curving back to it. The splitting-off and reabsorbing process can also be considered a life cycle from the quark state before emission to the next quark state, that is, after emission. Such a first-order life cycle is shown in Fig. 1.5.

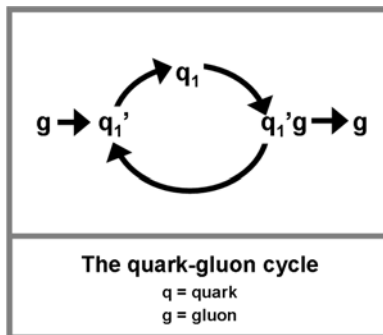


Figure 1.5. An example of a first-order interaction cycle based on quark-gluon exchange

Fundamental particles: a second-order cycle

At high energies, (e.g., in the extremely hot, minute, early universe) the weights of fundamental particles are enormous, their distances minute and the forces between them relatively small.

For this reason all fundamental particles, including quarks, are supposed to have moved around in a relatively unbound state in a kind of 'soup'. In this soup, the exchange of virtual photons caused two electrons to repulse each other, while the exchange of gluons between quarks led to mutual attraction. Attraction based on gluon exchange can also be depicted as two first-order interaction cycles that combine into a second-order interaction cycle (Fig. 1.6).

A construction rule of the operator hierarchy states that the highest complexity mechanism, which in this case is represented by gluon exchange, is the most likely candidate for integrating the first-order cycles. The quark-gluon exchange is complex because, unlike other force-conveying particles, gluons can split and reunite.

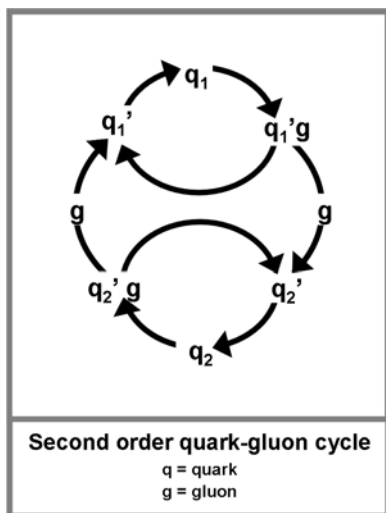


Figure 1.6. A second-order interaction cycle based on quark-gluon exchange

The emergence of the hadrons (in the cooling plasma)

The expansion of the universe cooled the quark-gluon plasma. This reduced the energy density to below the level where quarks and gluons condensate into small bundles of two or three quarks. This bundling is called confinement.

Responsible for quark confinement is the color force. This strong force originates in the color charge and is responsible for quark confinement. Color charge is conveyed by gluon exchange. As the result of the color force, single quarks do not exist because, like the stretching of a rubber band, the color force increases when two quarks are pulled away from each other. At a certain point, the energy in the stretched 'rubber band' becomes equal to the energy required to create new quarks. At that moment, the color force-field snaps and two new quarks are formed at the loose ends. The separation of two quarks always results in two pairs of bound quarks and never in two separate quarks.

The color charge comes in three colors: red, green and blue and three anti-colors: anti-red, anti-green and anti-blue. Quarks carry a single color: red, green or blue. Anti-quarks carry a single anti-color: anti-red, anti-green or anti-blue. Gluons are color neutral because they carry a combination of a color and an anti-color (for example, red/anti-green). Observations have shown that the color charge of a system of interacting particles must always be neutral and that the color charge must always be conserved in interactions between systems. It is

quite special that gluons carry color charge because other force-carrying fundamental particles, such as the photons that convey the electromagnetic force, do not carry charge themselves.

The emission of a gluon changes a quark's color because the gluon takes a color/anti-color combination when emitted. Thus, when a blue quark emits a blue/anti-red gluon, the quark changes color to become red (blue=red + [blue + anti-red]).

The color force is considered the mechanism causing the confinement of exactly two quarks in mesons and exactly three quarks in baryons. Mesons are relatively unstable because a quark and an anti-quark quite easily annihilate each other. A baryon is relatively stable. From all baryons, the proton is the most stable because it is based on the perfect combination of three quarks with different colors: red, green and blue.

From the perspective of the operator theory, particles consisting of two or three quarks are called hadrons. Hadrons combine two closures: the hypercyclic interactions resulting from second-order production-absorption cycles based on gluons, and the closure resulting from the confining influence of the color charge. The latter closure occurs if temperatures are low enough (Fig. 1.7).

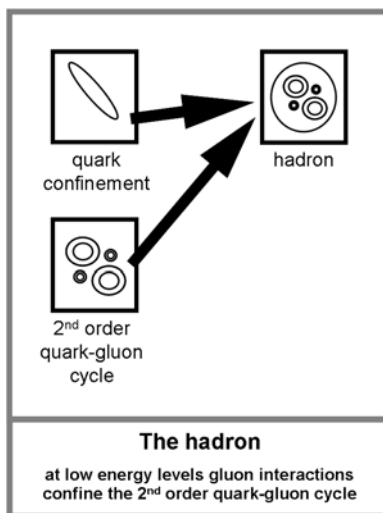


Figure 1.7. Formation of a hadron resulting from the combination of a second-order quark-gluon cycle and quark confinement

Hadrons: a first-order cycle

After creating hadrons, adding more quarks (assuming this will yield a stable system type) does not create a new system complexity. Higher complexity would be possible, however, if a hadron could support a cyclic process that could be used for higher order interactions. In the context of the operator theory, we should now look for the most complex mechanism allowing the simplest, new,

first-order cycle. The latter is represented by the emission and absorption of small hadrons. In this process, pions, which consist of a quark and an anti-quark, are the most important unit for two reasons. Firstly, pions are the lightest and therefore 'cheapest' to produce. Secondly, pions are the most stable of all mesons and can bridge a relatively large distance before they disintegrate. In fact, the swarm of pions surrounding a hadron is so dense that it represents the main part of a hadron's mass (Fig. 1.8).

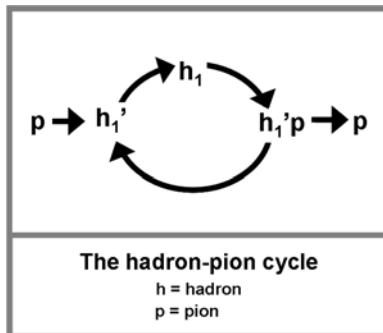


Figure 1.8. A first-order interaction cycle based on hadron-pion exchange

Atom nuclei: a second-order cycle

From the viewpoint of the operator hierarchy, the pion exchange between hadrons represents a second-order interaction cycle (Fig. 1.9). The exchange is an important mechanism for two reasons. Firstly, the force of the pion exchange is strong at small distances. It is so strong, in fact, that it overpowers the repelling forces between positively charged protons and, for this reason, can make protons and neutrons lump in small units, each called a nucleus. Secondly, without pion exchange, the universe would be devoid of neutrons because any separate neutron has a 15-minute half-life. At this decay rate, and without new neutrons being formed, the universe would have lost virtually all its neutrons within a few hours. By continuously exchanging pions, the protons in the nucleus change state to become neutrons and the neutrons change to protons. Thus, the neutrons are never 'pure neutrons' and cannot easily decay.

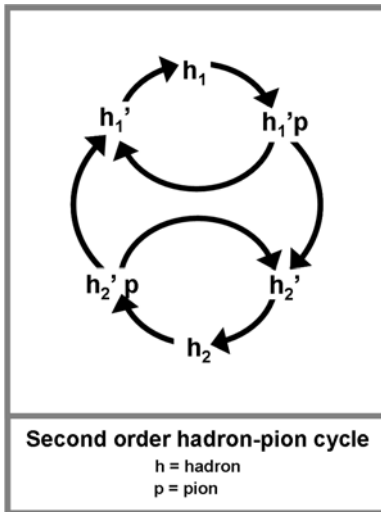


Figure 1.9. A second-order interaction cycle based on hadron-pion exchange

The electron shell

Nuclei were never alone in space. In the early universe they were surrounded by a dense ‘soup’ of quickly moving particles, including many other multi-hadron particles with which they could interact/mix. As long as the kinetic energies were high enough to overcome the repelling force of the positive charge of the protons, the ‘identity’ of the multi-hadron particles could change. The system changed when temperatures in the universe lowered because of expansion. At temperatures below 3000 °K, electrons became slow enough to be captured by the positive charge of the protons. After that moment, an environment that contained free electrons and bare nuclei condensed into the current state where the nuclei are surrounded by a number of electrons that fits closely to the number of protons in the nucleus. The result is a zero or close to zero net charge and the ‘interfacing’ of the nucleus by the electron shell inhibiting interactions between nuclei.

The atom

The atom results from combining the preceding two closures: the closure creating the hypercyclic interaction of the nucleus and the closure creating the interfacing by the electron shell (Fig. 1.10). These two closures together allow atoms to emerge.

Interestingly, because the operator theory demands a second-order interaction cycle as the hallmark of a nucleus, the system consisting of a proton and an electron, which is generally regarded as a hydrogen atom, is not considered an atom, but an atom-like interaction system.

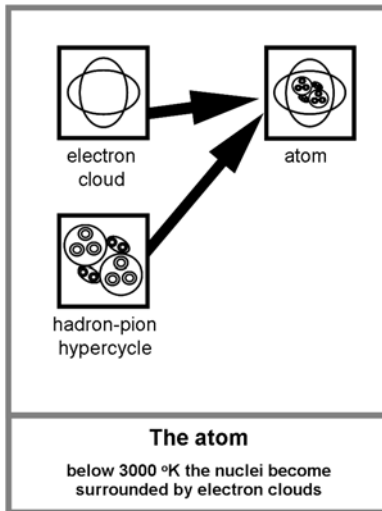


Figure 1.10. Formation of an atom resulting from the combination of a second-order hadron-pion cycle and an electron shell

The multi-atom (or 'molecule')

After the atom, the next most direct step in system complexity must come either from a closure in the internal structure of the atom, which the laws of nature do not allow, or from physical connections between atoms, e.g., a transition from a single-atom state to a multi-atom state. Multi-atom systems show a recurrent interaction between atoms due to their electron shell: they exchange electrons between their shells in what are considered 'covalent bonds' (Fig. 1.11). This exchange can result in grids (e.g., in metals) or in complex three-dimensionally organised structures (e.g., molecules).

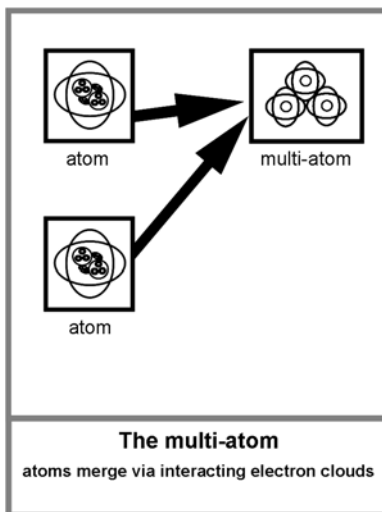


Figure 1.11. Formation of a multi-atom resulting from covalent bonds between atoms

The first-order catalytic reaction cycle

Adding atoms to any multi-atom system may create more complex molecules, but these will always be multi-atomary. For a next closure type, the operator theory suggests that one should look for the most complex emergent property. This is offered by the three-dimensional structure of connected atoms and the catalytic reactions which a three-dimensional structure allows for.

If we take an enzyme as an example of catalytic molecules, we can analyse its reactions as a reaction cycle. The catalyst (C) binds to a substrate (S) and modifies it. The result is that the substrate molecule (S) is changed into a product (P) and the original catalyst is regained. This process represents a first-order reaction cycle (Fig. 1.12).

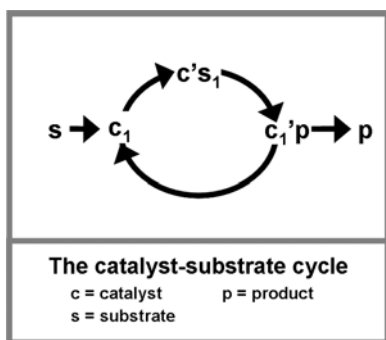


Figure 1.12. A first-order interaction cycle based on a catalyst that binds to a substrate and that is released after the formation of a product

The second-order catalytic reaction cycle: autocatalysis

In its least complex form, a second-order reaction cycle emerges when the product of a given catalytic reaction A equals the enzyme of cycle B and *vice versa* (Fig. 1.13). Such a reaction cycle is catalytically closed, which in principle allows it to catalyse itself as a set. This process has been named 'autocatalysis'. Various authors, notably Eigen and Schuster (1977, 1978a, 1978b, 1979) and Kauffman (1993) have proposed theories about catalytic hypercycles. Dittrich and Speroni di Fenizio (2007) have named a set of self-maintaining molecules an 'organisation'.

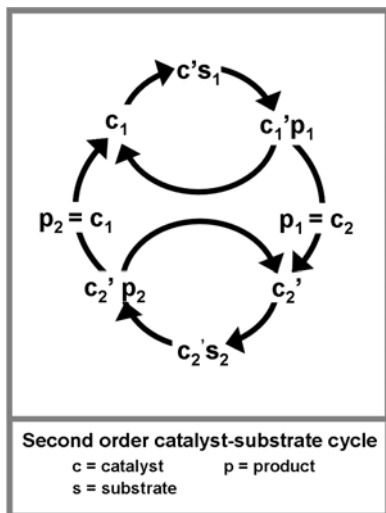


Figure 1.13. A second-order interaction cycle based on two catalytic reaction cycles that produce each other's catalysts

The cell membrane

The autocatalytic set can reach a spatial limit when the molecules form a kind of lumped aggregate or when a mediating membrane surrounds the hypercyclic reactions. A simple lumping of molecules creates a unit, but would still allow the mixing of such lumps and would not protect the autocatalytic set from disturbance of reactions by molecules from outside the lump. A surrounding layer that mediates the passage of molecules to and from the interior allows a system that does not show such problems. This advantage may explain why selective forces have favoured a membrane that surrounds the autocatalytic set.

From a chemical point of view, it is rather easy to form membranes from fatty acids in pro-biotic chemical environments. Various suggestions for such processes can be found in Oparin (1957), Claessens et al. (2007), Fanelli (2008) and Hernández-Zapata et al. (2009), among others.

The cell

As long as the reactions of an autocatalytic set float in a larger chemical solution and show no structural system limit, the set cannot be considered an individual entity. A lack of individuality is problematic in recognising when an autocatalytic set produces enough material to have made one or more copies of all its constituents. After a full round of catalysis, an autocatalytic set has, in principle, reproduced in some way, but what about the offspring? It -- or they -- float in between the parent's molecules and cannot be separated from them. As diffuse entities, the offspring cannot be recognised as units, and they cannot go their own way or experience individual selection.

Only a system limit that acts as an interface for the autocatalytic set (which does not imply that it acts as an interface for *all* atoms and molecules inside it) and that would at least result from the catalytic process but may also participate in it, would give the word 'autocatalytic' a structural meaning. Once surrounded by a membrane, every autocatalytic reaction cycle has become part of a structural unit, a cell, that can reproduce by forming new structural units or cells and that is recognised as an individual because of its unique autocatalytic set and membrane as system limit. The cell results from a merger of the closure creating hypercyclic interactions based on catalytic molecules and the closure surrounding the autocatalytic set with a membrane (Fig. 1.14). The two closures together define the prokaryotic/bacterial cell.

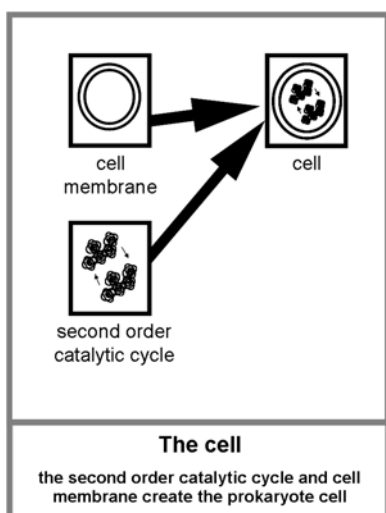


Figure 1.14. Formation of a cell resulting from the combination of a second-order cycle based on molecular catalysis and a membrane

As a consequence of cell-based autocatalysis, the cell's functioning goes hand in hand with the degradation of environmental energy. Any system that maintains or even increases its dynamic organisation by degrading energy from the environment is considered a dissipative system. This does not mean that all dissipative systems are cells. The structure of a tornado, for example, is created by a dissipating air-pressure gradient. Yet, a tornado does not conform to the first-next possible closures defining the cell.

Another consequence of cell-based autocatalysis is that the system must 'struggle' to stay alive because an autocatalytic set of molecules represents a dynamic equilibrium state between degradation of the set, on the one hand, and maintenance, growth and/or reproduction, on the other. This equilibrium shows a minimum complexity boundary. If more molecules are lost from the set than are required for autocatalysis, the circular chain-reaction breaks down and the system sinks below its lowest complexity boundary. In short, it 'dies'. To prevent death, or in other words, to stay alive, the cell must balance the production and

losses of the minimally required set of reaction-cycle molecules and membrane molecules to maintain itself. If no buffers are available the minimum requirement for survival/living is maintenance.

Cell-based autocatalysis may also lead to more than just survival. Under favourable conditions, the production rates of catalytic molecules and other products will exceed their degradation rates and this will increase the quantities of all cell constituents. With a doubling of all constituents, the cell can split in two without losing functionality. In principle, such an event marks the cell's reproduction.

Producing offspring represents an energy barrier. This situation is comparable to energy barriers in enzyme reactions. Analogous to enzyme reactions, passing the barrier represents a thermodynamically-favourable dynamic condition. Reproduction strongly increases the chance that the gradient dissipation processes will persist, while mortality will eventually block the process in all non-reproducing entities. When two or more cells reproduce and create dissimilar offspring that are individually selected for their viability in a given environment, one can start talking about Darwinian evolution.

The cell with endosymbiont/karyos

With respect to a first-next possible closure creating an internal compartment in the cell (Fig 1.15) one may consider two possibilities: the endosymbiont and the nucleus. As both possibilities involve structural and functional closure and uncertainty exists with respect to the events that have led to their formation, it is difficult to decide which of the two represents the first-next possible closure.

Support that an endosymbiont preceded the nucleus comes from genetic analyses (Rivera, 1998) and observations of traces of endosymbionts in so called 'primitive eukaryotes', the eukaryote cells that do not harbour endosymbionts (Clark, 1995). The presence of traces suggests that the studied cells have lost their endosymbionts in a process of evolutionary specialisation. Additionally, recent theories about the origin of the nucleus make plausible that genetic material coding for membrane lipids was transferred from an endosymbiont to the host cell. This transfer allowed the host cell to create a rich internal membrane structure that supported the development of a nuclear membrane (Martin and Russell, 2003). Functional dependence supposedly started with a strictly anaerobic archaebacterium hosting a facultative anaerobic α -proteobacterium. Endosymbiosis was established on the basis of H₂ and CO₂ production by the α -proteobacterium. The Archaeal host then metabolised the H₂ and CO₂ to methane (Martin and Russell, 2003). Further support that the endosymbiont represents the first-next possible closure comes from the non-nucleate phase the eukaryote cell passes during cell-division. This periodic loss of the nucleus is a strong indication that the nucleus never was an

endosymbiont, because an endosymbiont cannot easily 'abandon' its membrane.

Depending on the criteria applied, the endosymbiont and the nucleus can both be regarded as the first-next possible closure. Starting with a bacterial/archaeal cell, the property of engulfment of an endosymbiont may be regarded as the high complexity state that allows transition to the endosymbiotic state. In this case, the hypercycle of the endosymbiont causes the structural closure in relation to a hypercycle, and the recurrent interactions with the hypercycle of the host cell represent the recurrent functional relationship. However, after having transferred control over its metabolism to the host cell, one may also consider the endosymbiont as an organelle. The endosymbiotic organelle now allows for a high complexity cell, while the nucleus and its mediating role between two functional levels in the cell represent structural and functional closure. As the repeating of internal closure levels is not accepted by the operator theory, the choice for either one of these situations makes the other obsolete and will not affect the overall structure of the operator hierarchy.

In practice the coupling between the endosymbiotic relationship and nucleus formation is so strong that cells with endosymbionts that lack a nucleus play no role in existing phylogenies. On this basis, this thesis refers to endosymbiotic cells as 'endosymbiotic/eukaryotic' or as 'eukaryotic'.

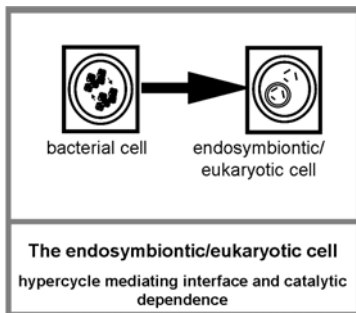


Figure 1.15. Formation of an endosymbiotic/eukaryotic cell resulting from the combination of a mediating membrane and a second-order catalytic set of molecules

The bacterial or archaeal multicellular

The literature offers various examples of non-endosymbiotic 'multicellularity' (Fig. 1.16) including Myxobacteria, Actinomycetes and Cyanobacteria (the blue-green algae) (e.g. Bonner, 1998). When considering multicellularity in the context of the operator theory, we should search for a new mechanism supported by the cell, because this mechanism will allow for a new closure type. The most complex state of a bacterial/archaeal cell shows internal compartments surrounded by membranes and can interact with other cells by means of plasma strands. Based on these complexity criteria, the operator theory regards functional differentiation of colonial cells not a sufficient criterion

for multicellularity. In other aspects, the discussion of prokaryote multicellularity does not differ much from the discussion of eukaryote multicellularity. For this reason prokaryote multicellularity is not addressed in more detail.

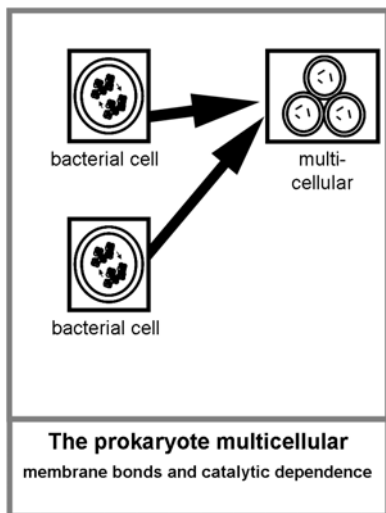


Figure 1.16. Formation of a multicellular operator resulting from recurrent bonds between cells and recurrent catalytic dependence

The eukaryote multicellular

Starting from eukaryote cells, the first-next possibility for closure is that in which interacting cells create a multicellular organism (Fig. 1.17). Independent development of multicellularity in many branches of the phylogenetic tree indicates the existence of powerful evolutionary forces in the direction of cell cooperation. A basic reason for this lies in intrinsic advantages, such as higher enzyme concentrations for digesting food, larger size and the three-dimensional use of space. Once multicellularity has developed, forces between interacting multicellular units will represent the dominating selective factors.

What exactly defines a multicellular organism? To be recognised by the operator theory as a unit system, the interactions between the cells in any multicellular should create a new emergent property that unifies the interacting cells both functionally and structurally. To become a structural whole requires structural closure, which means that recurrent structural bonds have to be created between the cells. Functional closure, then, requires recurrent interactions. This is fulfilled by mutual autocatalytic dependence of the cells. Based on this reasoning, I propose that multicellular operators can be defined as a group of cells that show a combination of structural linkage and functional interaction causing at least one recurrent process that, under ambient conditions, is obligatory for the autocatalytic functioning of the contributing cells. In cases where cells interact structurally and functionally but do not have to interact recurrently for their autocatalytic functioning, the cellular unit must be considered

a multicellular colony. Many multicellular systems, including mammals, pass through a single-celled stage (the zygote) and multicellular colonial stage (for example, the two-, four- and eight-celled stage of a human embryo) before they develop into a multicellular organism.

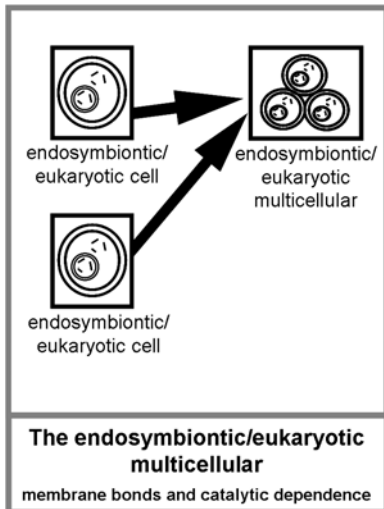


Figure 1.17. Formation of an endosymbiotic/eukaryotic multicellular operator resulting from recurrent bonds between eukaryotic cells and their recurrent catalytic dependence

Several reasons explain why the above general definition of multicellular operators allows many different system types. Firstly, cells can be connected in several ways. Secondly, cells may functionally interact in several ways. Thirdly, interactions between cells may be based on different combinations of structural and functional possibilities. Finally, as soon as organisms consist of many cells, the interactions between the cells may create hierarchies of internal processes that may range from local to general.

An aspect that is still not covered by the above definition is that interactions between cells may lead to different 'cooperation intensities' that lay between the following extremes: 'brittle' interactions and intense communication.

Relatively 'brittle' interactions are formed when the cells are bound in the least forceful way by membrane proteins and when the diffusion of proteins conveys the intercellular communication. In this case, the overall system is hardly more than a colony. The slug-like structure plasmodium illustrates this. A plasmodium is formed when many individually dwelling and genetically different cells of slime mould come together. The cells in the plasmodium are kept together by membrane proteins and communicate with each other through chemical signals. Together the cells produce higher concentrations of digestive enzyme, ensuring a better survival under low food conditions. They also reproduce together. To reproduce, they must depend on the multicellular stage to initiate differentiation and the construction of a stalk on which spores are formed.

At the other end of the spectrum, we find cells that intensively communicate through plasma strands. Such plasma connections are allowed through gap junctions between animal cells, through plasmodesmata between plant cells, and through incomplete cell walls such as in some fungi or developing insect eggs. Multicellularity requires, however, that only the plasma be connected, while the genetic material is retained in the cell.

From the point of view of first-next possible closure, the operator theory expects a new type of structural and functional closure as the basis for multicellularity. Because individual cells already can show chemical communication, multicellularity should involve a new type of intracellular communication. The most likely candidate for this are the above mentioned plasma connections between cells. Accordingly, the use of closure dimensions in the operator theory suggests that cells in a multicellular organism typically must communicate by means of plasma connections between their cells.

Several aspects in relation to the above definition of multicellularity require some discussion.

Firstly, although the above definition does not exclude an organism consisting of cells with different autocatalytic sets, genetic conflicts about which genetic material participates in reproduction will generally select against chimeras.

Secondly, the success of a multicellular organism in maintaining its organisation depends on its capacity to deal with prevailing environmental conditions and to adapt or to repair its organisation after it has been damaged, for example, the re-growth of a twig from a willow tree that has been stuck in the ground. If the weather is not too warm, too cold, or too dry, etc. and the stick has enough buffered resources, it may survive long enough to regenerate roots and start growing, and eventually become a willow tree. In extreme cases, even single cells of an organism can be induced to regenerate the multicellular structure. With a little help, for instance, by *in vitro*-culture, this applies to many plant cells. The callus that forms and the leaves and small plants that may emerge from it can be considered multicellular operators in the *in vitro* environment. Yet, they need roots and a certain size and strength before they have assembled all the tools needed for internal interactions to survive as a plant in an outdoor environment where they can develop towards a reproductive stage. The example of a twig shows that the interaction between the environmental conditions and the state of any particular multicellular organism determines whether a colony of cells can regain organism structure. The above definition of multicellular operators is explicit in recognising this relativity.

Thirdly, lichens and plants with mycorrhiza are 'multicellular organisms' consisting of two or more closely interwoven types of cells that belong to different species. As lichens frequently disperse in the interwoven form, it seems as if their reproduction is based on a mixture of cell types. However, lichens can be classified as a symbiosis because the fungi show sexual reproduction without the algae's genetic involvement and can survive, at least temporarily, as individual multicellular organisms during this stage.

Finally, a multicellular organism may produce structural material that supports its growth. This material is generally more persistent than the organism. For example, a flash of lightening may split a tree's bark and root system into two separate halves. These two halves may continue to grow. Although the two tree halves are still connected through the wood, they show no intercellular communication anymore and have become separate organisms.

The first-order neuron cycle

Because adding more cells to a multicellular organism does not affect its closure type, multicellularity forms a serious complexity barrier. The operator theory now suggests a search for the most complex property that interacting cells allow and that represents the shortest route to a novel functionality. If chemical communications between cells by diffusion gradients (as already existed as the basis for multicellularity) is compared with communication by cell-specific contacts over large distances that neural extensions of cells allow, the latter represents a new interaction and introduces a higher complexity interaction type. These qualities make it the preferred choice in the context of the operator hierarchy.

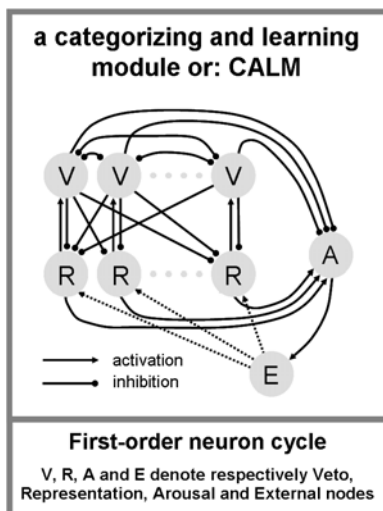


Figure 1.18. The figure shows a first-order interaction cycle based on neuron interactions. These types of modules of interacting neurons function as the most basal neural memory and are Called Categorising And Learning Modules (CALMs).

Based on interactions between nerve cells, groups of cells with closed excitation-inhibition dynamics can be created (first-order interaction cycle) (Fig. 1.18). Such groups of interacting nerve cells or 'modules' can exhibit special, novel dynamic properties. One example of such new dynamics is the categorising and learning function performed by the neocortical minicolumns. Another example is the oscillation pattern of 'interior olive' modules in the cerebellum, which function as neural metronomes (McCormick, 1995). Several authors have advocated that such first-order interactive modules are the brain's basic functional units (Mountcastle, 1975; Szentagothai, 1975). In the following text I will refer to first-order neural modules as 'Categorising And Learning Modules' or CALMs, a name that Murré (1992) and Murré et al. (1989, 1992) introduced for computer simulations of the neocortical mini-columns.

The neuron hypercycle

A disadvantage of the single CALM is that an earlier learned task is easily forgotten during the training of a next task. To overcome this problem, Happel (1994) has examined the possibility of coupling CALMs in a recurrent way (Fig. 1.19). Due to the circular stimulation of CALMs in a recurrent network, the interaction strengths of the connections between the cells in the CALM network adapt until they reach a stable state that supports dynamic patterns of nerve firing. These dynamic patterns can be periodic or chaotic. The transitions between periodic and chaotic behaviour are relatively abrupt. Such abruptness agrees with the almost discrete limits found in the state space of the neural network dynamics. These limits separate observations in what appears as distinct classes. The inclusion of a temporal aspect implies a large extension of state spaces compared to any first-order recurrent, non-hypercyclic network. As Happel (1997, PhD thesis chapter 4: 'Modular functions') shows, an interesting property of recurrent networks is that they can capture the complexity of newly learned tasks with little loss of earlier experiences.

The emergence of the neural hypercycle is the second time that an operator emerges as a consequence of an internal differentiation. The first case is, of course, the endosymbionts in the eukaryote. The reason why this 'internal' closure must be preferred above potential cooperation between organisms is that the operator hierarchy is based on first-next possible closure steps. Compared to cooperation between multicellular organisms (e.g. fungi, plants, algae), the interactions between multicellular neural units offer a more direct transition than those between individual organisms. The fact that the cooperation between multicellular organisms represents a less direct route makes organism interactions inconsistent with the operator hierarchy.

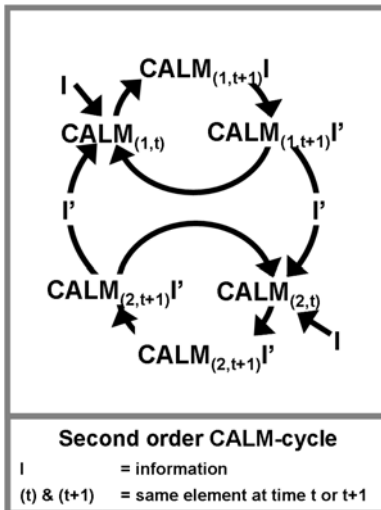


Figure 1.19. A second-order neural interaction cycle based on recurrent interactions between CALMs

The neural hypercycle probably emerged after primitive neural webs were formed. Several reasons explain why this sequence occurred. Firstly, the neural hypercycle requires a minimum amount of nerve cells to form neuronal modules and their interactions. Secondly, an organism needs 'knowledge' about its environment to survive. Plotkin (1994) defines 'knowledge' as any kind of system structure that enables an entity to respond to and act in its environment. Using this definition, there is no inherent knowledge in the CALM-modules of a newly born organism, because it has not yet learned anything. It is therefore necessary that an animal can start its life with a more or less prewired neural circuitry that allows for reflexes. Due to selected-for, gene-based ontogeny, these reflexes will provide the right responses to survive and to reproduce. In a later phase the supporting environment of a pre-wired brain will allow the emergence of brain structure that is capable of learning. As predetermined structure also strongly reduces the time to learn something, some predetermined structure in the brain is also useful for organisms that have to learn. The above discussion shows that learned behaviour, which is based on CALM-webs, must be considered to have evolved in a context of a hardwired brain that produces most of the organism's behaviour that it did not have to learn.

The sensory interface

The sensory interface that surrounds all hypercyclic neural networks has never existed as a separate entity. It co-evolved with the neural network in multicellular organisms and provided the neural network with information about its environment.

The sensory interface can be divided into two parts: an observing part, the 'perception interface', and an activating part, the 'activation interface'. The perception and activation interface are both integrated into the 'vehicle' in which the network resides. In organisms, the perception interface includes sensors focused on the outside world, such as eyes, ears, nose, etc., and all sorts of proprio-receptors within the organism such as chemo-receptors, stretch receptors, temperature receptors, etc. The activation interface includes nerves that, for example, stimulate muscles for activity directed at the outside world and stimulate the neuro-secretory cells for internal regulation of physiological processes.

The memon

The memon is created by a combination of two closures: a closure creating second-order recurrent interactions between neurons in a recurrent CALM network, and a closure creating a physical limit in the form of the sensory interface (Fig. 1.20). These two closures together allow the memon to emerge.

The name memon comes from Dawkins (1976) who used the word meme for cultural replicators that thrive in brains and for the artificially manufactured products of brains, such as books, computers, and so on. In the operator theory, however, the word meme is used in a differentiated way: it describes more precisely a whole range of memic entities that play a role in the functioning of memons.

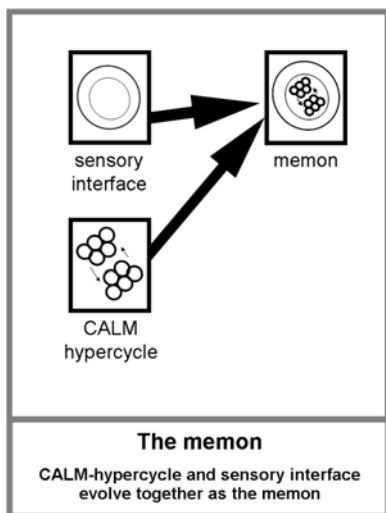


Figure 1.20. Formation of a memon resulting from the combination of second-order neuron interactions and an interface

A differentiated definition of a meme is required because memons may be involved in replicating various memic entities (Jagers op Akkerhuis, 2001):

1. Memons may exchange ideas. We suggest using the concept 'abstract meme' (or a-meme) for such abstractions, for example, melodies, ideas, stories, theories, and jokes that may reside in functional meme networks and can be transmitted from memon to memon in the communication process. This is closest to the meme concept as introduced by Dawkins (1976).
2. Memons will actively create physical 'traces' of their thoughts, such as books, houses, computers, radio waves, etc. These traces can best be designated as 'physical meme models' or 'physical memes' (p-memes) because these entities represent 'real-world/physical' representations of the abstract memes. A-Memes also replicate through these physical models because the observation of a nice model will inspire the observer to mimic it.
3. The concept 'coding meme' (or c-meme) could be used to define any string of codes that contains the information to construct fully or partially the neurons and connections of a neural network. Only if this code is supplemented with the interaction strengths can it be used to copy fully the network's knowledge. In fact, c-memes code for a neural network architecture and associated knowledge much in the same way as genes code for the chemistry playing a role in the survival of cellular beings.

As far as I know, the above way of differentiating between various memic entities does not yet play a role in modern 'memology' (e.g., Wilkins, 1998; Blackmore 1999).

In principle, memic neural networks are not necessarily bound to organisms but can be housed in any kind of vehicle. A memon may even be built from material other than organic cells. In fact, any material and any other signal transmission than electrical may be used. What counts is that the dynamic processes in a memon allow an equivalent of the neural hypercycle with interface.

Is the operator theory a falsifiable approach?

A good theory should be falsifiable. Because the operator hierarchy rests on mechanistic closure processes for every step in its construction and is not just a superficial description of some accidentally ranked system states, it should be possible to point out certain aspects of the theory that are open to falsification. This falsification process can be split into the following three questions that coincide with major aspects of the structure of the operator hierarchy:

1. *Can it be proven that the individual steps in the operator hierarchy are the first-next possibilities for the suggested closures?*

The operator hierarchy can be tested step-by-step to see whether it is based on existing system types and realistic pathways for their creation. This control method focuses on the physical existence of the system types in the operator hierarchy and on proof for the transitions through which they have been formed.

For most of the system types in the operator hierarchy, the physical existence is part of generally accepted scientific knowledge. Apart from philosophical discussions about how to prove that anything exists, little scientific doubt exists about the measurability of entities such as atoms, molecules, cells, etc. The fact that 'there really is something out there' that corresponds with our mental models is supported by the increasing accuracy with which these systems and their individual and interactive properties can be described and by the fact that the use of different ways of observation yield identical results (Kragh, 1999).

In this context the mechanisms have already been discovered by which relatively simple systems can be artificially recreated from lower level building blocks, for example, by creating hadrons from nuclear particles, atom nuclei from hadrons, atoms from nuclei and electrons, and molecules from atoms. Higher level systems have not yet been recreated by *de novo* self-organisation. Yet, I am confident that with increasing scientific insight and technology, the day will soon come when the cell will also be added to the list of systems for which it will be possible to recreate the appropriate self-organisation conditions.

All minor transitions in the operator hierarchy can be tested to see whether they comply with the concept of first-next possible closure. Testing this requirement is simple. One need only to show that at any position in the hierarchy, the present logic is incorrect and needs to be improved by adding a step that currently is not part of the hierarchy or by removing a step that currently is included in the hierarchy. If only a single system can be added or removed, the structure of the operator hierarchy in its present form must be considered invalid. This would lead to the need either to improve the operator hierarchy or, when this is not feasible, to reject it.

2. *Can the re-arrangement of the operators be tested to see whether they follow a coherent logic according to closure dimensions?*

The rules for recognising closure dimensions can be tested. For example, the interface closure dimension should successfully apply to all operators that it characterises. These operators are the fundamental particle, the quark confinement, the electron shell, the cell membrane and the sensory interface. The validity of closure dimensions can furthermore be tested by their extrapolation and subsequent use for predictions of future system types. This point refers to predictions of the emergent properties of several not yet

existing system types with a higher complexity than the hardwired memon and to the prediction that the present 'fundamental particles' (e.g., quarks) are the lowest level of closed, finite structure. Of course, the prediction of a system type that does not yet exist is difficult to falsify. The time may soon come, however, when complex memic systems will be constructed. At that future moment, it will become possible to show that, for example, hypercyclic technical neural circuitry must indeed form the basis for technical intelligence. Similarly, it can be shown that these future memons use structural auto-copying (the copying of the neural network) as a simple means to provide their offspring with the knowledge they need to live and to survive. The prediction that fundamental particles form the least complex, basic system type on which the operator hierarchy is founded would become testable with increasing insights into the lowest levels of matter's organisation. If a still lower level of organisation of matter based on structurally closed units could be proven to exist, this would lead to adaptation or rejection of the current structure of the operator theory.

3. *Is it possible to falsify the operator hypothesis? In other words, can the suggestion be proven or disproven that nature's possibilities for constructing closed system topologies are so limited that the currently identified operators and closures indeed represent the only options?*

Answering the latter question requires insight into the whys of all details of the operator hierarchy's structure. However, the most important question that needs to be answered is why every primary operator introduces a new closure dimension. Such insight is not only needed to understand the operator hierarchy, but it also offers pathways to falsify the operator hypothesis; a fundamental understanding may indicate that there are other ways to create closures/operators but these are not included in the present theory. Currently, this subject is unknown territory and offers a major challenge for future research.

In conclusion

Various fundamental aspects of the operator theory can be refuted in some way or another. Consequently, the theory represents a refutable construction.

Thermodynamics and stability

It is the author's conviction that a general approach to system hierarchy should fully agree with thermodynamic laws but should not be distracted by thermodynamic justification from its main theme: the hierarchy of organisation.

No system in our universe has ever been found to violate thermodynamics on a large scale and for a long time, or when it does, any increase in internal

organisation is compensated by a bigger increase in disorder outside the system's limits (Prigogine & Stengers, 1984). Since no deviations have ever been demonstrated from this rule, it is a rather theoretical exercise to demand proof that any existing system does not violate the laws of thermodynamics. A consequence of this reasoning is that self-organised system states must represent a thermodynamically advantageous phenomenon. Otherwise, nature would never have been able to repeatedly produce complex systems from less complex elements. In short, as long as we limit a general system hierarchy to systems that exist in our universe, we may take the thermodynamic justification for granted and focus on structural aspects of complexity instead. When predicting future system states, however, these states must be checked for consistency with thermodynamic laws.

In addition to thermodynamics, stability is another factor determining the presence of systems. The reason is that systems will be selected away when they are unstable as the result of a problematic internal organisation or as the result of disintegrating interactions with the environment. Only those systems that combine an easy production with a long enough 'shelf life' prevail in the evolution of system types. This is, for example, the reason why hydrogen is so abundant in the universe or why the light and easily formed pions convey the force between hadrons in the atom nucleus. And if an operator shows reproduction, the production of offspring allows it to escape the limits of its proper existence and structural stability by creating one or more copies before it dies.

Neither entropy production nor production of higher level particles is homogeneously distributed in the universe. Once organised structures have formed, increasingly complex structures start to emerge at an increasing rate. Kurzweil (1999) has integrated these observations into his 'Law of time and chaos', which states that *'In a process, the time interval between salient events (that is, events that change the nature of the process, or significantly affect the future of the process) expands or contracts along with the amount of chaos'*. Thus, in a chaotic environment, salient events occur at a low rate, and when order increases, this rate increases. Assuming that first-next possible closures can be regarded as salient events, Kurzweil's viewpoint fully merges with the operator hierarchy.

Outline of the thesis

The major aim of this thesis was to search for rules that guide the development of structural complexity in the universe and that can be used to create unity in science by improving the analysis of hierarchical organisation in biology, ecology and other sciences.

In relation to these goals, basic principles of physical and ecological hierarchies were studied. The need to follow a fundamental approach was based on the observation that these hierarchies were generally flawed by imprecise and/or overly general rules for selecting and ranking elements.

The subsequent search for a methodology that would allow a structured analysis of hierarchy was based on two premises: (1) all the elements in a strict hierarchy must have their proper positions, such that elements can neither be removed nor added without corrupting the hierarchy, and (2) it is possible to find a ranking rule to create a strict hierarchy for all particles in nature, regardless of whether these particles are abiotic or biotic.

It is thought that the value of the thesis lies in the fact that identifying a strict hierarchy is of general importance for science for two reasons. Firstly, it can have a restructuring influence whenever existing practice is flawed by less than strict hierarchical rankings. Secondly, a strict framework for the hierarchical ranking of operators can be used as a strong instrument to integrate different fields of science. The product of this thesis, therefore, must be considered of a qualitative rather than quantitative nature, in the sense that the final aim is to contribute to the structuring of scientific thought. In relation to the above goals, the subjects discussed in the chapters in this thesis are arranged more or less in order of increasing generality and from fundamental to applied topics.

Chapter 2. The birth of an idea

This chapter presents the basic principles underlying the operator hierarchy. The text elucidates the choices that were made to overcome major difficulties when deciding which elements should be included in the hierarchy and which should not, and the formulating of strict rules for ranking. In this chapter general rules for evolution are deduced. These rules can be applied to all operators, regardless whether they are particles or organisms.

Chapter 3. The future of evolution

Predicting is difficult, especially predicting the future. Yet, analogous to using the periodic table of elements to predict new atoms, the strict structure of the operator hierarchy can be used to predict new operators. All the operators predicted in the nearby future will be technical neural network organisms. The realisation that neural network organisms cannot use genes to copy their

knowledge forms the basis of a critical appraisal on the lack of parallelism between the concepts of genes, representing autocatalytic information, and memes, defined by Dawkins as cultural replicators.

Chapter 4. A backbone for system science

This chapter demonstrates how the operator hierarchy can be used to organise various aspects of natural organisation. It is advocated that the hierarchical relationships between the operators be ranked in a strict way, but that the situation is different within operators and in systems consisting of interaction operators. With respect to the latter situations, a new methodology is introduced that looks at hierarchical relationships from four different points of view: displacement, information, construction and energy (DICE).

Chapter 5. On life and death

The definition of life has long been a major puzzle in science. The difficulty of reaching a consensus may have various causes, including: (1) the difficulty of deciding on the minimum requirements that organisms must show to be considered living beings; (2) the fact that many definitions include facultative aspects, such as reproduction or metabolism; (3) the confusion about the concepts of life, as a property of matter, and living, as the dynamic activity of systems representing life, while there is also confusion about the use of life as the ensemble of all life on earth in contrast to life as a property relating only to organisms; and (4) the confusion about whether a mechanistic explanation of the cell offers a sufficient basis to define both bacteria, protozoa, plants and animals. In relation to the latter points, the operator hierarchy has the advantage of offering a completely new, hierarchical context to deal with problems of definition, which -- *mutatis mutandis* -- also helps to solve definition problems with respect to the concepts of the organism and of death.

Chapter 6. Getting the biggest part of the pie

Although Darwin talked about selection acting against the less well endowed, the evolution process became known as the struggle for life and survival of the fittest. Fitness has become related to the number of successful offspring. For various reasons, this represents a limited way of measuring evolutionary success. First of all, this idea makes it impossible to measure the success of units of evolution during periods when they are not reproducing, for example, when they are involved in non-reproductive processes, such as competition through subterranean shoots or the growth of a colony. Furthermore, abundance is not always an accurate predictor of the impact that offspring can have on ecosystem processes. To contribute to this topic, it is suggested to focus on the control that evolutionary units have over resources in their environment. In the same way as dimensions for hierarchy have been used in the operator theory, dimensions for resource dominance have been proposed for analysing evolutionary success.

Chapter 7. Towards consistent definitions for the operator theory

Although the operator theory represents a straightforward reasoning that focuses on how self-organisation steps produce a long sequence of operators, the reasoning behind this simplicity is quite intricate. To define as clearly as possible the logic of the operator hierarchy, this chapter discusses the definitions of the concepts used in the operator theory.

Chapter 8: Centripetal science: contributions of the operator hierarchy to scientific integration

The main goal of this thesis was to develop an integrating theory that can counteract the forces of hyperspecialisation and compartmentalisation resulting from the knowledge explosion. The most important result of this goal was the development of the operator theory. This chapter discusses the contributions of the operator theory to several well-known integrating theories, such as a cosmic timeline, ecological hierarchy, periodic tables, Darwinian evolution and also discusses a meta-level analysis of how unifying concepts can be linked to the levels of the operator hierarchy.

Chapter 9: General discussion and conclusions

This chapter places the conceptual framework of the operator hierarchy and its applications in a broader context. This process is guided by the search for answers to the following five questions: (1) what kinds of novel theoretic developments have accompanied the elaboration of the operator hierarchy, (2) what impacts may the operator theory have on science, (3) what aspects of the operator theory require discussion because of potential weaknesses, (4) how can the operator theory be evaluated, and (5) what routes are open for future development.

The birth of an idea

Operators, the Lego-bricks of nature. Evolutionary transitions from fermions to neural networks

What seems to physicists to be a hopelessly complicated process may have been what nature found simplest, because nature could only build on what was already there.
(Francis Crick)

Abstract

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, 1969, 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.

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, Belousov, 1993, Laszlo, 1994, Capra, 1996, Szathmáry and Smith, 2002).

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, 2000). For example, the cyclic restriction of enzymatic interactions and a confining cellular environment are required before the arising, 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 Fig. 2.1.A to illustrate the close relationship between structural and functional aspects of such systems. A less abstract version (Kauffman, 1993) is shown in Fig. 2.1.B 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 Schrodinger (1944), Prigogine and Stengers (1984), Eigen and Winkler (1983), Schneider (1988), Schneider and Kay (1994), 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.

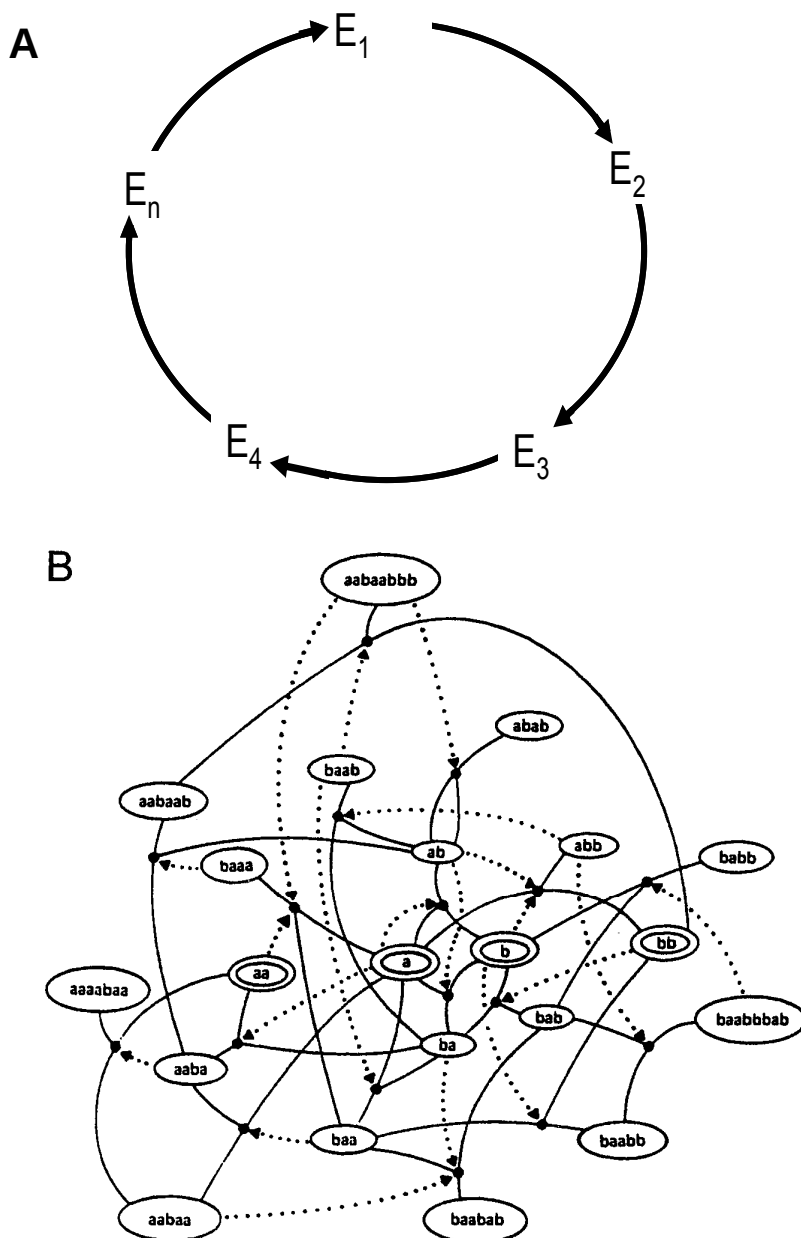


Figure 2.1. Two representations of an enzymatic hypercycle. Part A shows a more abstract, cycle oriented representation, which can be found in the work of Eigen (1977). Here E_1 to E_n represent enzymes. Part B shows a network representation of cyclic enzymatic processes (after Kauffman (1993) 'The origins 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.

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 (Fig. 2.2). 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 built 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 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).

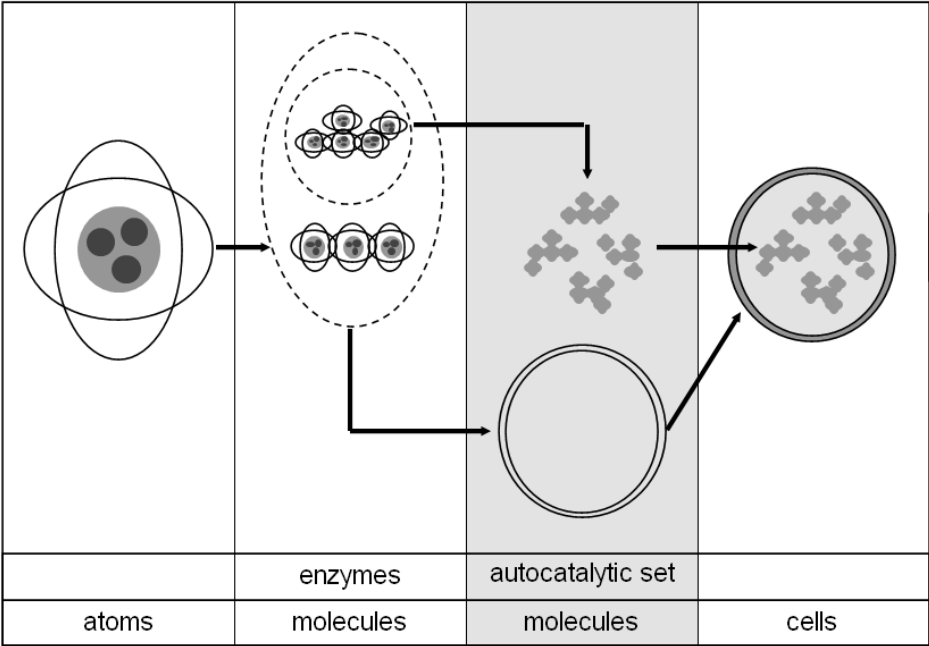


Figure 2.2. Example of a basal pattern in operator evolution: interactions leading from atoms to cells. The steps being explained in more detail in the text, the following phases can be distinguished. Atoms combine to molecules, some of which can act as enzymes. Sets of enzymes may show catalytic closure 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.

As is shown in Fig. 2.3, 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, Kaku, 1987, Witten, 1988, Hawking, 1988, ’t Hooft, 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.

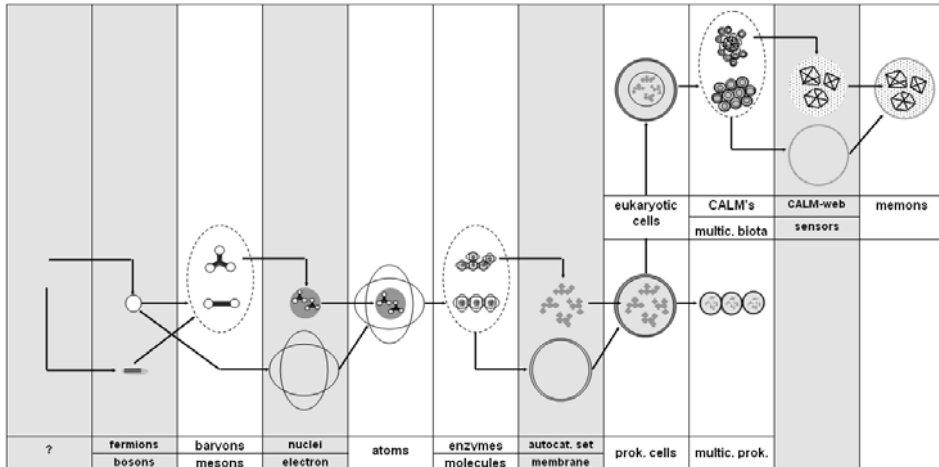


Figure 2.3. Inventory and ranking of all operator systems known to science. System types are ranked according to emergent properties as is explained in the text. Phases during which systems types are not considered operators are shaded. The inventory shows two marked regularities. Firstly, the sequence 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 Fig. 2.4.

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 neurosciences. 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 (Murre, Phaf and Wolters, 1989, 1992, Murre, 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 feed-forward 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 Fig. 2.3 in a staircase-like manner, as is shown in Fig. 2.4. 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. Fig. 2.4 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 level, that of neural hypercycles, does not yet extend beyond the memons.

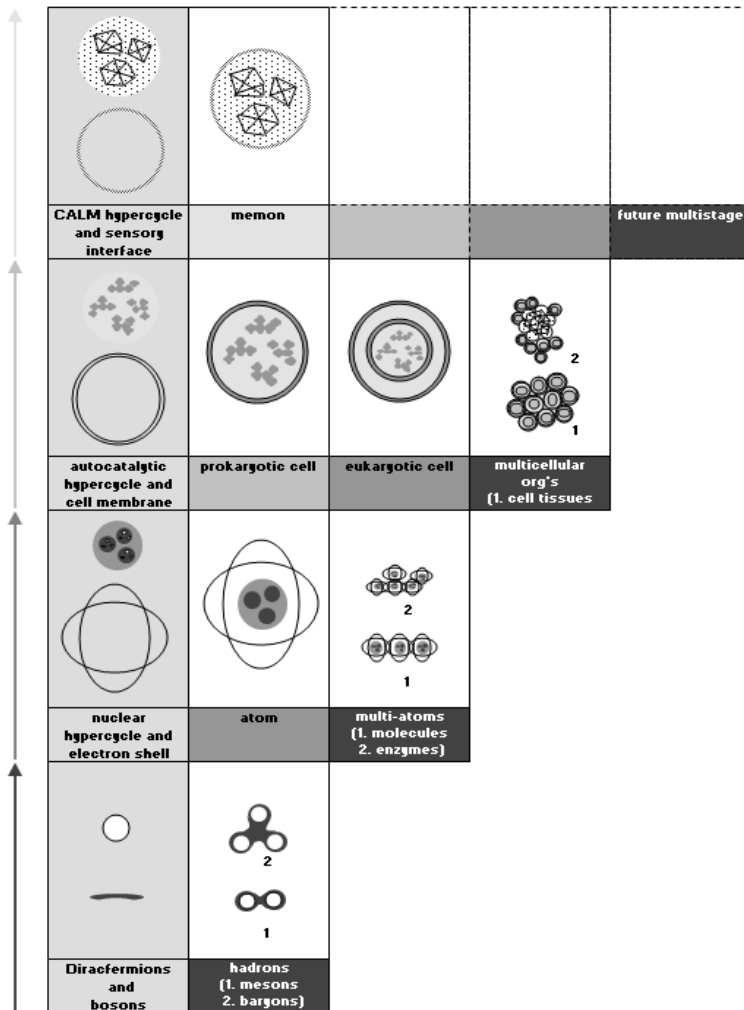


Figure 2.4. A 'periodic table of operators'. The inventory of operators shown in Fig. 2.3 has been split up into segments starting with a particular hypercycle (the grey bands in Fig. 2.3) and ending with multiplets of operators which contain this hypercycle. The vertical axis (A) indicates the occurrence 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 develop directly 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.

In addition to the connections between the rows, the scheme shows 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 emphasise 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 Fig. 2.3 and 2.4 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 operators¹. 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 1969, Pagels, 1985)

¹ While writing later publications, the picture of analysing hierarchy using three dimensions (interaction systems, internal differentiation and operators) emphasised that also internal differentiations may allow for the formation of more complex operators, for example the nucleus in eukaryote cells and the neural network in memons.

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 periodic table of atoms (Mendeleev 1871). In analogy, we expect that the periodic 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.

Acknowledgements

The authors thank the following persons for stimulating discussions and/or commenting on earlier drafts during the development of the above theory: J. Axelsen, W. Bakker, C. Damgaard, B. Happel, P. Henning Krogh, F. Jagers op Akkerhuis, H. Lakkenborg, H. Løkke, V. Simonsen, K. Skovbo Jensen and E. Wattel. M. Bayley is thanked for improving the English. This paper was supported in part by the project 'Complex Systems' of the Danish Ministry of Environment and Energy.

The future of evolution

Extrapolating a hierarchy of building block systems towards future neural network organisms

The future belongs to those who believe in the beauty of their dreams
(Eleanor Roosevelt)

Abstract

Is it possible to predict future life forms? In this paper it is argued that the answer to this question may well be positive. As a basis for predictions a rationale is used that is derived from historical data, e.g. from a hierarchical classification that ranks all building block systems, that have evolved so far. This classification is based on specific emergent properties that allow stepwise transitions, from low level building blocks to higher level ones. This paper shows how this hierarchy can be used for predicting future life forms.

The extrapolations suggest several future neural network organisms. Major aspects of the structures of these organisms are predicted. The results can be considered of fundamental importance for several reasons. Firstly, assuming that the operator hierarchy is a proper basis for predictions, the result yields insight into the structure of future organisms. Secondly, the predictions are not extrapolations of presently observed trends, but are fully integrated with all historical system transitions in evolution. Thirdly, the extrapolations suggest the structures of intelligences that, one day, will possess more powerful brains than human beings.

This study ends with a discussion of possibilities for falsification of the present theory, the implications of the present predictions in relation to recent developments in artificial intelligence and the philosophical implications of the role of humanity in evolution with regard to the creation of future neural network organisms.

Introduction

There is an old saying: to predict the future one has to know the past. But what should one think of as the past of evolution? How can the evolutionary process be traced back and what can historical steps teach us about the future?

Interpreting evolution in a broad sense, as has been advocated by Laszlo (1994), the evolutionary process has a long history; a history that goes back to a time when the universe showed little differentiation; it was small and extremely hot. It is now widely accepted that after an explosion referred to as the Big Bang, the baby-universe expanded and cooled down. From that moment onward, the overall universe became increasingly disorganised. Yet, some parts show a process of complexity increase, the occurrence of which is indicated by the subsequent emergence of new types of building block systems and associated interaction systems.

The building block systems are given special attention in the present study. From a beginning with only elementary particles, the universe has gradually become enriched by the emergence of more and more building block systems. Earlier studies focusing on these building blocks and their hierarchy include Feibleman (1954), Simon (1962), Bertalanffy (1968), Teilhard de Chardin (1969), Koestler (1978), Heylighen (1995), Close (1983) and Jagers op Akkerhuis and Van Straalen (1998). At present, the 'ancestral tree' of the building blocks includes the quarks, the hadrons, the atoms, the molecules, the prokaryotic and eukaryotic cells, the multicellular individuals and the multicellular individuals showing a neural network capable of learning.

As is discussed by Jagers op Akkerhuis and Van Straalen (1998) the emergence of any building block adds new aspects to the environment in which it interacts with all other building blocks. This environment consists of interacting building blocks and can for this reason be considered as an 'interaction system'. Examples of interaction systems are galaxies, stars, planets, stones, water, meteors, ecosystems and societies. As is shown in Fig. 3.1, a close relationship can be recognised between the hierarchy of building blocks and the ranking of interaction systems.

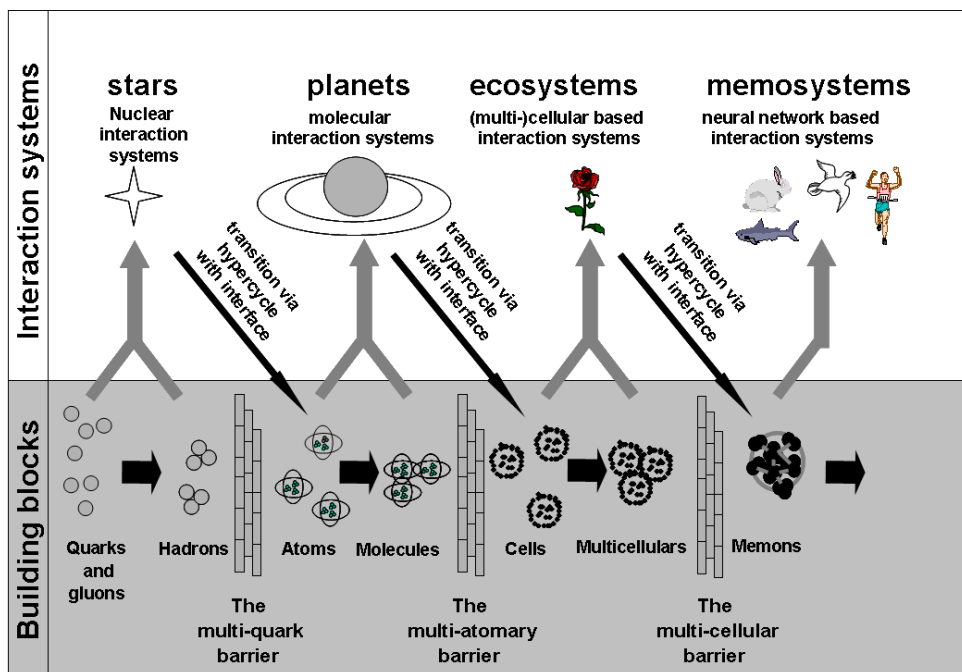


Figure 3.1. Building block systems and interaction systems. Lower part: building blocks and their multistages: quarks and hadrons, atoms and molecules, unicellular and multicellular organisms, and neural network organisms. Upper part: interaction systems such as the early universe, stars, ecosystems and societies. Horizontal, black arrows: transitions from a single operator to its multistage. Grey forked arrows: contributions of operators to the interaction systems in which they represent the highest level building blocks. Contributions of operators from lower levels are not indicated separately.

The main aim of this study is the prediction of new life forms via the extrapolation of the hierarchy of the building block systems. In this process we deliberately leave the interaction systems, i.e. stars, planets, etc., out of the discussion. This means that even though interaction systems play an important role as environments that mediate the emergence of new building blocks, the discussion in this study is limited to the formation of the building block systems. The reason is that their subsequent emergence can be ranked in a clear hierarchy offering a unique basis for extrapolations towards future systems.

In the form of the 'operator hierarchy' or 'operator hypothesis', Jagers op Akkerhuis and Van Straalen (1998) discuss the hierarchical relationships of natural building blocks. The building blocks were christened 'operators', for their capacities to operate in an environment and adapt their phenotypes to a broad range of environmental conditions, without losing the most essential aspects of their organisation. As the operator hypothesis holds such an important position

in the present study as the basis for all extrapolations, we will begin with a short resume of the operator hierarchy.

The operator hierarchy

The operator hierarchy (Fig. 3.2) is based on a strict, stepwise approach to the complexity of building block systems. Each step is the result of a specific emergent property that causes the transition from building block A at level X to a more complex building block B at level Y. Figure 3.2 shows that the approach recognises major and minor transitions.

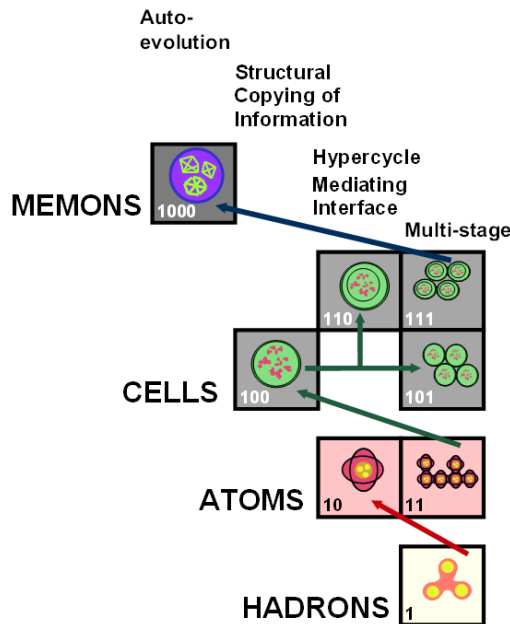


Figure 3.2. The operator hierarchy. The different evolutionary pathways (lines with arrows) are shown in direct relationship with the emergent properties of the operators (vertical columns). In accordance with the focus on major and minor transitions, the operators are given binary numbers. I: The hadron, 10: The atom, II: The multi-atom, 100: The cell, 101: The simple multicellular, 110: The eukaryote cell, III: The eukaryotic multicellular, 1000: The hardwired memon.

Major transitions

Each major transition, as recognised under the operator hypothesis, creates an entirely new operator type and the beginning of a new major layer (Fig. 3.2). Four examples of operators that according to the operator hypothesis were created via major transitions are the hadrons (the proton and neutron), the atoms, the prokaryotic cells and the organisms showing a hypercyclic neural

network. Of all operators, these four systems are special because each forms the first system of a next row in the operator hierarchy. For this reason they are also called 'first of the row operators'. According to the operator hypothesis, major transitions are always characterised by emergent hypercyclic dynamics. On the basis of enzymatic reactions in cells, Eigen and Schuster (1977) have described hypercyclic dynamics as being cyclic arrangements of elements which themselves are cycles of reactions. A very readable explanation of hypercyclic enzyme reactions in cells can also be found in Kauffman (1993). To define clearly what the operator hypothesis regards as the typical hypercyclic dynamic for each transition, the cycles and hypercycles are shown in Fig. 3.3 and will be discussed in more detail below. With the exception of the hadron, that has such low complexity that the multi-property just emerged and containment is not yet possible, all later major transitions are derived from multistage elements and show containment of the hypercyclic dynamics by an emergent interface.

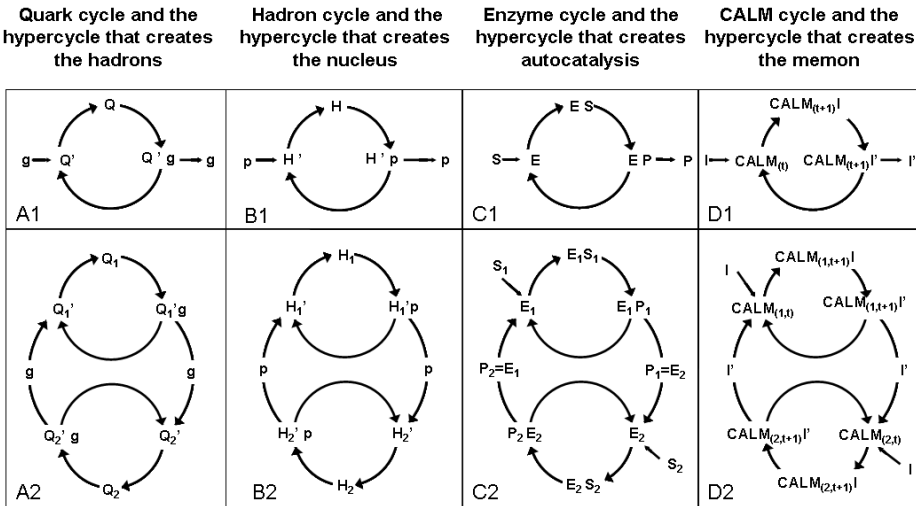


Figure 3.3. Emergent hypercyclic processes that mark the four major evolutionary transitions. A1: First order reaction cycle of a quark (Q). The quark emits a gluon (g) and becomes a lighter quark (Q'). A2: Second order cyclic process in which two quarks mutually exchange gluons. B1: First-order reaction cycle of a hadron (H). The three-quark hadron (H) emits and absorbs a small two-quark particle (a pion, p). B2: Second-order cyclic process in which two hadrons mutually exchange pions. C1: First-order reaction cycle of an enzyme reaction. The enzyme (E) binds to a substrate (S), transforms it to a product (P), and regains its original form. C2: Second-order cyclic process in which two enzyme reactions mutually create the enzyme for the other cycle. D1: First-order cyclic process on the basis of a group of neurons, called a CALM, because it acts as a categorising and learning module. The CALM_(t) receives information (I) and becomes a CALM_(t+1), which can forward information to become the original CALM in a new starting state CALM_(t+1). D2: Second-order reaction cycle in which the perception and release of information proceeds between two or more CALMs.

Minor transitions

The minor transitions are associated with emergent properties that occur within a major layer. The operator hypothesis states that these minor transitions reflect the emergent properties of major transitions occurring earlier. The names of the minor transitions are shown on top of the columns in Fig. 3.2. How the properties of major and minor transitions are linked is explained in short in the following lines.

The formation of the hadron is the first major transition. The hypercyclic dynamics in the hadron (see Fig. 3.3A1 and 3.3A2) create a system that shows emergent multiness of elementary particles. Multiness, as an emergent property, recurs from now on at each higher level, in the form of the last minor transition in every row.

The second major transition leads from the hadron to the atom (Fig. 3.2). In addition to a hypercyclic nucleus (Fig. 3.3B1 and 3.3B2), the atom shows an electron shell as interface that mediates the interactions of the nucleus with the world. This property is called a hypercycle-mediating interface (HMI). With the latter naming I deviate from Jagers op Akkerhuis and Van Straalen (1998) where this property is called internal information compartmentation (IIC). The reason is that more emphasis should be put on the emergent occurrence of the interface. From this moment on, the HMI property will show up in higher levels immediately before a multistage.

Some atoms may show a minor transition and become a multistage: i.e. a molecule, a metal grid, etc. Only a selection of these multistages, notably enzymatic catalysts can show a reaction cycle that can be linked in hypercyclic dynamics (Fig. 3.3C1 and 3.3C2). The latter marks the next major transition from molecules to cells.

Besides their hypercycle and containment, cells show the capacity to structurally auto-copy the information in their hypercycle. As can be seen at the top of Fig. 3.2, this property is called Structural (auto-)Copying of Information. The SCI property can be seen to recur, at any higher level, before the HMI stage that in turn precedes the multistage. From the prokaryotic cell, a minor transition may lead directly to the prokaryote multistage, as can be observed in blue-green algae. A different route leads first to the gaining of a hypercycle-mediating interface and then to the eukaryote multistage.

Within the multicellular environment, certain cells, the nerve cells, have gained the capacity to let thin cell extensions construct recurrent activation/inhibition interactions. In this way small units of cells are formed, showing a unit structure that in artificial neural network research has become known as 'categorising and learning modules' or CALMs (Murre *et al.*, 1989, 1992). These CALMs show a

recurrent interaction and thereby a first order interaction-cycle. If these CALMs are coupled again, creating a next recurrent connection, this results in a hypercyclic circuit (Fig. 3.3D1 and 3.3D2). The surrounding of these neural circuits by an interface of sensory/activation cells fulfils the requirement of the operator hierarchy for a next major transition; from multicellular individuals *without*, to multicellular individuals *with* 'brains'. Multicellulars with hypercyclic brains have been named 'memons' by Jagers op Akkerhuis and Van Straalen (1998) to which study we also refer for a more in-depth explanation of the latter transition. The word memon is selected as a general term for individuals that show an emergent hypercyclic neural network with interface. It should be noted that the group of memons includes all animals with a brain that, at least locally, shows hypercyclical activity. This implies that most animals and human individuals are included, but no plants or fungi.

How the memon may develop via minor transitions to more complex life forms is discussed below as part of the present extrapolations.

HOW TO QUANTIFY EMERGENT PROPERTIES

All emergent properties in the operator approach are based on changes in the organisation of the systems involved. A simple quantification of an emergent property is, therefore, not possible, because an emergent property implies a new system configuration, and its new property cannot be quantified in terms of the old configuration. This forms a serious obstacle for attempts at quantification. This general problem of emergent properties is discussed by Holland (1998) in his recent book 'Emergence'. We strongly support his proposal for a solution by defining emergent properties on the basis of special models called 'constrained generating procedures' (CGP). With respect to CGP models, Holland (1998) says: "The models ...are dynamic, hence *procedures*; the mechanisms that underpin the model *generate* the dynamic behaviour; and the allowed interactions between the mechanisms *constrain* the possibilities, in the way that the rules of a game constrain the possible board configurations." Thus, when basic functional elements, the mechanisms, create a constrained interaction pattern, a new system is created which, as an individual entity, may show unprecedented functional properties: the emergent properties. In line with the reasoning by Holland (1998) and Simon (1962) a CGP that shows persistent dynamics, may itself act as a building block for the creation of higher level CGPs. In the latter case, CGPs can be used as the building blocks of multilevel CGP hierarchies. This is exactly the way in which the present study deals with building blocks and emergent properties. By selecting persistent physical building blocks that themselves can act as the building blocks for the next level system, such as atoms, molecules, cells, etc. a continuous hierarchy can be recognised. On the basis of CGPs it is possible to formulate a mathematical

description for any emergent property, as is discussed in Chapter 7 of Holland (1998).

A few words should furthermore be directed to those that expect quantitative predictions from the present approach. In principle I regard the presence of a hypercycle as a quantitative aspect, namely as the prediction of a specific CGP, the structure of which can be quantified in terms of the links between the contributing mechanisms. Further quantitative predictions are not aimed at during the present extrapolations. The reason is that aspects regarded as quantitative, such as the weight, colour or DNA structure, are not very relevant in this context. The weight may help to describe a particular atom 'species' but different atoms can vary considerably in weight, ranging from helium to the trans-urane elements. A specific weight, therefore, is not a group property. Another example is given by unicellular organisms. These change weight/colour/precise DNA structure during their lives and/or between generations. Again, the weight/colour/DNA are not essential aspects of their group property, which is their existence as a cell. The observations that all species of atoms are atoms and all species of unicellular organisms are unicellular organisms are based on common properties shared by all members of the group. These *group properties* form the focus of the present study.

PREDICTIONS

The working hypothesis of this paper is that the internal logic of the operator framework (illustrated in Fig. 3.2) can be extrapolated to more complex systems than hardwired memons. As can be deduced from Fig. 3.2, all evolutionary stages that are presently predicted are memons. This implies that it may be wise to discuss some concepts regarding memic systems before we proceed, so that no confusion will arise when in a later stage exotic memic properties are discussed.

Meme concepts

In this study, the concept of a memon is used for any operator within the memic layer, e.g. all systems that show an emergent hypercyclic neural network and interface. The memons that emerge first will show a hardwired neural network that is based on autocatalytic cells, the nerve cells or neurons, or that is based on technical hardware. Higher level memons may also show a programmed neural network. Memons are involved in the copying of various memic entities, which we will define in more detail here. Firstly, the concept 'functional-meme' (or f-meme) could stand for the actual neural network that in its structure harbours learned knowledge and, therewith, abstract memes. Secondly, a 'coding meme' (or c-meme) could be used to define any string of codes that contains the information to construct a certain neural network. In fact, a coding

meme codes for neural network architecture and associated knowledge much in the same way as a gene code for a catalytic molecule playing its role in the survival of the cell. Thirdly, they may exchange ideas. We suggest using the concept 'abstract meme' (or a-meme) for such abstractions, for example melodies, ideas and jokes that may reside in functional meme networks and can be transmitted from memon to memon in the process of communication. This is closest to the meme concept as introduced by Dawkins (1976). Finally, memons will actively create physical 'traces' of their thoughts, such as books, houses, computers, radio waves, etc. These could best be indicated as 'physical meme models' or physical memes (p-memes), because these entities represent 'real world' models of the concepts represented by abstract memes.

Which rationale can be used for extrapolations?

The operator hierarchy offers a structured basis for extrapolations (Fig. 3.2). Yet, it can be deduced that there is an aspect of the predictions for which the historical data does not give full information on future possibilities. The reason for this lies in the question of whether or not the emergent properties are independent. In principle, each time an independent emergent property is added, this would double the number of possible system types. The operator hierarchy (Fig. 3.2) shows that for hadrons, there is only multiness. For atoms, there is a single degree of freedom, which leads to two system types: single atoms and multi-stages. Next, prokaryotic cells have two degrees of freedom, which leads to four system types: prokaryotic cells, eukaryotic cells and their multistages. However, even though the latter indicates two degrees of freedom, it cannot be deduced from this example whether the four system types are the result of dependent or independent combinations of the two degrees of freedom. For the next level, the memic level showing three degrees of freedom, this implies that it is not possible to predict whether six or eight memic system types will emerge. Independence of the emergent properties would result in a total of eight possible system types, e.g. $2 \times 2 \times 2 = 8$ combinations, dependence would lead to a total of six, because any next minor transition would only be possible following the immediately preceding minor transition.

Now that we have discussed some basic aspects of the present predictions the time has come to predict properties of future memons.

Prediction 1. The memic multistage: a robust prediction

Our first prediction is based on a conservative approach that selectively uses the most obvious aspects of the operator hierarchy: the major transitions. Major transitions are a robust basis for extrapolations because each time the multistage is reached, a major innovation, e.g. the creation of a new building block type, is obligatory for the continuation of evolution. For this reason, the iteration between 'first of the row' operators and their multistages forms a robust principle on which to base predictions.

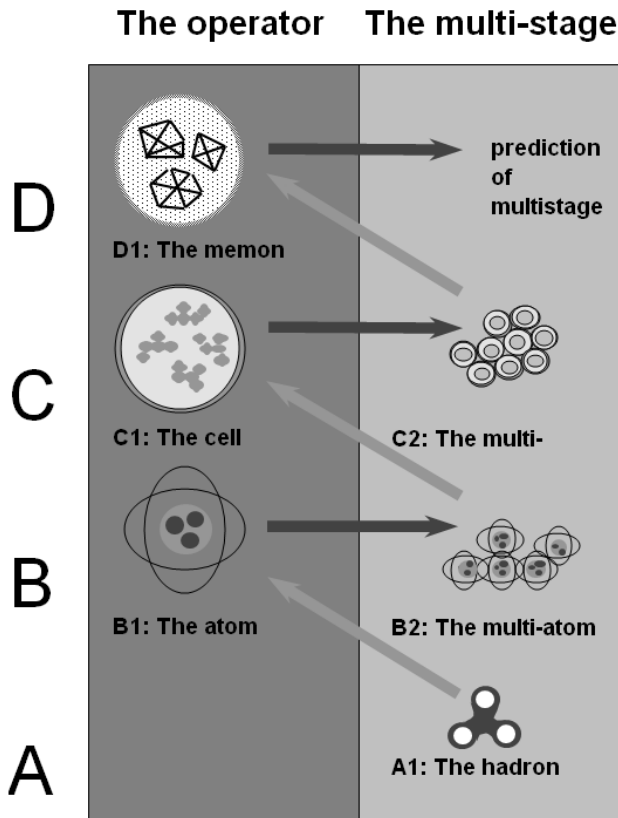


Figure 3.4. The lowest and the highest complexity operators that are based on systems showing the same type of hypercycle. A1: the hadron, a quark multistage. B1: The atom. B2: The atomic multistage. C1: The cell. C2: The cellular multistage. D1: The individual with a hardwired hypercyclic neural network. This is called the ‘memon’.

Focusing on major transitions only, the operator hierarchy can be summarised as is shown in Fig. 3.4. From this starting point, two predictions on future system types are available. The first prediction is that some day systems will evolve which show a multistage that is based on elements showing neural network architecture. The second prediction is that local units within this multistage will form the basis for a new cyclic interaction, which will lead to the next hypercyclic interaction forming the basis of the next evolutionary level.

As the above conservative prediction is strictly based on the most fundamental aspects of the operator hierarchy, there is a large probability that the prediction of a future multistage is correct. But how much information is gained with such a prediction? In fact, the information is limited, because insight is still lacking on the specific properties of the memons that form the building blocks of the

multistage. A most serious error, which is easy to make at this stage, is to start considering how, for example, human brains, as a neural network type of considerable complexity, can be imagined to function as a multistage. To do this would deny the possibility of stages in between any newly formed building block and its multistage (see Fig. 3.2). This may not seem problematic for the step from the atom to the multi-atom stage, because this step leaves no room for additional system types anyway. But serious problems arise for cells, which may be prokaryotic or eukaryotic, each creating its proper type of multicellularity. Prokaryotes have given rise to multicellular blue-green algae. Eukaryotes have formed fungi, plants and animals. There is a world of difference between the intercellular communication in blue-green algae on the one hand and that of fungi, plants and animals on the other. The lesson from this is that the complexity of the building blocks has a major influence on the potential complexity of the multistage. The assumption that human neural networks would be the building block for the multistage leads to the imagining of a multistage with ridiculously primitive properties. The error would be similar to explanations of multicellular life on the basis of prokaryotic units only. As will be shown in the following text, the solution to this problem lies in the recognition of the other steps of complexity increase that the operator theory helps to recognise between any newly emerged operator and its multistage.

Prediction 2. The hardwired memon and its multistage

The most straightforward detailed prediction is that the 1000-memon, or hardwired memon, develops directly to a multistage (memon 1000 and 1001 in Fig. 3.5). This results in a primitive multistage having limited prospects for becoming of any evolutionary importance. The reason is that the transition to this multistage will be difficult and slow, especially for memons based on cells. This is caused by two major drawbacks of these systems. The first drawback is that genes code for the structure and quality of cellular neural networks that, for this reason, can only evolve over many generations, via reproduction and selection. A second drawback is that their bodily construction and interfaces are based on organic cells, with many limiting consequences for the way in which they can become physically linked into a multistage and for the way in which the linked individuals can exchange information. The construction of a technical hardwired memon may improve on this situation, because its technical construction and interface would bring more powerful ways within reach for physical connection and communication with other memons.

Prediction 3. The SCI-memon and its multistage

Much more promising are the prospects for the pathway towards the structural (auto-)copying of information (SCI) multi-stage. For this pathway, a hardwired memon first evolves to the SCI-state before it evolves to a multistage (memon 1100 and 1101 in Fig. 3.5).

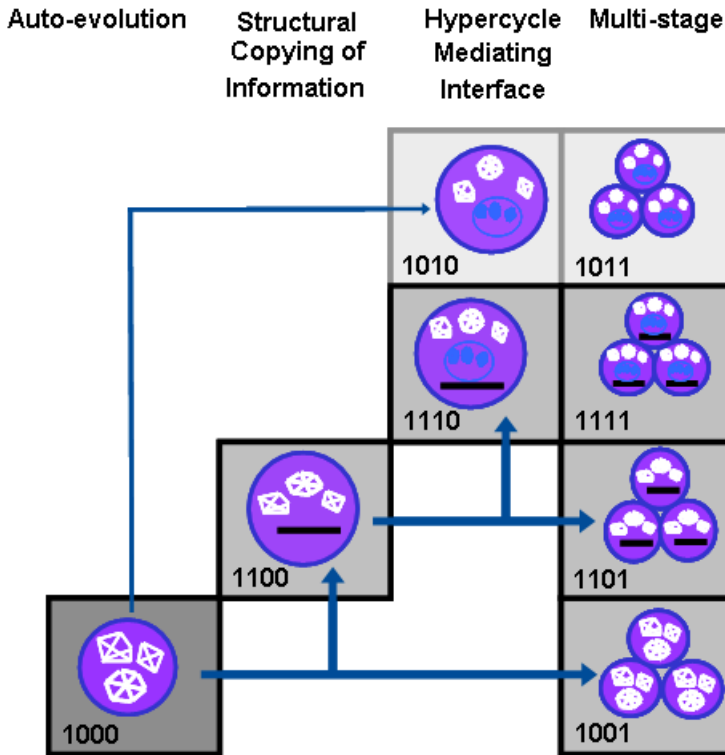


Figure 3.5. Predictions of future memons. 1001: Predicted multistage of the hardwired memon. 1100: Predicted memon with the SCI (structural copying of information) property. 1101: Predicted multistage of the SCI memon. 1110: Predicted memons showing SCI and Hypercycle Mediating Interface (HMI) properties. 1111: predicted multistage of the 1110 memon. 1010: Predicted HMI memon. 1011: Predicted multistage of the 1010 memon.

The SCI property has occurred earlier in evolution in cells. Here autocatalysis implies that a full structural copy of the information in the cell is produced, which, in present day cells is for the largest part allocated in DNA and/or RNA. The autocopying process for neural network information does not involve DNA. Yet, it requires that the memon can copy the architecture of all neurone connections and the interaction strengths of all synapse connections. This leads to the very strict requirement that it must have access to all this information. There is no way in which a memon can (auto-)copy its neural network without full information about the architecture and interaction strengths. It is hard to imagine how a cellular memon could do this. This would require sensory cells which by some means find out what cells are connected to each other and in addition measure the strength of each synapse and report this to the individual. Apart from the physical tour de force to host large amounts of additional sensory cells in the

brain, we consider the chance that this evolves naturally extremely small if not impossible. Even genetic manipulation may prove an insufficient tool to reach such a complex goal.

The prospects that computer based memons gain insight into the exact state of their brain are much better. The only thing they need is an extra interface that helps them read the arrays with information about their cell-cell contacts and synapse strengths, which information is kept off record anyway in programmed memons. From the moment that network structure and interaction strengths between cells can be examined, a whole world of new properties opens up, which allows a number of exciting predictions.

The first prediction based on the SCI property is that, for reasons discussed above, SCI-memons would with very high probability be technical constructions. Accordingly, the SCI-property strongly guides predictions in the direction of computer-based entities. Despite its technical construction, the SCI-memon and human beings have a similar basis for their neural network structure. In principle this allows for 'human' processes, such as intelligence, creativity, curiosity, etc. But a technical construction will also imply important differences with respect to energy procurement and living environment. Energy procurement will focus on electricity. And, because a technical memon does not breathe air, they can colonise underwater environments, planets without an atmosphere, or even a free position in space, supposing that other resources for normal functioning are available.

That SCI-memons most likely show a technical basis is furthermore of marked importance for the evolutionary debate. The reason is that SCI-memons cannot evolve as a special case of organic life. As they are technical constructions, it is simply impossible that they evolve as offspring from cellular parents. Instead, SCI-memons have to be built either by cellular memons, as a special kind of tool (a p-meme!) that starts defining its proper goals in life, or by technical memons, as a special kind of constructed offspring.

The moment that SCI-memons can copy their knowledge structurally this will cause an earthquake in memic evolution, the importance of which can hardly be overestimated. As an exploration of the possibilities, the text below gives some examples:

1. SCI-memons can for the first time in memic evolution reproduce their whole personality by simply producing a structural copy of their neural network. This copy will automatically contain all learned knowledge. Note that despite discussions about cloning, human beings absolutely lack a similar option. Humans cannot perform a structural reproduction of their whole personality, e.g. of all nerve connections and interaction strengths, simply because they lack access to the network topology and interaction strengths. What human

beings copy upon reproduction is the genetic coding for a human being which will show a mixture of parental phenotypic properties and which upon birth has a neural network showing a good deal of genetically based pre-structuring, but which is devoid of learned knowledge. This means that the body and the overall network structure are roughly copied, but without even a trace of anything the parents have learned. As the structural copying of the parental knowledge is blocked, the transfer of knowledge to the offspring requires a long detour via many years of education. For SCI-memons reproduction of their complete knowledge can take place almost overnight as long as an appropriate technical device is available to which the information can be copied and in which it can become operational. This shows that if the intelligent technical memon has taken shape, it is but a small step to a whole population of such memons. In fact, technical memons will find that the copying of a full parental network is costly in terms of energy and time. The parental memon may therefore consider the production of small network-vehicle combinations with the best possible capacities for learning and maintenance, and the capacity to actively enlarge their bodily and memic construction to develop into fully-grown memons themselves.

2. The working with and/or copying of network topologies will require some kind of coding to handle the information about the topology and the interaction strengths of the neural connections in the copied network parts. As discussed above, these code-strings hold a position in memons, which is similar to the DNA in cells. Where specific regions on the DNA, the genes, code for specific proteins, it will now become possible to recognise specific regions of coding, which code for network structures with certain properties.
3. SCI-memons can use the access to their own neural network to create one or more shunts of network parts, in each of which they can introduce small modifications to study which network configuration yields the best results. This implies that real-time, goal-oriented improvement of network configurations has become reality. In fact, not only the configuration of such networks can evolve. Several other features too may evolve, including the signalling procedures between neurons, the integration functions via which the neurons decide whether or not to signal subsequent nerve cells and the ways in which coding memes are coding for neural network constructions. Further aspects of technical memons that follow more or less from the above three points are also interesting. In order to stay focused on the major aspect of this study and avoid technical details, we will only shortly mention these aspects without going into details. These aspects are: the possibility of c-meme trade, the acceleration in memons of thinking speed with computing speed, the tendency towards the development of modular network architecture and the capacity of technical memons to integrate very different technical equipment directly into their interface.

SCI-memons have a much better chance of reaching multicellularity than the hardwired memons (1000 in Fig. 3.5). The main reason being, of course, that

they may show very high evolution speed, due to properties such as: a programmed network structure, the possibility of internal experimenting with network parts, the creation of similar copies, the acquisition of informed network parts via trade and the possibility of (re-)programmable interfaces. Increasing competition for living space on earth and for available resources in new environments, such as local networks of a company or a spaceship and larger networks, such as the global inter-net, will force SCI-memons to cooperate for survival. In some cases this will drive SCI-memons to dependence on cooperation and to structural connection, marking the transition to the SCI-multi-memon state.

Prediction 4. The HMI-memon and its multistage

The next predictable property of a future memic operator is that of Hypercycle Mediating Interface (HMI) (memon 1110 and 1111 in Fig. 3.5). Fig. 3.2 shows that the HMI property has occurred earlier in evolution, i.e. in atoms and eukaryotic cells. In atoms, the Hypercycle Mediating Interface emerges for the first time in the form of the electron shell. In eukaryotic cells the situation is more complex. Here, a new interface is added to the already existing interface around the cell, creating a second interface: the nuclear envelope.

In cells, large 'libraries' of information are stored in the form of DNA/RNA. In prokaryotic cells the unpacking of the information and the functioning of the coding for enzymes occur in the same compartment. In eukaryotic cells, the storage part of the information has become sequestered to the nucleus, from where coded information is transported through pores in the nuclear envelope to the soma before it is transcribed to functional enzymes. This shows that the nuclear membrane separates the cell into two compartments. In the nucleus the information of the cell is for the largest part handled in a coded form. Outside the nucleus the information is active in the form of enzymes. Accordingly, the HMI property is associated with an extra internal interface that separates different levels of the expression of the information.

This observation offers information about possibilities for future system configurations, because the continuation of this sequence would imply a three-layer HMI in future memons. But, assuming that this extrapolation is valid, it remains in our opinion quite hard to imagine at the present state of the understanding of the operator hierarchy what the second layer would look like in practice. Starting simply, two situations will be visualised showing an extra interface. These can then be combined to create a tentative prediction of a two-layer IIC-memon.

Imagining only a single layer, as in prokaryotic cells, it would be quite natural to assume that the HMI-memons find increasing use for coding memes, in the shape of code-strings that represent the topology and strengths of all the neural

connections of modular network parts. The reason for the popularity of c-memes is that they offer a highly efficient method of coding to store away all information that via experience and learning was gathered in the neural networks. This implies that, by using c-memes, little energy is required to maintain large reservoirs of knowledge, of which only a minor part would have to be unpacked and used in response to specific environmental conditions, after which it could be packed away again in its new, more experienced form. In contrast to networks and code strings that are stored temporarily in the active working memory of the memon, a more profound storage of c-memes would imply that these are stored away in a form which is not directly accessible, for example in a high capacity data-storage medium. A potential candidate for this process is the three-dimensional storage in crystals that are programmed and read by means of laser beams. But the storage and retrieval of large amounts of c-memes will require a special interface to decode the information. The new coding and the related interface would imply an additional Hypercycle Mediating Interface.

There is another way, via which an additional interface could evolve in these future memon systems. To understand this, we have to place ourselves in the situation of an SCI-memon that has just copied its network structure into a new vehicle. Unfortunately, this imaginary new vehicle which is furnished with a lot of new technical properties, differs in many aspects from the previous one. This implies that the memon has to go through a long process of revalidation and practice with its new 'body' for adjusting its neural circuitry to the new phenotypic properties. Such a practice period could be made a lot shorter, and larger differences between the old and the new vehicle could be allowed, if the neural network of the memon possessed translation interfaces allowing a rapid adjustment of the memon's 'proper' interface to various types of vehicles. It will probably be most efficient to have only a selection of such interfaces active, namely those that yield the highest survival value under given circumstances. Other interfacing networks can then remain stored as c-memes in the central meme library.

The combination of an internal c-meme library with a translation interface would, in principle, allow a two-level Hypercycle Mediating Interface.

Prediction 5. From the hardwired memon, via the HMI-memon without SCI properties towards the multistage

Assuming independence of the minor emergent properties, a comprehensive discussion of the possibilities for future memons should also include the route from hardwired memons to HMI-memons, without the intermediate stage of the SCI-memon (the route from memon 1000 via 1010 towards system type 1011 in Fig. 3.5). Even though it could be a theoretical possibility, the direct transition from hardwired memons to HMI memons must be expected to suffer from technical problems due to a low rate of evolution. The reason is that hardwired

memons cannot read their neural network state. If the HMI-memon without SCI properties will arise at all, it will certainly have problems reaching a multistage. The contribution of this option to the mainstream of operator evolution must, therefore, be considered minimal, and the existence of these type of operators be considered more of theoretical importance.

Conclusions and discussion

The above extrapolations present a panorama of possibilities for future organisms. First of all, it appears that the most likely next stages will be technical neural network organisms, because this is by far the most probable option for constructing a system type that can show structural auto-copying of information. The reason is the structural copying of information requires that the network structure and synapse strengths can be assessed by the organism itself and copied. Even if genetic manipulation were to proceed far beyond the present level, it is hard to imagine that brains could be developed showing extra cells in-between present brain cells, capable of analysing the neural network structure and reporting this to the individual. Secondly, the predictions strongly suggest that man must create the next stage in the operator hierarchy, because it is hard to imagine the development of a technical construction from a cellular basis. The predictions also show that, one day, neural network organisms can be created that can copy themselves. For this purpose one could simply imagine a 'body factory' constructing phenotypes that can be bought by any existing memon for the purpose of copying a neural network structure onto the new phenotypes computer space. From that moment onwards, humanity will have to live amongst such intelligent technical 'organisms'. Thirdly, the operator framework depicts evolution as an open, ever extending process, in which the next major transition coming will be based on a hypercyclic interaction between multimemic elements, most likely within the 'environment' of a multi-memic organism that is supported by a technical vehicle. Fourthly, the operator approach suggests that if technical memons are not constructed, this will block, on earth, the evolutionary sequence that leads from one operator to the next. We stress that this does not affect the evolution of cellular organisms, including cellular memons, which, of course, will continue.

One may now ask what the novelty is of the above insights, especially because there is a growing awareness that technical developments will before long create machines that will compete for resources with cellular life as we know it. For example Kelly (1994) in his book 'Out of control' uses citations of C. Langton to convince the reader that:

"There are these other forms of life, artificial ones that want to come into existence. And they are using me as a vehicle for its reproduction and its implementation'. ... 'By the middle of this century, mankind had acquired

the power to extinguish life. By the end of the century, he will be able to create it. Of the two, it is hard to say which places the larger burden of responsibility on our shoulders."

The new life-forms are frequently expected to become a threat. Warwick (1997) makes the following three statements in his book 'The march of the machines' in a chapter, which is called 'Mankind's last stand?'

"1. We humans are presently the dominant life form on Earth because of our overall intelligence. 2. It is possible for machines to become more intelligent than humans in the reasonably near future. 3. Machines will then become the dominant life form on Earth."

A last example of predictions of intelligent future life forms is given from Kurzweil (1999) who in his book 'The age of spiritual machines' presents a time line of the evolution of the universe. In the time-line section about the year 2099 he writes the following:

"Machine-based intelligences derived from extended models of human intelligence claim to be human, although their brains are not based on carbon-based cellular processes, but rather electronic and photonic equivalents'. ... 'The number of software-based humans vastly exceeds those still using native neuron-cell-based computation."

These predictions show that the idea of computer based intelligence has become a generally accepted subject amongst leading scientists. Also the present study shows that for our human successors, a life amongst technical memons simply represents the next stage in evolution.

Yet, in comparison to the above-cited deductions, there are several aspects in the present study, which offer exciting novel points of view. First of all, the just cited predictions lack a structural rationale. They reach as far as the extension of existing trends in computer speed, hardware capacity and programme complexity, but lack a backup by a hypothesis for the evolution of system complexity, for which we apply the operator hierarchy. The use of the operator hierarchy allows descriptions of structural properties of future system types and the indication of goals for construction efforts. Secondly, it is of importance that the aspects of the operator hypothesis are open to scientific inquiry and/or falsification. This holds both for the assumptions that underlie the steps in the hierarchy and for the overall rationale dividing emergent properties in major and minor transitions. Thirdly, by indicating a pathway for further development showing the structural aspects of future evolution, the question of how fast developments will go can be dealt with in a more precise way. Finally, the evolutionary rationale of the operator hierarchy shows that the coming into existence of the next system type is part of a larger evolutionary context. Accordingly, the present approach indicates the necessity that the human beings on earth start considering whether or not they want to live amongst technical

memons. In addition it extends this reasoning to considerations about mankind's role in the case where the decision is made not to produce these systems and therewith block the major evolutionary pathway on earth. All these statements deserve more attention and are discussed in detail below.

Degrees of freedom in the operator hierarchy

A question, which is left unanswered by the operator hierarchy, is whether the minor transitions represent independent degrees of freedom. In other words, can the properties of a layer, such as multiness, internal information compartmentation (HMI), structural copying of information (SCI) and auto-evolution, occur in random combinations or do they occur in sequence? The present understanding of the operator hierarchy does not allow a conclusive decision. This leaves an interesting field for further development.

Putting the operator hypothesis to the test

The most important assumption of the operator hierarchy is that hypercyclicity forms the major requirement for the major transitions in evolution. Furthermore, the containment of the hypercycle is also required for all operators of a higher complexity than the hadron, whilst both properties occur as emergent properties immediately after a multistage has been reached. This aspect is open to falsification both with respect to existing and future system types. The hypercycles and their containment have been discussed in the above text. For the transitions from hadrons to atoms and from molecules to cells there are no problems with the recognition of the just mentioned emergent properties. For the transition from multicellular units to the neural hypercycle the proof is still rather thin. If more evidence becomes available that the auto-evolving capacity of present day neural network organisms, such as humans, is strictly and only possible because of a hypercyclic coupling of neurons, this will support the theory. Turning the argument around, a proof for auto-evolving intelligence without hypercyclic circuits would falsify the present approach. Likewise, the assumption that the operator hierarchy includes all possible operators can be tested for validity. Proof that an additional operator exists in-between the steps of the present operator sequence would falsify the operator hypothesis.

When will technical memons become reality?

An important aspect of hypercyclic neural networks is that science has no means to predict the skills of any newly developed neural network architecture. This implies that it remains unclear how to construct the powerful neural networks that will finally allow technical memons to become intelligent. As the functional properties of neural networks cannot be predicted, skilled networks will have to be created via technical evolution, which implies the testing of large numbers of randomly constructed, simulated memons, the selection of the best as parents for a new series of networks, etc. The necessity of using trial and error when developing future intelligent neural networks represents the Achilles-

heel of computer intelligence. How soon computer based neural networks will become intelligent, and finally more intelligent than mankind, depends on how much the processes for the evolution of artificial brain structures can be accelerated. There are prospects for acceleration, because nature has already shown that an architecture on headlines, which at this moment is offered by genes, offers enough manageable modularity to produce human intelligence. The use of genetic codes as a basis for the evolution of brain structures can be imitated, also for technical neural networks. How this can be done has been shown by Happel (1997) and requires a smart combination of special genetic algorithms for neural network structure, efficient selection strategies and fast computers. As these aspects are all available, the evolution of intelligent neural networks can be expected in the near future.

From practical questions about survival amongst technical memons to philosophical questions about our impact on the major evolutionary pathway when the global population decides not to create them.

One of the major questions which are discussed in the recent literature (Kelly, 1994; Kurzweil, 1999) is whether humanity should develop intelligent technical memons if it is unpredictable how they will behave towards us. As they may become faster and more intelligent than human beings and, because they will also require resources for their functioning, it is likely that they will compete for resources with human beings and manipulate the behaviour of humans for their purposes. A little precaution in constructing 'them' may therefore be a good thing.

It remains an open question, though, whether it will at all be possible to stop scientific activities that finally lead to their construction. Given the more or less autonomous process of scientific innovation and development, it can be expected that even when the required knowledge is not specifically or purposefully developed, it will be developed indirectly.

So far, the aspects deal only with the consequences of the interaction between human beings and technical memons, not with more philosophical aspects of the choice (not) to create technical memons. This choice can be approached from at least two sides, a systems viewpoint and a religious viewpoint. From a systems viewpoint the operator sequence simply reflects a universal self-organisation process which proceeds as the blind consequence of earlier phases in the process. We can recognise a direction, but no goal. In this case evolution can be blocked without problems, because there is no reason why any next stage should be reached.

On the other hand, the evolutionary sequence of the operator hierarchy can be regarded as the reflection of some kind of larger plan. As it will be hard to prove

the existence of such a plan, I regard this as a religious viewpoint. Yet, under the assumption of a larger plan, it becomes extremely difficult to find valid arguments that give us the right to act against evolution.

The above shows that the question of whether or not technical memons should be developed is a complex case on which the last words have not been spoken. The operator hierarchy certainly deserves a place in this discussion.

In conclusion

The present paper has examined possibilities for the prediction of future organisms. For this purpose we began with a short resume of the structure of the operator hierarchy. Subsequently, the logic of the operator hierarchy was extended yielding several predictions of future memic individuals, for which the operator hypothesis strongly suggests that they will be of technical construction.

The present approach can be considered unique in its contribution to comparative system hierarchy because of the level of detail with which it predicts structural properties of future organisms. I consider it an exciting challenge to develop this field further and thereby improve the understanding of the cosmic evolution process and our capacity to predict more and increasingly detailed aspects of future organisms. The most direct practical value of the present predictions lays in the suggestion of hypercyclic neural networks as the basis of artificial intelligence. The fact that the operator hierarchy reflects a universal evolutionary process may also have some spinoff in the field of philosophy. I sincerely hope that the ideas presented in the above text will stimulate creative suggestions for elaboration and improvement.

Acknowledgements

We thank Peter Schippers, HenkJan Bulten and two anonymous referees for constructive comments on earlier drafts of this paper and Daphne Wittich-Rainey for improving the English.

A backbone for system science

Analysing hierarchy in the organisation of biological and physical systems

“Is evolution a theory, a system or a hypothesis?”

It is much more: it is a general condition to which all theories, all hypotheses, all systems must bow and which they must satisfy henceforward if they are to be thinkable and true.”

(Pierre Teilhard de Chardin)

Abstract

A structured approach is discussed for analysing hierarchy in the organisation of biological and physical systems. The need for a structured approach follows from the observation that many hierarchies in the literature apply conflicting hierarchy rules and include ill-defined systems. As an alternative, we suggest a framework that is based on the following analytical steps: determination of the succession stage of the universe, identification of a specific system as part of the universe, specification of external influences on a system's creation and analysis of a system's internal organisation. At the end, the paper discusses practical implications of the proposed method for the analysis of system organisation and hierarchy in biology, ecology and physics.

Introduction

Hierarchies of biological and physical systems published in the literature show inconsistencies in the use of ranking rules and element types. With the aim of improving on this situation, the present paper discusses an alternative method for analysing the organisation of systems.

A hierarchy can be described as a situation, in which entities are subordinate to other entities, the latter being considered as a higher level. The organisation of nature is profoundly hierarchical, because from its beginning, interactions between simple elements have continuously created more complex systems, that themselves served as the basis for still more complex systems. Scientists have sought ways to capture the essence of this complexity in easy to understand hierarchies, which typically rank systems in a linear way.

The literature offers numerous examples of linear hierarchies in biology and ecology. Koestler (1978) distinguishes the following levels in the internal organisation of organisms: organ system, organs, tissues, cells, organelles, molecules, atoms and sub-atomic particles. A hierarchy that focuses on abiotic elements is the cosmic onion (Close, 1983), which includes bulk matter (e.g. a planet), atoms, nuclei and quarks. A hierarchy by Weiss (1971) includes gene, chromosome, nucleus, cytoplasm, tissue, organism and environment. This range is similar to that proposed by Odum (1959) who visualizes a biological spectrum from protoplasm to cells, tissues, organs, organ systems, organisms, populations, communities, ecosystems and biosphere. Haber (1994) extends this range to organisational levels in the universe, from atom to molecule, protein molecules, cells, tissues, organ systems, organism, population, community, ecosystem, landscape, human society, biosphere, earth, solar system, stellar system and the universe. A similar structure, with even greater detail, is presented by Korn (2002). In what is called a hierarchy of biological levels of organisation, Høgh Jensen (1998) presents the following range: molecule, cell, organ, whole plant, plant community, pastoral system, farming and the agro-ecosystem. Focusing on energy budgets, de Kruijf (1991) presents a hierarchy in which populations are the elements for modelling energy budgets of communities, which in turn are the elements for modelling ecosystems, considered the basal elements of a landscape. Naveh & Lieberman (1994) present a similar ranking in which organisms are embedded in populations, populations in communities, and communities in ecosystems.

A problem with many of the above examples is that they are based on compromises with respect to the types of elements that are included and the ranking rules being used. To get an impression of these problems, one may look at the use of the organism concept in the following sequence: atom, molecule,

organelle, cell, organ, organism, population, community, ecosystem, planet and so on. This sequence suggests that all organisms form a uniform system class that can be ranked at one position in the hierarchy. Yet, the word organism is used for many different system types, such as bacteria, eukaryote unicellulars, and multicellulars without and multicellulars with neural networks. Each of these represents a system type deserving a proper position in a complexity hierarchy. In addition, every organism type has a different internal organisation, which also shows hierarchical aspects. For example in bacteria, this includes mainly molecules, whilst in multicellular eukaryotes this may include tissues, organs, specialised eukaryote cells, organelles, and so forth. It can thus be concluded that the analysis of hierarchy in biology requires at least two dimensions, one for the hierarchy of organism types and a second for the internal hierarchy. Also at the ecosystem level, the above example of hierarchy is not strict. For example, astronauts on the moon illustrate that the entire population of a species need not necessarily be part of one planet, but may be found distributed over several planets. We may thus conclude that there are serious problems with the rigour of any hierarchy showing similarity with the above example. This is a disquieting conclusion particularly because many hierarchies in the literature do show similarity with our example.

In relation to the latter conclusion, the main goal of the present paper is to suggest a method for analysing system organisation by means of a stepwise procedure that recognises different aspects of hierarchy and can be summarised as follows. The analysis starts with the largest system that is known, the universe, because this sets the stage for later identification of systems and the analysis of their organisation. Since its emergence, the universe has passed through a number of developmental stages that can be named after the highest-level elements (atoms, molecules, cells, etc.) that exist in the universe at a certain moment. To know the developmental stage of the universe is relevant for the analysis of system organisation, because it determines what systems may be present and need to be included in an analysis. Next, a local part of the universe is identified representing the system that we want to analyse. This can be a large system, such as a galaxy, or a small system, such as a molecule. The third step of the present analysis focuses on the way in which the organisation of the selected system may be the result of influences from elements surrounding it. The advantage of this step is that it makes visible mediating forces that have played a role during the formation of the system. This assures, for example, that the shape of the DNA molecule will be explained not only on the basis of its existence from nucleic acid molecules, but also in relation to its functioning in a cell. The fourth step can then be used to further analyse the organisation of elements in the selected system. This implies that the parts and their interactions are studied to create a picture of the internal organisation of the system. If necessary, iteration of the fourth step can be used to further analyse the internal organisation of each individual part of the system. The above

process prevents the analysis of a system from resulting in a simple linear representation. The above four steps can be summarised as follows:

- (1) The developmental stage of the universe is determined using the highest complexity system that is present.
- (2) A system is selected based on interacting elements that determine the type and scale of the system.
- (3) Mediating influences on the system are taken into account.
- (4) It is investigated how the selected system is composed of elements.

These four steps are explained in detail below, following the discussion of important concepts that form the theoretical basis behind the proposed analysis.

Theoretical basis of the analysis

Before continuing with an explanation of the proposed method for the analysis of biological/physical systems, attention has to be paid to a number of aspects that lie at its basis. These aspects include definitions of the system concept, hierarchy and mechanisms, the introduction of a strict basis for analysing hierarchy in systems, the discussion of viewpoint dependence of hierarchies and the occurrence of transitions between system types.

(1) Systems, hierarchy and mechanisms

First, it is useful to discuss definitions of biological/physical systems, elements and hierarchy.

(a) Biological/physical systems and their elements

The system concept is derived from the Greek word *synthithemi*, meaning 'I put together'. Systems consist of parts that belong together because they show a relationship. These parts are also named elements. To be considered an element, an entity needs to show at least one relationship with at least one other entity, in this way creating the system that it can be regarded as an element of. By accepting that the universe represents a system which does not contribute to any higher-level system, the universe becomes a primeval system concept. All systems in the universe can subsequently be regarded as elements, representing equally many biological/physical sub-systems.

(b) Biological and physical systems

When regarding systems as biological or physical this implies that these systems show a material and/or energetic existence. According to this focus, the concepts of wood and marble are excluded from the approach, while the specific brain states that are associated with a human's thought about the categories 'wood' or 'marble' are included. This excludes from the analyses any hierarchies

that are based on temporal, spatial or symbolic aspects such as duration (seconds, minutes, hours, etc.), separation (various measures for lengths, surfaces, volumes, etc.) and numbers (1, 2, 3, etc.).

(c) Hierarchy

The hierarchy concept relates to an ordering of entities into a sequence that is based on a relation that shows three properties (e.g. Bunge, 1969; Simon, 1973): (1) It is transitive, which means that if a has a lower hierarchical position than b and b has a lower position than c, then a has a lower position than c. (2) It is irreflexive, which means that a can never hold a hierarchical position below itself (3) It is asymmetrical, which means that if a holds a lower position than b then b cannot hold a lower position than a. The latter implies that as soon as a group of entities shows a circular relationship, one must consider them as having 'stepped out' of the particular hierarchy. Elements showing a circular relationship require a new way of analysis, basing hierarchical considerations on the relationships between different groups of circularly related elements.

In system science, the importance of a circular pattern of relationships has long been underestimated. It is only recently that an increasing body of literature has arisen emphasising the importance of circular interaction patterns for recognising elements and hierarchy. Such publications include discussions of the hypercycle (Eigen & Schuster, 1979; Kauffman, 1993), emergent organisation (Laszlo, 1996; Ponge, 2005), major evolutionary transitions (Maynard Smith & Szathmáry, 1995a, 1995b), meta-system transitions that are regarded as the quanta of the evolution of complexity (Turchin, 1977), relational closure (Heylighen, 1989a, 1990), closure in different scientific contexts (Bunge, 1992; Chandler & de Vijver, 2000) and the operator hierarchy (Jagers op Akkerhuis & van Straalen, 1999; Jagers op Akkerhuis, 2001).

The concept of hierarchy has a long history and has been applied in many different ways and situations of which a few examples will be discussed presently. A well-known approach to system analysis uses the three-level hierarchy that includes the world, the system and its elements. Applying this approach in an iterative way, the former system and element become the new world level and system level of the next analysis. In different forms, this three-level approach can be recognised in theoretical publications, for example, a review of principles of hierarchy theory by Feibleman (1954), the holon approach that was proposed by Koestler (1978), a hierarchy of system levels by Varela (1979) and an approach based on doublets by Jaros & Cloete (1987).

The literature offers specifications of various aspects of hierarchy (e.g. reviews by Klijn, 1995; Valentine, 2003). If a higher level in a hierarchy consists of physically joined elements, like parts of an alarm clock or cells in a multicellular organism, this represents a constitutive hierarchy (Mayr, 1982). If the elements

are not physically connected, but associated in a series of increasingly inclusive entities, such as organisms in a population, this is considered an aggregative hierarchy (Mayr, 1982). If elements of levels lower than the next-lower level contribute to a certain level in a hierarchy this represents a cumulative hierarchy. An example is the cumulative constitutive hierarchical organisation of multicellular organisms, in which, for example, bone and blood plasma, which do not consist of cells, together with tissues and organs form the organism. The cumulative constitutive hierarchy in organisms has also been called a somatic hierarchy (Eldredge, 1985). If low levels in a hierarchy represent systems that are separated in time from the higher levels and do not function as units in the higher levels, this is called a tree (Valentine, 2003). In addition to being hierarchic, trees are defined as having a single root and showing a single parent for each node. For this reason, the parent-offspring relationship (family tree) is not strictly a tree, but more a treelike network. The pedigree of species that forms the phylogenetic tree or 'tree of life' can be considered a tree as long as the speciation is based on a representation of the gene-pool of a species as a single parental node. Networks or webs, then, may show nodes with connections to a variable number of other nodes irrespective of their hierarchical level.

(d) Mechanisms

If a pattern occurs in a biological or physical system, it always shows a relationship with some sort of underlying process or explaining mechanism causing it.

The most general mechanism in nature is the fact that spontaneous processes are associated with a decrease of energy gradients and increasing chaos/entropy. This general principle does leave room for a system to move in the opposite direction by showing a local increase in its organisation (associated with a decrease in entropy) as long as the related entropy decrease is compensated for by an equal or larger increase outside the system (e.g. Prigogine & Stengers, 1984).

Another mechanistic aspect is the relative stability of a system. From any two systems showing an equal chance of formation, the system that shows the best combination of internal stability and stability during interactions with other systems will show the highest chance of functioning successfully and existing for a long time.

Still another mechanistic aspect is the self-organisation of systems in response to certain attractor states. Selforganisation implies that interactions between systems autonomously create patterns. The most important aspect of self-organisation in nature is the formation of circular interaction patterns creating physical units. Although there may be different mechanisms behind the

emergence of atoms or cells, the occurrence of a circular interaction pattern is a constant. This aspect will be discussed in detail in the next section.

(2) A strict basis for the hierarchical ranking of system types

For later analysis of hierarchy in the internal organisation of systems, a special approach is used that recognises a strict division of all systems into two major groups.

The systems of the first group are discussed in detail by Jagers op Akkerhuis & van Straalen (1999) and Jagers op Akkerhuis (2001), who refer to these systems as the operators, indicating clearly that these systems show a specific, internal organisation allowing them to operate as individuals and produce effects in their environment. The name operator was chosen, even though it was realised that this name could cause confusion because it has applications in other fields, such as mathematics, the telephone business and information science.

Systems that are not operators belong to the second group, the members of which can be regarded as interaction systems.

Because the operator theory forms an essential aspect of the present study, we first present a short summary. According to the operator viewpoint, an operator of type x creates a next operator of type $x+1$ by means of a first-next possible closure. Closure refers simultaneously to the formation (the closing process) and presence (the closed state) of a circular pattern in the interactions between the system's elements. The adjective 'first-next possible' refers to the demand that the closure must be the first possibility for a new type of closure in system $x+1$ after the preceding closure created the operator of type x . The demand of first-next possible closure implies that the elements showing this property can be ranked in a strict way, creating what has been called the operator hierarchy, in which every operator holds a unique hierarchical position (Fig. 4.1). In the operator hierarchy, there are two transitions between system types that are based on first-next closures: the major and the minor transitions (Jagers op Akkerhuis, 2001). A major transition creates a completely new type of closure. According to the operator theory, major transitions form the basis of the superstring, the quark-gluon plasma, the hadron, the atom, the cell and the organism with a hypercyclic neural network with interface, which is named a memon in the operator hierarchy. A minor transition recreates a system property that came into existence during a preceding major transition. For example, the multiparticle property that emerged as the result of a major transition in the hadrons occurs again as the result of a minor transition at more elevated levels in the hierarchy, creating the molecule, the prokaryote multicellular organism and the eukaryote multicellular organism.

Using a *sensu stricto* interpretation of the operator hierarchy, only the systems in Fig. 4.1 showing a hypercycle with interface represent operators. This includes the hadron, the atom, the multi-atom (e.g. molecules, metal grids, etc.), the bacterial cell and the bacterial multicellular, the eukaryote cell and the eukaryote multicellular, and the memon. For additional information about the operator hierarchy, see Jagers op Akkerhuis & van Straalen (1999), Jagers op Akkerhuis (2001) and the present author's website www.hypercycle.nl.

The operator theory may have marked effects on the analysis of organism types in biology. As Fig. 4.2 shows, all species of organisms and the representation of their ancestral tree (the tree of life) can be translated into a sequence of operator types including bacterial cells, eukaryote cells, prokaryote and eukaryote multicellulars and organisms with hypercyclic neural networks (memons). Versions of the scheme of Fig. 4.2 that exist in the literature (e.g. Alberts *et al.*, 1989) generally include only the levels of prokaryote unicellulars, eukaryote unicellulars and eukaryote multicellulars. Because the operator hierarchy offers strong arguments to regard the transition towards multicellular eukaryotes with a hypercyclic neural network (memons) as of similar importance as the transition from prokaryote to eukaryote cells and from uni- to multicellular organisms, we suggest including the level of the memon in this type of analysis.

As stated above, the operator hierarchy allows a distinction between the operators and all other systems, regarded as interaction systems. It will be shown next that this distinction is a useful tool for the analysis of hierarchic organisation in systems. As an example, let us discuss the simple situation of a system (S) that contains a water molecule (M) and a water droplet (D) (Fig. 4.3). The operator hierarchy regards the water molecule an operator and the droplet and system S interaction systems. The droplet represents an interaction system because it consists of interacting water molecules that do not show first-next possible closure, which, following the molecular stage, is autocatalysis; a property not shown by D. The system S also represents an interaction system, because it contains elements the interactions of which do not show first-next closure.

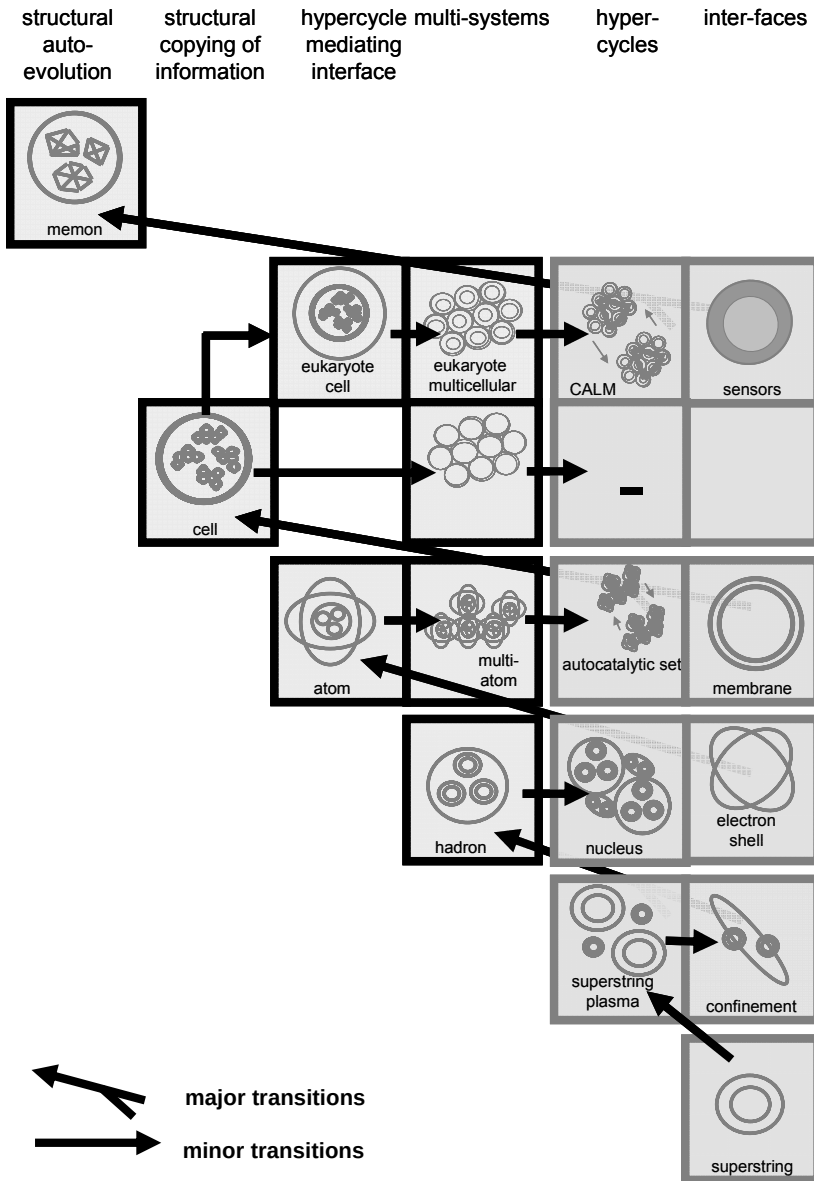


Figure 4.1. The ranking of system types according to the operator hierarchy (Jagers op Akkerhuis & van Straalen, 1999; Jagers op Akkerhuis, 2001). Grey boxes indicate non-operator systems that play an important role in the operator hierarchy as intermediate closure states. Black upward arrows represent major transitions creating a new operator that shows a completely new type of closure. Black right-pointing arrows represent minor transitions. Empty cells and dashes indicate stages that have not yet evolved, but according to the logic of the hierarchy may potentially exist. Systems in the same vertical column share a common closure type. 'Interface' represents an emergent boundary. 'Hypercycle' represents an emergent

second-order interaction cycle. 'multi-operator' represents an emergent recurrent interaction between operators of the preceding type. 'Hypercycle mediating interface' (HMI) represents an interface that mediates the interactions of the hypercycle of the system involved with the world. 'Structural copying of information' (SCI) represents the property of systems to autonomously copy their structure and in this way reproduce their information. 'Structural auto-evolution' (SAE) represents the property of systems to improve, while living, the neural structures that contain their information. CALM stands for a Categorizing And Learning Module, representing a hypercyclic neural interaction pattern.

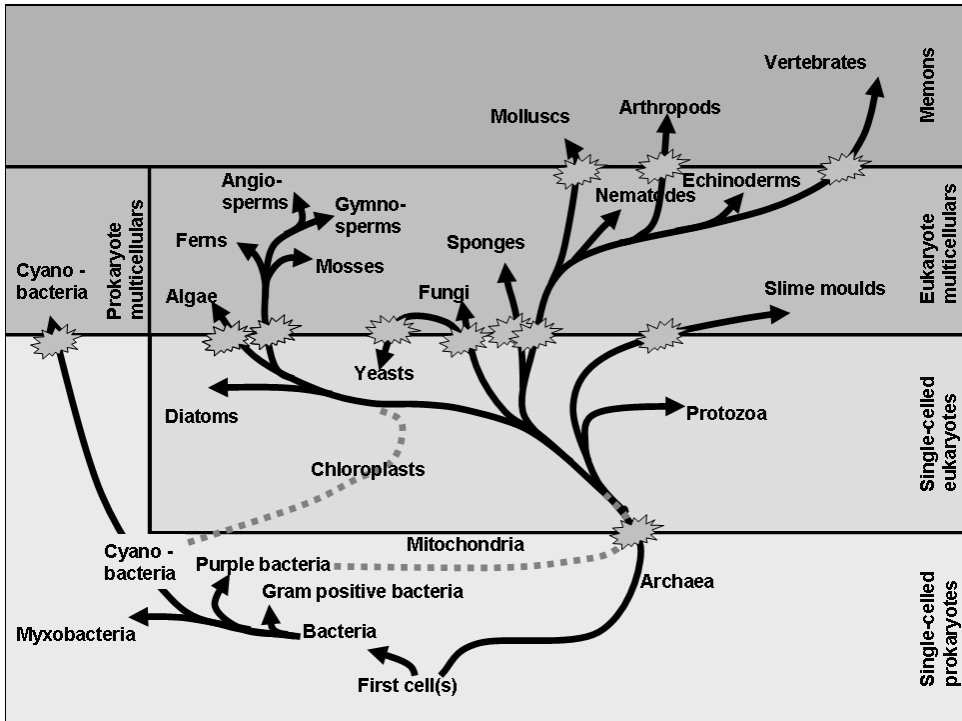


Figure 4.2. A schematic representation of the phylogenetic tree. Organisms are ranked according to speciation patterns, at the same time indicating when a specific lineage passes through one of the major levels of structural organisation recognised by the operator hierarchy

For later discussion, it is practical to distinguish two major types of interaction systems: compound objects, in which elements by their interactions create a material unit, and interaction groups, in which elements interact as separate material units. The water droplet in our example can be regarded as a compound object. Any molecule that escapes from it becomes a separate operator: a water molecule.

Compound objects always show one or more unifying forces between one or more types of contributing elements that create a stronger coherence between the particles in the compound object than between the object and its

environment. At the point where the influence of these forces comes to a halt, the compound object has its limit that forms the basis for its distinction and manipulation as a material unit relative to its environment. The limit makes the compound object recognizable in space and time and may cause specific emergent properties (Ponge, 2005). Examples of compound objects are: a drop of water (in oil or in air, but not in water, because a water droplet in water neither shows a recognizable outer limit nor shows specific unifying forces), a planet, a bowl with soup, a lump of clay, a piece of dead wood, a brick, a lump of small magnetic parts of iron clinging together on a table, a piece of cotton cloth (unified by the molecular forces between molecules in the cotton fibres and by physical forces keeping together the interwoven strands of fabric), a hair, etc.

Interaction groups, then, consist of particles that show specific interactions that make them recognizable as a group, without this leading to any physical unity. Examples are: atoms and molecules in a gas, a tornado, a heap of loose sand particles (not kept together by roots, fungal hyphae or such like), organisms of a population/ species in an ecosystem, bees belonging to one hive, an autocatalytic set in a chemical solution, stars and planets in a galaxy, a football team, etc.

Although operators, compound objects and interaction groups show distinct types of organisation, they have all evolved from operators and may respond to changing conditions by a change in organisation from one type to the other. For example, a group of loosely interacting atoms in a gas (an interaction group) may condense to form a compound object, such as a drop of rain or a snowflake. The atoms may separate again when the system is heated. Clearly also a change in environment may alter the status of a system. For example, a drop of water is characterised as a compound object in air, but not in water.

It is recognised that between every pair of subsequent system types, transition states may exist that cannot be classified as representing one of the two system types. Transition states are also a natural phenomenon during the formation of a higher-level system type from elements, for example, during the creation of operators. In my opinion, the existence of transition states does not justify the rejection of organisational system classes.

(3) Viewpoint dependence of hierarchy: the DICE approach

The operator hierarchy has been introduced as a special way of ranking a limited subset of natural systems in a strict hierarchy. It was also shown that systems that are not operators can be classified as different forms of interaction systems, either compound elements or interaction groups. This provides a basis for the analysis of the internal organisation of both operators and interaction systems. The internal organisation of these systems can be looked at from two perspectives: that of the elements and that of the interactions.

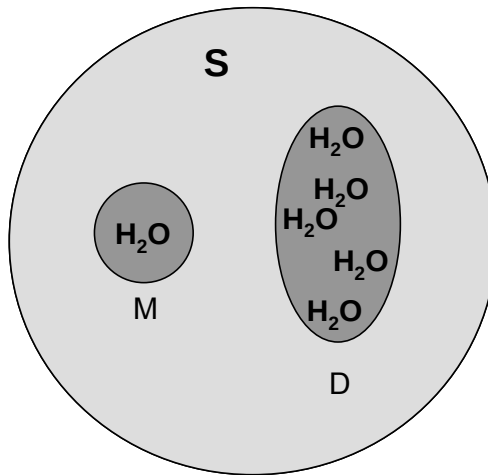


Figure 4.3. A system *S* containing a water molecule *M* and a drop of water *D* and water molecules (H_2O).

(a) Elements

A general analysis of system organisation must account for the fact that the elements in a system are not always operators, but may also be compound elements and interaction groups. For example, the internal organisation of a dog (an operator of the memon type) includes interaction systems, such as organ systems, organs and tissues, and operators, such as many specialised eukaryote cells. Likewise, an interaction system, such as a galaxy, includes interaction systems, such as the stars, planets, comets, dust particles, etc., and operators, such as atoms, molecules, cells, etc. If the operators, compound elements and interaction groups are defined, the identification of elements in a system will not be problematic.

(b) Interactions

A general analysis must acknowledge that relationships of elements in a system are the result of many types of interactions, each of which may lead to different patterns of relationships among elements. To make this 'many patterns problem' tangible, interactions can be arranged according to a limited number of 'organisational dimensions'.

For example, a focus on the relationship 'a causes the displacement of b' can be regarded as one of the rankings of organisms according to a displacement dimension. Displacement may furthermore relate to interactions involving migration, phoresy, endochory, etc. Interactions between the same individuals will sort differently when focusing on the relationship 'a has genes that are used by b'.

This relationship represents one aspect of the information dimension. Information may furthermore include interactions involving speciation, life histories, behaviour and communication. Rankings will again change by focusing on constructional interactions. Construction includes the way objects are arranged in a system, the creation of objects by individuals, constructional aspects of phenotypes and the contribution of chemicals in food to the construction of an organism, for example, by means of vitamins, proteins or toxins. Finally, the relationship 'a eats b' is an example of an energetic viewpoint. Other aspects of the energetic dimension may include behaviour aiming at maximising resource dominance (e.g. Jagers op Akkerhuis & Damgaard, 1999), the metabolism of an organism, energy flows in a food chain and physiological effects of temperature, light, etc. As has been emphasised by Arditi, Michalski & Hirzel (2005) the structure of a food-web may differ markedly from a construction-chain, indicating that each of the above dimensions will result in a different analysis of relationships and hierarchy in a system.

Together these four different dimensions will henceforth be summarised by the acronym DICE (displacement, information, construction and energy). It is argued here that until all the four DICE-viewpoints have been investigated, the analysis of the organisation of any system is principally incomplete.

To summarise the above, there are important practical consequences of the DICE approach. Firstly, it shows that each viewpoint that is used for analysing a system results in another arrangement of relationships. Secondly, the dimensions of the DICE approach offer an easy way to check whether the analysis of a certain system shows major flaws.

(4) Systems that change operator type during their existence

The operator hierarchy also has consequences for the analysis of system types that occur during development. For example during conception, the unicellular organisms of the sperm cell and egg cell fuse to form a zygote, which also represents a unicellular organism. Development can now proceed along different lines. In species with determinate cleavage of the zygote, the blastomere cells depend immediately on each other for their survival and are never separate individuals. In other taxa, for example many mammals, the blastomere cells specialise much more slowly and have the potential to develop into individual multicellular organisms when separated. Accordingly, the mammalian zygote represents a colony of structurally linked cells. In a later phase, the cells become obligatorily interdependent and the colony changes into a multicellular organism. In animals, the development of the embryo passes through a stage where a hypercyclic neural network forms. From that moment on, the embryo becomes a memon. Other interesting examples are slime moulds. Individual cells of these organisms may live as separate individuals and even multiply asexually at this

stage. On certain occasions, the cells aggregate and form slug-like units, which show all properties of a multicellular stage, with chemical bonds between their cells and a mutual dependence with respect to a common metabolism and reproduction.

Above, I discussed transitions between complexity levels in operators. However, transitions between complexity levels also occur in interaction systems. As an indicator for the complexity level, we proposed the use of the highest level operator in an interaction system. According to this viewpoint, a planet starts its life as a chemosystem and changes towards an ecosystem when the first cell emerges. Any subsequent level organisation of a planet can be named after newly emerging organisms, which, for example, may lead to the recognition of an ecosystem at the unicellular eukaryote level, at the multicellular eukaryote level (e.g. plants and fungi) or at the memon level (includes most animals).

Analysis of hierarchy in biological and physical systems

The method proposed in the present paper includes the following four steps: (1) identification of the developmental stage of the universe, (2) identification of the type and scale of the system, (3) specification of mediating influences affecting the formation of the system and, (4) analysis of the internal organisation based on the four dimensions of the DICE-approach. These steps are explained in the sections below.

(1) Identification of the developmental stage of the universe

As a first step, the present method assesses which types of systems must potentially be included in the analysis. The presence of system types is considered to depend on the succession stage of the universe. According to the operator hierarchy, succession stages of the universe can be defined on the basis of the highest complexity operator that is present. Based on this viewpoint, the universe has passed through a number of abiotic stages that are associated with the emergence of, for example, hadrons, atoms and molecules, and biotic stages that are associated with the emergence of prokaryote and eukaryote cells, multicellular organisms and memons. Because operators and interaction systems show a mutual dependency with respect to their formation, the evolutionary sequence of operators shows a correlation with the presence of interaction systems in the universe; this relationship is illustrated in Fig. 4.4. Although in Fig. 4.4 the presence of the highest-complexity operator determines the succession stage, the universe may show large areas in which evolution lags behind. Due to this heterogeneity, the universe at the stage of unicellular eukaryotes (white shading in Fig. 4.4) may contain large parts in which cellular life has not yet emerged and where the analysis of system organisation does not have to take into account the activities of organisms. Furthermore, the scheme

shown in Fig. 4.4 holds open the possibility that operators of early stages either become parts of higher-level operators or may remain present as individual entities through later succession stages of the universe.

(2) Identification of a system of interest

This step is used to identify the system of interest. This implies that the scale of the system is specified in relation to its characterisation as operator or interaction system. For example, if the selected system is a galaxy, it consists of celestial bodies (and dark matter) kept together by gravitational interactions. According to the present analysis, a galaxy represents an interaction group depending on compound elements (the stars and planets). The scale for analysing its organisation depends on judgments about the limit to the gravitational influence it has in space. The situation becomes quite different if the system chosen is a plant. This represents an operator of the eukaryote multicellular type. The scale for analysing its organisation is that of the individual and is limited by intercellular connections.

(3) Mediating influences

The third step involves a further characterisation of the system by analysing whether the system has obtained its specific form under the influence of a higher-level operator or because of specific interactions within a larger interaction system. The advantage of this step lies in the fact that it makes explicit that any analysis of the organisation of a system requires reference to the surrounding environment and/or higher level that mediated its construction. On the one hand, systems exist that typically owe their form to specific interactions within interaction systems. For example, carbon atoms form during nuclear interactions in stars, crystals form under specific environmental conditions on planets and the canopy of a forest affects the selection of new seedlings. On the other hand, systems may experience mediating activities of higher-level operators. For example, a fossil and a DNA molecule could never have obtained their present form without the mediating influence of an organism.

(4) Internal organisation

The fourth and last step is an investigation into the elements composing the selected system and how they are related. The elements may be operators, compound objects or interaction groups. One can analyse the internal organisation of these elements in an iterative way, focusing on systems elements, the elements therein, etc. When it comes to finding explanations for the functioning of a system, it is often sufficient to go down one or two levels. As a consequence of the DICE approach (see section 11.3) there is no one best hierarchical ranking of interactions in the system, because the ranking of the elements may vary with the viewpoint that is adopted for acknowledging hierarchy.

Care should be taken when analysing the organisation of interaction systems. For example, the ranking from the organism, to the population, to the community and the ecosystem, which can be observed frequently in the literature, should not make the reader think that organisms are first parts of populations, which then are parts of communities, which finally are parts of ecosystems. Instead, this hierarchy only involves abstract subsets, and not structural elements. Fig. 4.5 illustrates that the organism interacts as an individual with other systems in the ecosystem without creating new structural elements.

On the basis of this reasoning, a population, a community, a food chain and other groups of individuals must be considered abstract subsets, each being based on a specific selection of interactive properties of the individuals. Nevertheless, even though the interactions of the individuals in such abstract groups may not lead to physical units, they do cause very real dynamics. This can easily be demonstrated by the example of mating and genetic recombination in populations of species that reproduce sexually. Due to sexual reproduction, the offspring obtain different gene combinations. On the one hand, this helps to maintain good gene combinations in part of the offspring, the part carrying the most deleterious mutations experiencing a survival disadvantage. On the other hand, the recombination of genes during sexual reproduction brings about new gene combinations that allow a flexible adaptation of a species to changing fitness landscapes.

Subsequent stages of the universe ->

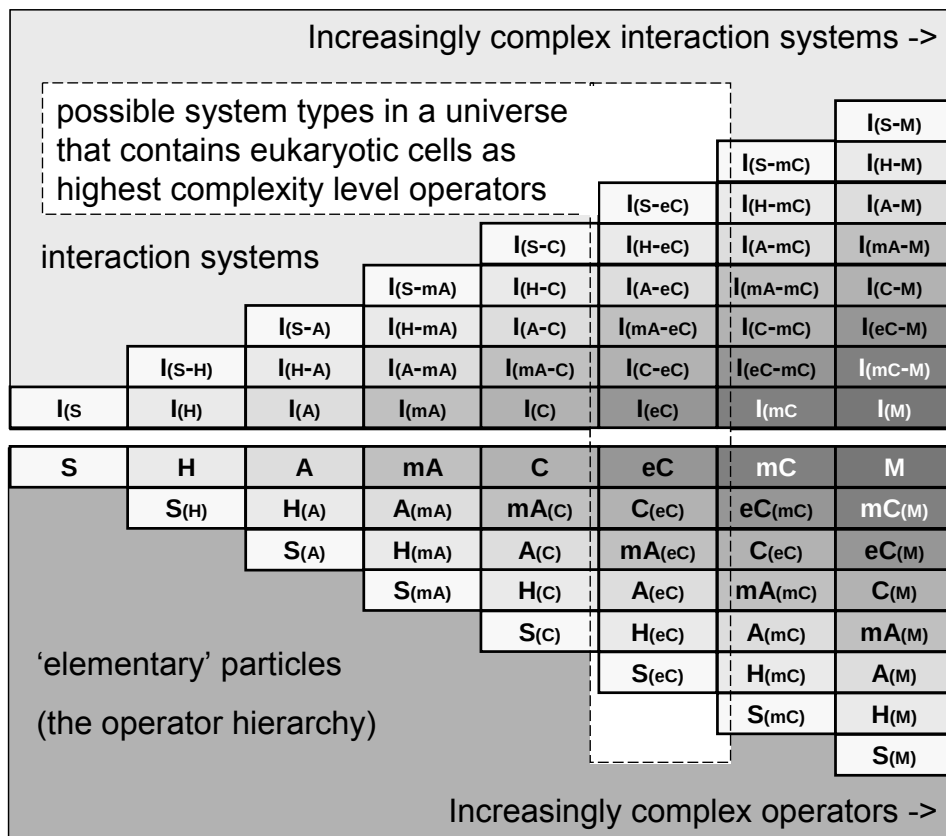


Figure 4.4. System types associated with different succession stages of the universe. Each successive step to the right adds a box both to the operators (lower panel) and to the interaction systems (upper panel), the boxes being pushed outward at each step. From left to right, subsequent columns indicate all system types, both operators (bottom) and interaction systems (top), which potentially exist during the following succession stages of the universe. Abbreviations: S = superstring stage, H = hadron stage, A = atom stage, mA = multi-atom stage, C = prokaryote cell stage, eC = eukaryote cell stage, mC = multicellular organism stage (including in this case both prokaryote and eukaryote multicellulars) and M = memon stage. The coding I(X-Y) indicates all possible interaction systems containing type X as the highest-level operator in a succession stage of the universe that contains Y as its highest-level operator. For example, the coding I(eC-M), covers all possible interaction systems that show eukaryote cells as the highest level elements in a universe in which memons exists. For the operators the coding X(Y) is used to indicate all possible operators of type X in a stage of the universe that contains Y as its highest-level operator.

Applications of the new method

The application of conflicting hierarchy rules and the inclusion of ill-defined systems flaw many existing analyses of hierarchy in system organisation. To solve this problem, an alternative method is proposed in the present article. Below, possible contributions of the new method to the field of system analysis are discussed.

(1) Distinguishing between evolutionary sequence and construction sequence

Many hierarchic approaches to system organisation use an organism concept that covers all types of organism and link this to an internal organisation of organisms that includes organs, tissues and cells. This viewpoint disregards fundamental differences in complexity among organisms, thus failing to give an accurate analysis of their internal organisation. To avoid such problems, the present approach uses the operator hierarchy to determine (and rank) the complexity level of the organism before analysing internal organisation. This approach also solves the problem that ranking of systems according to an evolutionary sequence does not always correspond with ranking according to complexity. For example, before the emergence of the cell, evolution had neither the means nor a context for developing complex organelles, such as the endoplasmic reticulum. Therefore, cells evolved first, followed by organelles. The evolution of internal complexity has been discussed by Turchin (1977) who refers to it as the 'law of the branching growth of the penultimate level'. This law states that only after the formation of a control system C , controlling a number of subsystems S_i , will these S_i tend to multiply and differentiate. Examples of elements that have evolved in organisms as indicated by Turchin's law are organelles in cells and tissues, organs and specialised cells in multicellulars.

(2) Classifying and analysing systems in relation to their creation under the influence of higher-level operators

Analyses of the organisation of systems generally do not include mediating effects of higher-level systems and the environment. The present approach deals specifically with this aspect, increasing insight into the organisation of systems.

(3) Adapting the scale of the systems of interest in relation to specific interactions

Most analyses in the literature do not explicitly consider the scale of the systems involved. Populations, communities and pastoral systems are all mentioned without any specification of what sets the limits to these selections.

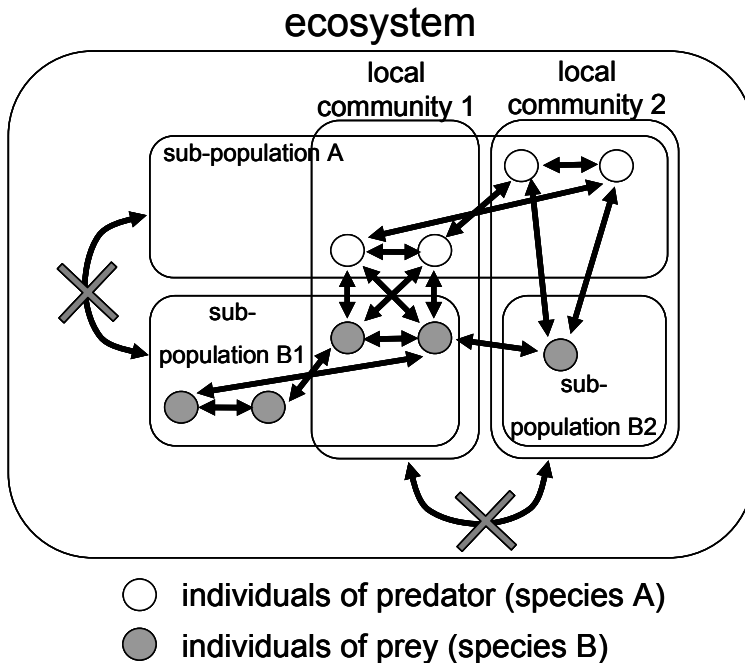


Figure 4.5. The partitioning of individuals into subsets of an ecosystem. Black arrows indicate interactions between individuals. Arrows marked with a cross indicate sets that do not interact as entities, such as populations and communities. The figure shows that it is always the individual (or a physically connected colony of individuals that acts as one individual) that interacts in the ecosystem, regardless of the subset it is assigned to.

(4) Specification of the type of hierarchy used in different hierarchical steps

In many existing hierarchies, it is not clear which properties determine the hierarchical ranking of any next level. Frequently, the ranking from sub-atomic particles to the universe gives the impression of an internal hierarchy, in which the top-down relationship 'is a part of' seems to fit most of the hierarchical steps. Galaxies are parts of the universe, solar systems parts of galaxies, planets parts of solar systems, ecosystems parts of planets, communities parts of ecosystems, populations parts of communities, organisms parts of populations, cells parts of organisms, organelles parts of cells, molecules parts of organelles, atoms parts of molecules, etc. Yet, apart from additional minor inconsistencies, the latter hierarchy is inconsistent because it is constructed from three distinct parts, the ranking of which is based on very different principles.

The first part involves the internal organisation of the universe down to the level of planets. This range is based on the general notion that smaller systems are parts of larger systems. Existing hierarchies of this type generally do not include

all types of celestial bodies, such as black holes, neutron stars, brown dwarfs, comets, etc. Moreover, according to this reasoning, there is no consensus on how to distinguish between a lifeless planet and a planet inhabited by organisms.

The second part involves subsets of the ecosystem ranked from the organism, via the population, to the community and the ecosystem. As has been discussed above, organisms are not first parts of populations, which then are parts of communities, which finally are parts of ecosystems. Instead, as was illustrated by Fig. 4.5, the organisms remain at any moment directly integrated into the ecosystem. It was also discussed above that the ranking of individuals in ecosystems is sensitive to point of view, as illustrated by the DICE approach, the application of which may result in a food web, a structural dependence web, an informational web, and so on.

The third part involves the internal organisation of elements in the organism. Considering the organism as just another operator, this part can also be generalised to relate to the internal organisation of operators. The present method covers this aspect in far more detail than most other methods. Using the proposed rationale, the analysis can be based on the recognition of internal elements, such as operators, compound elements and interaction groups. Accounting for the DICE discussion, several internal hierarchies can be recognised.

Finally, I would like to refer to the existing controversy about the usefulness of hierarchy in system science (e.g. Webster, 1979). On the one hand Guttman (1976), advocates that the use of levels of biological organisation

'if stated in any but the sloppiest and most general terms is a useless and misleading concept'. On the other hand, Weiss (1969) remarks that *'the principle of hierarchic order in living nature reveals itself as a demonstrable descriptive fact'* and Von Bertalanffy (1968) that *...'hierarchical structure ... is characteristic of reality as a whole and of fundamental importance especially in biology, psychology, and sociology'*.

The present study brings together these opposing viewpoints. On the one hand, it shows that it is indeed difficult to use hierarchy as a scientific concept. This will continue as long as approaches focus on ill-defined hierarchies that include various system types and ill-defined hierarchy rules. On the other hand, the present study shows that hierarchy can be studied with success and in detail by using the operator hierarchy as the basis at the same time paying close attention to the multi-dimensional nature of hierarchy in biological/physical systems.

Conclusions

- (1) The literature shows a controversy about the usefulness of hierarchy in analysing the organisation of biological/physical systems. On the one hand, it is postulated that hierarchy is the most general organising principle in nature. On the other hand, the identification of hierarchy in natural systems seems to be hampered by a sloppy use of concepts, giving reason to claims that hierarchy is of limited use. Especially linear hierarchies can be shown to suffer from minor and major flaws.
- (2) Solving the above problems requires a strict yet flexible way for analysing system organisation. With the operator hierarchy as a basis, we propose a method that includes the following four steps: (a) identification of the developmental stage of the universe, (b) identification of a system of interest, (c) analysis of mediating influences on the selected system, (d) analysis of internal organisation.
- (3) The present method of identifying contributes in three ways to the analysis of system organisation: (a) it offers a strict ranking of the operators, (b) it offers ways to identify compound elements and interaction groups, and (c) it acknowledges that the analysis of hierarchy in interactive relationships must focus on different analytical dimensions, notably displacement, information, construction and energy.

Acknowledgements

The author would like to thank two anonymous referees, as well as Hans-Peter Koelewijn and Jean-François Ponge for detailed comments on the manuscript, Chris Klok and Jan Klijn for constructive discussion and Claire Hengeveld for improving the structure and clarity of the text and correction of the English.

Bringing the definition of life to closure

Towards a hierarchical definition of life, the organism and death

“Life is a succession of lessons which we must live to be understood.”
(Ralph Waldo Emerson)

Abstract

Despite hundreds of definitions, no consensus exists on a definition of life or on the closely related and problematic definitions of the organism and death. These problems retard practical and theoretical development in, for example, exobiology, artificial life, biology and evolution. This paper suggests improving this situation by basing definitions on a theory of a generalised particle hierarchy. This theory uses the common denominator of the 'operator' for a unified ranking of both particles and organisms, from elementary particles to animals with brains. Accordingly, this ranking is called 'the operator hierarchy'. This hierarchy allows life to be defined as: matter with the configuration of an operator, and that possesses a complexity equal to, or even higher than the cellular operator. Living is then synonymous with the dynamics of such operators and the word organism refers to a select group of operators that fit the definition of life. The minimum condition defining an organism is its existence as an operator, construction thus being more essential than metabolism, growth or reproduction. In the operator hierarchy, every organism is associated with a specific closure, for example, the nucleus in eukaryotes. This allows death to be defined as: the state in which an organism has lost its closure following irreversible deterioration of its organisation. The generality of the operator hierarchy also offers a context to discuss 'life as we do not know it'. The paper ends with testing the definition's practical value with a range of examples.

Keywords: Artificial life, biology, evolution, exobiology, natural sciences, particle hierarchy, philosophy, Big History

Introduction

In a chronological overview of developments, Popa (2003) presents about 100 definitions of life, meanwhile demonstrating that no consensus exists. Many classical definitions include long lists of properties, such as program, improvisation, compartmentalisation, energy, regeneration, adaptability and seclusion (Koshand Jr., 2002) or adaptation, homeostasis, organisation, growth, behaviour and reproduction (Wikipedia: Life). Most properties in such lists are facultative; it is still possible to consider an organism a form of life when it does not grow, reproduce, show behaviour, etc. The inclusion of facultative aspects is a source of lasting difficulty in reaching consensus on a definition of life. Because of the seeming hopelessness of the situation, certain scientists have adopted a pragmatic/pessimistic viewpoint. Emmeche (1997) christened this viewpoint the “standard view on the definition of life”. He suggests that life cannot be defined, that its definition is not important for biology, that only living processes may be defined and that life is so complex that it cannot be reduced to physics. Others have warned that a comprehensive definition of life is too general and of little scientific use (e.g. van der Steen 1997).

In their search for a definition, other scientists have focused on properties that are absolutely necessary to consider an entity life. In this context Maturana & Varela (1980, p. 78) have proposed the concept of autopoiesis (which means ‘self making’). They use the following definition: “*An autopoietic machine is a machine organised (defined as a unity) as a network of processes of production (transformation and destruction) of components which: (i) through their interactions and transformations continuously regenerate and realise the network of processes (relations) that produced them; and (ii) constitute it (the machine) as a concrete unity in space in which they (the components) exist by specifying the topological domain of its realisation as such a network.*” Special about the autopoietic process is, that it is “*closed in the sense that it is entirely specified by itself* (Varela 1979 p. 25)”.

The concept of autopoiesis has increasingly become a source of inspiration for discussions in the artificial life community about how to define life (Bullock et al., 2008). Reducing the number of obligatory traits defining life to just one, autopoiesis is a rather abstract concept. People have sought, therefore, to describe some of the processes that underlie autopoiesis more specifically. An example of such a description is a triad of properties defining cellular life: container (cell membrane), metabolism (autocatalysis) and genetic program (e.g. Bedau, 2007).

These descriptions, however, have not resulted in a consensus definition of life. This has led Cleland & Chyba (2002, 2007) to suggest that a broader context, a 'theory of life', is required. In line with a broader framework, life may be regarded as a special realisation of the evolution of material complexity. According to Munson and York (2003), considering life in a general evolutionary context requires arranging "*all of the phenomena of nature in a more or less linear, continuous sequence of classes and then to describe events occurring in the class of more complex phenomena in terms of events in the classes of less complex phenomena..*". An important property of such a hierarchy would be that "*...an increase in complexity is coupled with the emergence of new characteristics ... suggesting that the hierarchical arrangement of nature and the sciences is correlated with the temporal order of evolution*". Similar views for integrating material complexity and the evolution of life can be found, for example, in the work of Teilhard de Chardin (1966, 1969), von Bertalanffy (1968), Pagels (1985), Maynard Smith & Szathmáry (1995, 1999, 2002) and Kurzweil (1999).

In contribution to these discussions, the present author has published an evolution hierarchy for all 'particles'. The latter hierarchy uses the generic word 'operator' to address both physical (e.g. quark, atom, and molecule) and biological particles (e.g. prokaryote cell, eukaryote cell, and multicellular). The word operator emphasizes the autonomous activity of the entities involved, which 'operate' in a given environment without losing their individual organisation. The hierarchical ranking of all operators is called the 'operator hierarchy' (see Figure 5.1) (Jagers op Akkerhuis and van Straalen 1999, Jagers op Akkerhuis, 2001, Jagers op Akkerhuis, 2008 and the author's website www.hypercycle.nl). Because the operator hierarchy is important for the definition of life proposed below, the outlines of this theory are summarised in the following lines

The operator hierarchy ranks operators according to the occurrence of a circular pattern, such as that which connects the beginning and end of a process or structure. Circularity causes a closed organisational state, also referred to as 'closure' (for discussions of closure see, for example, Heylighen 1990, Chandler and van de Vijver, 2000). Because closure causes a discrete 'quantum' of organisation (e.g. Turchin 1977, 1995 and Heylighen 1991), the operator becomes an 'individual entity', a 'whole' or a 'particle', while still retaining its construction of smaller elements. Closure thus defines the operator's complexity level and sequential closures imply a higher complexity level. An operator's closure is the cause of its existence and typical for its complexity. This implies that complexity is not measured in terms of the number of genes, functional traits or organs of an organism, but in a very abstract way, in terms of the number of closures. Upon losing its closure, the organisation of the operator falls back to that of the preceding operator. The actual shape of a closure can differ.

Biological examples of closure are the cell membrane and the circle of catalytic reactions allowing the cell to maintain its chemical machinery. It is essential for a strict ranking that a lower-level and a higher-level operator always differ by exactly one closure level. The single closure (eukaryotic cell) or parallel pair of closures (autocatalysis plus membrane of the cell) that define the next level are referred to as 'first-next possible closure(s)'. A consequent use of first-next possible closures allows physical and biological operators to be ranked according to the 'operator hierarchy' (Fig. 5.1). The operator hierarchy includes quarks, hadrons, atoms, molecules, prokaryotic cells, eukaryotic cells, multicellulars (e.g. plants, fungi) and 'animals', the latter representing an example of the operators that possess a neural network with interface and that are called 'memons' in the operator hierarchy.

Due to its focus on closure, the operator hierarchy represents an idealisation because it excludes potential transition states in between two closures. For example, several hundreds of metal atoms may be required before a functional Fermi sea transforms a collection of single atoms into a metal grid. Also, the emergence of multicellularity (discussed in detail below in the 'Levels of life' chapter) may require a colonial, multicellular state in between the single cell and the multicellular operator. The above shows that transition states form natural intermediate phases in the emergence of closures. The operator hierarchy does not include these transition states, however, because its hierarchical ranking is exclusively based on entities that already show first-next possible closure.

The main reason for writing this paper, and adding yet another definition of life to the listings, is that the operator hierarchy offers several advantages in solving definition problems. First, the definitions of the operators are generally applicable because they focus on the essences of organisation. For example, demanding autocatalysis leaves open which specific catalysts will perform the process. Second, the use of first-next possible closures ensures a critical filtering of only obligatory properties from property lists. Finally, the use of the operator hierarchy makes it easy to develop a hierarchy-based definition of life. In other words, the operator hierarchy offers a novel path for structuring and simplifying discussions about which entities are life.

THE OPERATOR HIERARCHY

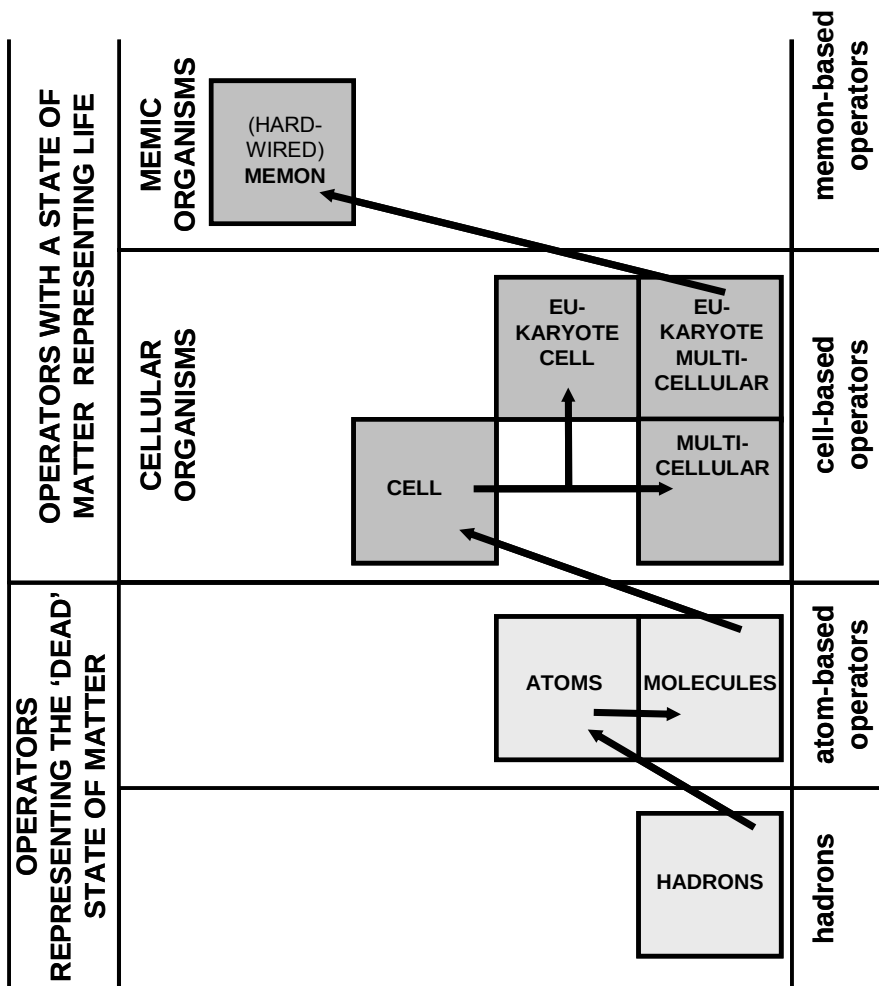


Figure 5.1. Using the operator hierarchy to define life and organisms. Arrows indicate how closures create operators (more information can be found in Jagers op Akkerhuis 2008, and the author's website www.hypercycle.nl).

The following paragraphs discuss different aspects of existing definitions of life and examine new ways to define the organism, living and death. At the end, a test of the practical value of the present definitions for the solving of a range of classical problems, such as a virus, a flame, a car, a mule and a mitochondrion, will be presented.

Defining life and the organism

Before discussing the use of the operator hierarchy for defining life, living and the organism, it is important to note that when talking about definitions, care should be taken that “*a definition is a series of superimposed language filters and only the definiendum (the term to be defined) can penetrate it*” (Oliver and Perry, 2006). Problems may arise when the words used for the definiendum and for the filter have a broad meaning or have different meanings in different contexts. It is thus useful to elaborate on the current context for ‘life’ before continuing.

‘Life’ has different meanings in different contexts. For example, people refer to the period between birth and death as their life (this is the best day of my life) even though lifetime would be more correct. In addition, the experience of ‘being alive’, or ‘living’, also carries the label of life (to have a good life). Other uses of life holistically refer to the importance of selective interactions in ecosystems that over generations lead to better-adapted life forms (the evolution of life). Ruiz-Mirazo et al. (2004) have proposed a definition of the latter type. They state that life is “*a complex collective network made out of self-reproducing autonomous agents whose basic organisation is instructed by material records generated through the evolutionary-historical process of that collective network*”. In philosophy, life is sometimes considered a graded concept for being because all what is, is alive in the measure wherein it is (Jeuken 1975). Due to the contextual dependence of these and other interpretations, it is improbable that a general definition of life can be constructed. Van der Steen (1997) indicates that even if such an overly general definition existed, it would probably be difficult to apply it to specific situations.

To avoid problems with generality and multiple interpretations of concepts, the present study adopts a limited viewpoint, presuming a one-to-one relationship between a definition of life and a specific material complexity. In this context, life is an abstract group property shared by certain configurations of matter.

The operator hierarchy offers a context for a general matter-based definition of life. Focusing on all operators showing a complexity that exceeds a certain minimum level, the hierarchy suggests a definition of life *sensu lato* as: matter with the configuration of an operator, and that possesses a complexity equal to or even higher than the cellular operator. Only the prokaryote cell, the eukaryote cell, the prokaryote and eukaryote multicellular, the hardwired memon and the potential higher-level operators fit this definition (Fig. 5.1). In addition to this general definition, various specific definitions are possible by focusing on operators that lay between a lower and an upper closure level. An example of a

specific definition is one describing cellular life (e.g. algae, plants and fungi) as: matter showing the configuration of an operator, and that possesses a minimum complexity of the cellular operator and the maximum complexity of a multicellular operator. The latter includes only the cell, the eukaryotic cell, the prokaryotic and the eukaryotic multicellular. It is possible to choose any of these approaches for defining living as: the dynamics of an operator that satisfies the definition of life.

The above approach results in a strictly individual based definition of life as a group property of certain operators. This definition has the advantage, that it offers a solid basis for defining the creation of offspring. Subsequently, the evolution of life can be dealt with as an emergent process occurring in any system with interactions between individual living entities that lead to differential survival of variable offspring, produced either without or with recombination of parental information.

The organism is the key ontological unit of biology (Etxeberria, 2004, Korzeniewski, 2004) and is also referred to as a 'living individual'. Understanding the latter requires insight into what is 'living', and what is an 'individual'. By defining 'living' as the dynamics of those operators that satisfy the definition of life, the operator hierarchy uses operators instead of individuals because operators define a being or an individual more strictly than the Latin concept of *individuum*. The word *individuum* stands for an "indivisible physical unit representing a single entity". This definition leaves a great deal of room for choice of the elements that form the physical unit and for the rules that determine indivisibility. These indeterminacies may be the reason for the discussion about whether certain life forms are organisms. Townsend et al. (2008) use the phrase 'unitary organism' to indicate the individual organism. However, certain jellyfish, for example, the Portuguese Man O' War (*Physalia physalis*), look like individuals, but consist of differentiated individuals, each with its proper neural network (e.g. Tinbergen 1946). In the operator hierarchy, the latter jellyfish are colonies, not organisms, because each contributing individual has its proper neural network as its highest emergent property, and the colony still lacks a recurrent interaction of the neural interfaces of the individuals.

The operator hierarchy now suggests a way to create congruency between the definition of life and the definition of the organism by accepting as organisms only entities that fit the operator-based definition of life. For example, using the general definition of life, only the cells, the eukaryotic cells, the prokaryotic and eukaryotic multicellulars and the memons are organisms.

Levels of life

a. The cell. The most important properties of the cell are the autocatalytic set of enzymes and the membrane. The autocatalytic set shows reproduction as a set. Every molecule in the set catalyzes a reaction that produces some other molecule in the set until any last reaction product closes the cycle. In different ways, reproduction as a set is part of various theories about the origin of life (e.g. Rosen 1958, 1973, 1991, Eigen 1971, Gánti 1971, Eigen and Schuster 1979, Kauffman 1986, 1993, Bro 1997, Kunin, 2000, Hazen, 2001, Martin and Russell, 2003, Hengeveld and Fedonkin, 2007).

Autocatalysis demands that a cell can potentially autonomously sustain its catalytic closure. Accordingly, if a cell allocates a part of its autocatalytic closure to another cell, the cell is no longer an operator. An example of the latter is the mitochondrion. It is generally accepted that mitochondria started the interaction with their host cells as autonomous endosymbiotic α -proteobacteria. Over many generations, these bacteria transferred more than 90 percent of their catalytic control to their host (Allen 1993, Berg and Kurland, 2000, Searcy, 2003, Capps et al., 2003, Lane, 2005). The loss of the potential of autocatalysis implies that mitochondria have become a special kind of organelle.

In addition to autocatalysis, the operator hierarchy demands an interface because a set of autocatalytic enzymes only gains the physical individuality that allows its maintenance when it functions in a limited space, the limits being part of the system. The integration of autocatalysis and the membrane is part of various important theories, for example, the theories of autopoiesis (Varela 1979) and of interactors (Hull 1981).

b. The eukaryote cell. A single cell has two dimensions for creating a next closure. One is to create cooperation between cells, which leads to multicellularity. The other is to create an additional closure mediating the hypercyclic functioning of the cell in the form of the nucleus. Interestingly, it is quite likely that the most important complexity boundary in cell biology, that between prokaryotic and eukaryotic cells, thanks its existence to the energy boost and genetic enrichment offered by endosymbionts. With respect to the emergence of eukaryotic cells, theories roughly divide along two major lines depending on whether the nucleus or the endosymbionts emerged first. In addition to other aspects, support for the nucleus-first hypothesis comes from allegedly primitive eukaryotes that show a nucleus without harboring endosymbionts. Genetic analyses (Rivera 1998) and observations of endosymbiont traces (Clark 1995), however, suggest that the 'primitive eukaryotes' are recent developments that lost their endosymbionts in a process of evolutionary specialisation. The endosymbiont hypothesis advocates that a

merger between a methanogenic bacterium that was member of the archaea and an α -proteobacterial endosymbiont created the eukaryotic cell (Martin and Russell, 2003). Subsequent transmission of genes for membrane creation from the endosymbiont to the host allowed it to produce membranes that formed the basis for the engulfment of the nucleus. Whatever the actual path taken by evolution, the operator hierarchy focuses on the occurrence of closure involving both structural and functional aspects of the host cell, resulting in an internal interface for the autocatalytic set and the mediation of its functioning. Even though endosymbionts may become obligatorily integrated in the functioning of their host cell by the transfer of part of their genetic regulation to the host cell, they do not mediate the functioning of the autocatalytic set of the host nor form an interface for its functioning. For this reason the operator hierarchy does not regard endosymbiosis, but the nucleus as the relevant closure that defines the limit between prokaryotes and eukaryotes.

c. The multicellular. When does a group of cells become a multicellular operator and, according to the above definition, an organism? In the operator hierarchy, multicellularity involves a structural and a functional component represented by structural attachment of cells and an obligatory recurrent pattern of functional interactions between them. As such, it is possible to define a multicellular operator (a multicellular organism *sensu stricto*) as: a construction of mutually adhering cells showing obligatorily recurrent interactions based on the same interaction type, that has the potential of maintaining it's functioning as a unit and that does not show memic structure.

Multicellularity has developed independently in many branches of the phylogenetic tree (reviews by, for example, Bonner 1998, Kaiser, 2001, Grosberg and Strathmann, 2007) presumably because it is associated with a range of evolutionary advantages. Multicellularity increases mobility and access to resources, and reduces predation, and finally yet importantly, the cells in genetically uniform multicellulars share the same genes and do not have to compete with each other for reproduction. Willensdorfer (2008) indicates that the alleviation of reproductive competition allows for a division of labour because "cells can specialize on non-reproductive (somatic) tasks and peacefully die since their genes are passed on by genetically identical reproductive cells which benefited from the somatic functions".

In some cases a multicellular organism results from the aggregation of individually dwelling unicellulars (for example, true slime moulds, Ciliates and Myxobacteria). More generally, a multicellular organism develops when daughter cells cohere after cell division. A simple, temporary form of multicellular life is present in slime moulds. Here, genetically-different, individually-dwelling cells aggregate and bind using membrane proteins to form a colonial state in which the cells intercellularly communicate by diffusion. At a certain moment,

obligatory interactions between cells lead to the formation of irreversible cell differentiation producing a reproductive structure. During this state, the slime mould cells are temporarily a multicellular organism.

With the evolutionary development of plasma connections, advanced multicellular life became possible. Plasma connections allow efficient and rapid intercellular communication, involving electrical signals, chemical signals and nutrient transport (Mackie et al. 1984, Peracchia and Benos, 2000, Nicholson, 2003, Panchin, 2005). Plasma connections have evolved in several lineages of multicellulars. Plasma connections between animal cells depend on gap junctions, between plant cells on plasmodesmata, in blue-green algae on microdesmata, and in certain fungi or in developing insect eggs on incomplete cell walls. The evolution of gap junctions some 700 million years ago coincided with an explosion of multicellular life forms.

Multicellular organisms may go through life stages that are not multicellular. For example, sexual reproduction involves single-celled egg and semen. Furthermore, during the two-, four- and early eight-cell stages most vertebrate embryos have loosely attached cells without obligatory dependency. Accordingly, they represent a colony. When separated from the colony, the cells show a normal development. Early separation of embryonic cells is the reason why identical twins exist. Embryo cells in the early stages can even mix with another embryo's cells of the same age and develop into a normally functioning organism, called a chimera, in which some organs and tissues belong to a different genotype than others. A definition of life should, therefore, respect that an organism's cells may differ in genotype. From the late eight-cell stage, the development of gap-junctions marks the emergence of regulation as a unit, which makes the cellular colony a multicellular.

The realisation of a multicellular's potential for maintenance depends on prevailing conditions. For example, a tree twig that is stuck in the ground may become a tree again if the weather is not too warm, too cold, or too dry, etc. and if the twig has the genetic potential for regeneration and is large enough, in good condition, etc.. Whether the twig is an organism depends on its potential to show all dynamics required for being a multicellular operator. This potential is in principle gene-based, but it depends on the condition of the phenotype and the environment for its realisation.

Sometimes two multicellular organisms show symbiosis, such as plants living in close association with mycorrhiza fungi in their roots. As the fungus and the plant already are multicellular on forehand, a plant with mycorrhiza represents an interaction between two multicellular organisms.

d. The memon. Attempts to define life frequently focus on the typical properties of the first cell. The underlying assumption may be that all organisms consist of cells and that, for this reason, the definition of the living properties of cells will automatically cover other, more complex organisations. According to the operator hierarchy, this reasoning is incomplete because, with respect to artificial intelligence, it unsatisfactorily excludes technical life *a priori*. The reason is that the fundamental construction of the brain is not principally different when built from cellular neurons, technical neurons (small hardware acting as a neuron) or programmed neurons (virtual devices modelled to act as neurons). Even though all organisms on earth currently consist of cells or show neural networks that consist of cells, the fact that technical memons may, one day, have a brain structure similar to cellular memons implies that a general definition of life must consider the possibility of technical memons.

Memons show a neuron network and a sensory interface. The basic neuron-units have been named categorizing and learning modules or CALMs and allow for a recurrent network of CALMs (Murre, Phaf and Wolters 1992, Happel 1997). The interface includes sensors that allow the memon to perceive its body and environment, and effectors that allow it to move the cellular vehicle it resides in. The interface and vehicle co-evolved during the evolution of neural networks. In principle, it is possible to construct a functional memon from any kind of technical hardware that provides the required neural architecture. This is the reason that the study of neural networks in biology shows a fundamental overlap with research on technical artificial intelligence. The recognition that memons show a recurrent network of CALMs surrounded by an interface allows Siamese twins with separate brains to be classified as two memons sharing the same vehicle and showing in this vehicle a partial overlap of their interfaces.

No life, no reproduction

According to some authors (e.g. the Von Neumann & Burks, 1966) reproduction is a pre-requisite for life. Like the chicken and the egg problem, it can also be said that life is a pre-requisite for reproduction. Clearly, any decision on this matter critically depends on the context that is used to define life. If the operator hierarchy is used, the least complex life form is the prokaryotic cellular operator. Two arguments currently suggest that life is a pre-requisite for reproduction. The first states that even though all other organisms originate from the first cell by reproduction, the first cell itself had an inorganic origin. The emergence of the first cell thus shows that life does not obligatorily result from reproduction. The second argument posits that organisms do not need to show reproduction, i.e., producing offspring, to comply with the operator-based definition of life; the operator-based definition demands that organisms show two closures: autocatalysis and a membrane. Autocatalysis can be regarded as reproduction

without creating offspring. As Jagers op Akkerhuis (2001) pointed out, autocatalysis implies that a cell autonomously creates a structural copy of its information, a process that is called 'structural (auto-) copying of information'. Before answering the question of whether the structural (auto-)copying of the cell's information means that it must reproduce, it is important to detail the concept of information. For the latter, I suggest applying Checkland and Scholes (1990) definition of information to the autocatalytic set. These authors have defined information as data with a meaning in a context. In line with this reasoning, Kauffman (1993) proposed that, by selecting the autocatalytic process as the context, every catalytic molecule becomes a data-unit with a catalytic meaning (the 'purpose' mentioned by Kauffman 1993, p.388) and represents a part of the information of the autocatalytic process. Following one round of autocatalysis, or more rounds to account for the loss of enzymes over time, the cell contains copies of all of its information. At that moment, it has autonomously performed structural copying of information and fulfils all the requirements of the operator hierarchy, even when it does not produce an offspring. Based on this reasoning, the capacity of autocatalytic maintenance is an obligatory requirement for cellular life and reproduction is a possible consequence.

The above implies that it is not relevant for a general definition of life to distinguish between life forms with or without replication, as Ruiz-Mirazo et al. (2004) has suggested. The latter authors distinguish 'proto-life stages' that do not show a phenotype-genotype decoupling (soma with genes) from 'real life' with genes. In line with the operator hierarchy based definitions, Morales (1998) warns that "*if reproduction is required: This is a troubling development, because it means that we could not tell whether something is alive unless we also know that it is the product of Darwinian evolution.*" The operator-based definition considers life as a prerequisite for reproduction instead of reproduction as a prerequisite for life. Consequently, worker bees, mules, infertile individuals and other non-reproducing organisms and/or phenotypes are life. This point of view also solves problems that may arise when demanding that memons be able to reproduce as a prerequisite for recognising them as life forms. In fact, none of the cellular memons living today shows reproduction, at least not reproduction of their neural network structure determining their closure. The things they pass on during reproduction are the genes of their cells, allowing the development of a multicellular organism with a neural network, capable of learning but devoid of inherited neural information other than reflexes.

Life holding its breath

The above chapter shows that reproduction is not a prerequisite of life but a possible consequence of it. Going one step further, it can also be concluded that metabolism is not a prerequisite for life. Many taxa such as bacteria, protozoa, plants, invertebrates and vertebrates have developmental stages showing natural inactivity (seeds, spores) or reversible inactivation when submitted to desiccation, frost, oxygen depletion, etc. The inactive state carries the name of anabiosis, after the process of coming to life again (for a review of 'viable lifelessness' concepts, see Keilin 1959). Another type of reversible inactivity showing marked similarity with anabiosis is the state of neural inactivity in memons following anaesthesia. An aesthetic that blocks the transmission of signals between neurons while leaving the remaining metabolic activity of the neurons intact causes a reversible absence of neural activity that corresponds to an anabiotic state of the memon.

Even in the early days of the biological sciences, scholars discussed whether dried or frozen anabiotic stages are alive at a very slow pace, or whether they are truly static states of matter. In 1860, the famous Société de Biologie in Paris wrote a lengthy report on this subject (Broca 1860-1861). Quite importantly, this report concluded that the potential to revive an anabiotic stage is an inherent aspect of the organisation of the material of which the object consists and that it is equally persistent as the molecular state of the matter forming the system. In short, the Société de Biologie found that "*la vie, c'est l'organisation en action*". Additional support for this conclusion came from Becquerel (1950, 1951) who subjected anabiotic stages to a temperature 0.01 degree above absolute zero, a temperature at which no chemical processes can occur, even not very slowly. Becquerel demonstrated that structure alone is enough to allow revival at normal temperatures. Anabiosis from absolute zero or complete desiccation has led to the conclusion that "*The concept of life as applied to an organism in the state of anabiosis (cryptobiosis) becomes synonymous with that of the structure, which supports all the components of its catalytic systems*" (Keilin 1959), or that "*life is a property of matter in a certain structure*" (Jeuken 1975). With respect to the question of: 'what certain structure?' the operator hierarchy suggests that all operators with a complexity similar to or higher than the cell answer this question.

Life as we do not know it

Considerations about "life as we do not know it" depend on assumptions. As a context for such assumptions, the operator hierarchy offers two advantages. First, the operator hierarchy has its basis in the general principle of first-next

possible closure. Second, the rigid internal structure of the operator hierarchy offers a unique guide for assumptions about life that we do not yet know.

Based on the general principle of first-next possible closure, the operator hierarchy shows a strict sequential ranking of the operators. Assuming that closures act as an absolute constraint on all operator construction, the operator hierarchy then has universal validity. Support for the latter assumption comes from the observation that, as far as we know, all operators with a complexity that is equal to or lower than the molecules seem to have a universal existence. If this universality extends to the biotic operators, the material organisation of higher-level operators, such as cells and memons, may then possibly be found in the entire universe. Such universality would significantly assist in the search for exobiotic life forms because alien life may show similar organisation to the life we do know, at least with respect to the first-next possible closures involved. The demand of closure still leaves a good deal of freedom for the physical realisation of operators. On other planets, different molecular processes may form the basis of the autocatalysis and interface of the first cells. Similarly, the operator hierarchy poses no limits to the actual shape, color, weight, etc. of exobiotic multicellular organisms. Furthermore, even though the presence of neural networks may be required for memic organisation throughout the universe, the operator hierarchy does not restrict the kind of elements producing these networks, or the details of the neural network structure other than demanding hypercyclicity and interface.

The rigid internal structure of the operator hierarchy allows predictions about the construction of life forms that have not yet evolved on Earth. Of course, any discussion of this subject involves speculation, but the operator hierarchy may well offer a unique starting point for such a discussion. In an earlier publication (Jagers op Akkerhuis, 2001), I have indicated various future operator types with a higher complexity than the cellular hardwired memon. To minimise the aspect of speculation, I would like to discuss here only the memon immediately above the cellular hardwired memon (see fig. 5.1), the so-called 'softwired memon'. According to the operator hierarchy, this type of memon should be able to copy information structurally. This means that the organism should be able to copy all of its information by copying the structure of its neural network. At a lower level in the hierarchy, cells do this by copying their genetic molecules. Softwired memons can also do this. They are based on a virtual neural network that resides in computer memory arrays. During their operation softwired memons continuously track all their neurons, neural connections, connection strengths and interactions with the interface. It is therefore only a small step for softwired memons to read and reproduce all the knowledge in their neural network by copying these arrays. On these grounds, it may be deduced that softwired memons (or still higher complexity memons) form the easiest way to satisfy the demands of the operator hierarchy for the autonomous, structural copying of

information. The operator hierarchy suggests therefore that life as we do not know it will take the shape of technical memons.

The above reasoning shows that the operator hierarchy offers clear criteria with respect to different forms of 'artificial life'. The acceptance of an artificial entity as life is only possible when it shows all of the required properties of an operator. Referring to the difference between strong artificial life and weak artificial life, which do and do not consider a-life entities as genuine life, respectively, it would be fully in line with the present reasoning to consider as genuine life all a-life entities that fulfil the requirements for being an operator.

On life and death

Given the present focus on states of matter, it is quite simple to define dead matter as: all operators that do not fit the general definition of life. It is more difficult, however, to define death.

Given the current point of view, death represents a state in which an organism has lost its closure. The use of closure in this definition helps prevent that "*.... the properties of an organism as a whole [would be confused] with the properties of the parts that constitute it*" (Morales 1998). However, organisms also loose their closure during transitions that are part of life cycles and that are not associated with the organism's death. For example, the closure of the organism is lost and a new closure gained when the zygote exchanges its unicellular organisation for the multicellular state of the embryo and when the multicellular embryo develops to a memic state. Is it possible to specify the loss of closure during death in a way that excludes closure losses during life cycles?

With respect to the above question of how to exclude the loss of closure during transitions in life cycles when defining death, the general process of deterioration offers a solution. During their lives, organisms deteriorate because of injury and ageing. The loss of closure marking death is always associated with the organism's irreversible deterioration. Demanding irreversible deterioration, therefore, helps to prevent that one would be tempted to consider, for example, a caterpillar as having died, when its tissues are reorganised during the transition via the pupae to a butterfly. Accordingly, it is possible to describe death as: the state in which an organism has lost its closure following irreversible deterioration of its organisation.

Using the above definition, death may occur in either an early or late phase of the deterioration process, and following the death of multicellulars, a short or long period may pass until the organism's body parts become dead matter. The latter has its cause in the hierarchical construction of multicellular organisms.

Accordingly, the loss of the highest closure implies a classification of the remaining body as an operator showing the first-next lower closure.

Death depends on the loss of closure. To illustrate the contribution of this statement to the analysis of death, the death of a memon can be used. Due to the memon's strongly integrated organisation, death may occur at various levels that affect other levels. For example, the multicellular regulation may be the first to collapse due to the loss of liver functions. After a certain period, this will cause failure of neural functioning, the latter marking the memon's death. In another situation, the neural functions may be lost first, and the memon is the first to die, dragging its body with it in its fall. However, sometimes enough neural activity may remain for a vegetative functioning of the memon's body as a multicellular unit. The vegetative state cannot maintain itself autonomously (in principle, a requirement for a multicellular organism) but it may continue given the right medical care. If this care is withdrawn, the multicellular body will start deteriorating after which the cells in the organs and tissues will start dying at different rates. At a certain point, the multicellular closure is lost, and separately surviving cells have become the next level operators to die. Physiological differences between cells now determine the period during which they can survive in the increasingly hostile habitat of the dead memon, which is cooling below the normal operating temperature of cells and which shows many adverse chemical changes such as the lowering of oxygen levels, the release of decay products of dead cells, etc. Shortly after the memon's death, it is possible to take intact body-parts, organs and cells from its body and sustain their functioning following transplantation to a favourable environment. For example, the offspring of cells from the cervix of Henrietta Lane are still cultured as He La cells in many laboratories.

The inutility of property lists

The above arguments and examples have explored the possibilities of using the operator hierarchy for creating coherent definitions of life, the organism, living and death. However, how should the outcome be evaluated? Have the present attempts led to definitions that could be generally accepted in the field? A way of evaluating this that has become rather popular is to check the results against lists of preset criteria. Those who want to evaluate the present approach in this way may want to examine the following lists of criteria.

Morales (1998) has published a list of properties for a definition of life that includes the following criteria: 1. Sufficiency (Does the definition separate living entities from non-living ones?), 2. Common usage (simple classification of easy examples), 3. Extensibility (Does the definition deal with difficult cases, such as viruses, mules, fire, Gaia, extraterrestrial life and robots?), 4. Simplicity (few ifs,

buts, ands, etc.) and 5. Objectivity (Criteria are so simple that everyone applies them with the same result). Emmeche (1997) offers another criteria list for a definition of life that includes the following: 1. The definition should be general enough to encompass all possible life forms. (The definition should not only focus on life as we know it.), 2. It should be coherent with measured facts about life, (It should not oppose obvious facts.), 3. It should have a conceptual organising elegance. (It can organise a large part of the field of knowledge within biology and crystallise our experience with living systems into a clear structure, a kind of schematic representation that summarizes and gives further structure to the field.), 4. The definition should be specific enough to distinguish life from obviously non-living systems. Emmeche (1997) furthermore states that a definition “should cover the fundamental, general properties of life in the scientific sense”. Korzeniewski (2005) has also proposed a list of criteria for a cybernetic definition of life, and Poundstone (1984) has extracted further criteria for life from the work of von Neumann & Burks (1966). Oliver and Perry (2006) have suggested a list more or less similar to that of Emmeche (1997) focusing specifically on properties of a good definition.

With respect to the use of criteria lists, I agree with other authors (Maturana and Varela 1980, van der Steen 1997) that it is not necessarily an advantage if a theory performs well or a disadvantage if a theory performs poorly according to a list of criteria; an approach's value does not necessarily correspond to its performance in these types of checklists. The match depends on the similarity in major goals and paradigms and the creator's influence on the selection and definition of criteria in a given list. In addition, the selection of ‘favourable’ lists can lead to false positives.

For the above reasons, I am convinced that it is only possible to evaluate the currently proposed definitions ‘the hard way’, i.e., by critically examining the internal consistency and transparency of their logic. In this respect, the present approach has the advantage of a fundamental bottom-up construction. It starts with defining elementary building blocks, the operators, and their hierarchical ranking in the operator hierarchy. To recognise and rank the operators, the operator hierarchy uses first-next possible closures. In the resulting hierarchy, the definition of every higher-level operator depends, in an iterative way, on a lower-level ‘ancestor’ until a lowest-level ancestral system is reached, which is presumably the group of elementary particles that according to the superstring theory may have a common basic structure. The result is a strict, coherent and general framework that is open to falsification: the operator hierarchy. Subsequently, the operator hierarchy offers a fundament to define a range of secondary phenomena, such as life, the organism, living and death. Because of the reference to the operator hierarchy, the present definitions are short, logical statements that show a high specificity with respect to whether a certain entity satisfies the definition (list of examples in the following paragraph).

Testing the definition of life

When using the operator hierarchy as a context for a definition, it is easy to conclude that viruses, prions, memes or replicating computer programs are not forms of life. Both a virus with a surrounding mantle and a viral strand of DNA or RNA are not operators, thus not life. Prions are molecules, thus not life. Memes, such as texts and melodies, are pieces of coding that memons can decode and replicate (Dawkins 1976). Accordingly, memes are not operators, thus not life. Ray (1991) has created computer programs that can replicate themselves onto free computer space, show mutation, and modify and compete for the available space in a virtual world called Tierra. Since its start, this virtual 'ecosystem' has seen the evolution of a range of different computer programs. In the same way as molecular viruses depend on cells, the programs in Tierra depend on a computer to copy and track their structure. Accordingly, they are not operators, thus not life. Sims (1994) has used genetic algorithms for evolving virtual computer creatures with body parts and a neural network with interface. The simulation of these animal-models allows virtual movement such as finding and grasping virtual food items. Sims's programmed creatures may possess hypercyclic neural networks and on these grounds show similarity to softwired memons. According to the operator hierarchy, a softwired memon should autonomously be able to copy its information structurally. Although I am not an expert in this field, it seems to me that Sims's organisms do not *themselves* keep track of their arrays with information about their interface and neurons, neural connections, and connection strengths, and that they do not autonomously organise their maintenance. Assuming that the latter interpretations are correct, Sims's computer animals are not yet life.

The use of the present definition also allows the effortless rejection of other systems that are not operators and sometimes receive the predicate of 'borderline situations', such as flames, whirlwinds, crystals, cars, etc. Technical, computer based memons, however, such as robots, can be operators when they show the required structure.

To summarise the practical applicability of the present definition of life, I include a list of the examples that were discussed in the text and supplement them with some additional cases. The examples in this list form three groups depending on whether the entities involved are operators or not, and whether they show a complexity that equals or exceeds that of the cellular operator. In the text below I use the concept of 'interaction system' (e.g. Jagers op Akkerhuis, 2008) for all systems that are not operators because the interactions of their parts do not create a first-next possible, new, closure type.

Group A. Systems that are not life because they are not an operator

1. An entire virus particle with external envelope (represents a simple interaction system)
2. A computer virus based on strings of computer code
3. A flame
4. A tornado
5. A crystal
6. A car
7. A bee colony (The colony is an interaction system, and the bees are organisms.)
8. A cellular colony not showing the requirements of multicellularity (The individual cells are organisms and thus represent life.)
9. A colony of physically connected cellular memons (as long as the individuals lack the required memic closure)
10. A robot (as long as it is a non-memic technical machine)
11. Computer simulations of organisms (including memons) that depend on external 'orchestration'
12. A cutting/slip of a plant that cannot potentially show autonomous maintenance given the right conditions (It lacks the closure required for multicellularity.)
13. A separate organ, such as a liver or leg (not potentially capable of autonomous maintenance)
14. Endobiotic bacteria having lost genes that are obligatory for autonomous maintenance. The transfer to the genome of the host of DNA coding for enzymes required in autonomous maintenance implies a partitioning of the autocatalytic closure between the endobiont and its host. Because of this, the endobiont is no longer an autonomous organism but has become a special kind of organelle.

Group B. Systems that are operators but that are not life because their complexity is lower than that of the cellular operator

1. A prion
2. Self-replicating DNA/RNA particles (catalyse their own copying in a solution containing the right building materials)
3. A DNA or RNA string of a virus that is copied in a cell

Group C. Operators representing life

1. A cutting/slip or other plant part that can potentially maintain itself given favourable environmental conditions
2. Anabiotic organisms (The fact that they are dried, frozen, etc. does not take their required closure away.)

3. Fully anaesthetised animal supported in its functioning by a mechanical heart-lung support and showing no neural activity (This can be regarded as a form of memic anabiosis with the potency to become active again.)
4. A computer memon or other technical memon (a memic robot)
5. An artificial cellular operator constructed by humans
6. A exobiotic cellular operator with another chemistry than that found on earth
7. Sterile or otherwise non-reproducing organism (e.g. a mule, worker bee, sterile individuals)
8. Endoparasites or endosymbiotic unicellular organisms living in cells and still possessing the full potential of autocatalysis

In conclusion

1. Overviews of the definitions of life from the last 150 years show that no consensus definition on life exists. In the light of the continuous failure to reach consensus on this subject, certain scientists have adopted a practical viewpoint, accepting, for example, the use of property checklists for identifying living systems. Others have advocated that the need for a generally accepted definition remains acute. Amongst the proposals for solving the problem is the suggestion to construct a broader context, a 'theory of life' before continuing with attempts to define of life.
2. Inspired by the latter suggestion, the present paper invokes a classification of the generalised particle concept, called the 'operator hierarchy'. This hierarchy has several advantages for defining life: first, it offers a general context for including and differentiating between life and non-life, and second, it offers the unique possibility to extrapolate existing trends in the evolution of material complexity and to use these as a guide for discussions about 'life as we do not know it'.
3. In close association with the reviewed literature, the use of the operator hierarchy allowed the following definitions to be suggested:
 - A. From the viewpoint of the evolution of material complexity, life is: matter with the configuration of an operator, and that possesses a complexity equal to or even higher than the cellular operator.
 - B. Living describes the dynamics of an operator that satisfies the definition of life.
 - C. The definition of unitary organisms can take the form of: the operators that fit the definition of life.
 - D. A multicellular organism (the cellular operator showing the multi-state) is: a construction of mutually adhering cells showing obligatorily recurrent interactions based on the same interaction type, that has the potential of maintaining its functioning as a unit and that does not show memic structure
 - E. Dead matter applies to all operators that do not fit the definition of life.

- F. Death is: the state in which an organism has lost its closure following irreversible deterioration of its organisation.
4. From the discussion of examples in the literature, it was concluded that the present set of definitions easily distinguishes life and non-life regardless of whether this is tested using the 'obvious examples', the 'borderline cases' or 'life as we do not know it'. This suggests that the present approach may well offer a practical step forward on the path towards a consensus definition for the states of matter representing 'life'.

Acknowledgements

The author would like to thank Herbert Prins, Henk Siepel, Hans-Peter Koelewijn, Rob Hengeveld, Dick Melman, Leen Moraal, Ton Stumpel and Albert Ballast for constructive discussion and/or comments on the manuscript and Peter Griffith for English correction.

The issue of 'closure' in Jagers op Akkerhuis's operator theory

Comments by Nico van Straalen

In this issue of *Foundations of Science* Jagers op Akkerhuis (2010a) proposes a definition of life based on his earlier theory of operators. A great variety of objects fall into the category of operator, and by introducing this term Jagers op Akkerhuis was able to draw a parallel between elementary particles, molecules, cells and multicellular organisms. The common denominator of these operators is their autonomous activity and maintenance of a specific structure. Consequently, operators were classified in a logical and hierarchical system which emphasizes the commonalities across what is normally called non-life (atoms, molecules) and life (cells, organisms). One very attractive aspect of the classification is that it joins the objects traditionally studied by physicists, chemists and biologists into one overarching system. Obviously, the hierarchy crosses the traditional border between life and non-life, so it should be possible to develop a definition of life from the operator theory. This is what Jagers op Akkerhuis attempts to do in the present paper. However, I believe he misses the point.

In the operator hierarchy, successive levels of complexity are separated by 'closure events', e.g. when going from hadrons to atoms, from molecules to cells and from multicellular eukaryotes to memic organisms. One of these closure events actually defines the origin of life: the transition from molecules to cells. Death, as defined by Jagers op Akkerhuis, is the loss of this closure, a fall-back from cells to molecules. There is another important transition, the origin of self consciousness, a closure event that accompanies the highest level of complexity in the classification of operators. Life with this level of complexity (maybe call it 'hyper-life'?) is included in Jagers op Akkerhuis's definition of life.

Another interesting aspect of the operator system is that it is strictly hierarchical, that is, every operator can be classified on a more or less linear scale and the big leaps forward are punctuated by closures on that scale. This aspect of the system is reminiscent of the 'Great Chain of Being', or *scala naturae*, which was the dominating view of life for many centuries. In evolutionary biology, it is now recognised that pathways can split and run in parallel, maybe even achieving similar closures independently from each other. I am not sure how this aspect fits into the operator classification of Jagers op Akkerhuis.

To define life in terms of the operator theory I believe the focus should be on the transition from molecules to cells and the closure aspects of this event. In other words, the closure of operating systems defines life better than the classification of operators. However, Jagers op Akkerhuis seems to add another seemingly

hopeless definition of life to the nearly 100 already existing. Classifying what is life and what is not is, I believe, a rather trivial exercise. Everybody knows that a flame is not life, and it only becomes a problem when you spend too many words on it. Rather than classifying things into living and non-living entities I believe the challenge is to understand how the transition from non-life to life can take place, that is the how the closure in Jagers op Akkerhuis's hierarchical classification of operators, comes about.

The issue of closure is intimately linked to that of emergence. Both concepts recognise that the characteristic properties of a living system cannot be reduced to its component parts only, but also depend on the way in which the components are organised in a network. The properties that arise from interactions between components are said to be 'emergent'. Emergent properties are not shared by the components; they 'appear' when many components start interacting in a sufficiently complex way.

The concept of emergence plays an important role in genomics, the science that studies the structure and function of a genome (Van Straalen & Roelofs, 2006). After about a decade of genome sequencing, scientists started to realise that the genome sequence itself does not define the organism. The human genome turned out to contain no more than 24.000 genes, much less than the earlier assumed 124.000. This raised the question how it could be possible that such a complicated organism as a human being could be built with so few genes. Obviously the pattern of gene and protein interaction defines human nature much more than the genes and proteins themselves. A new branch of biology was defined, systems biology, which was specifically geared towards the analysis of interacting networks, using mathematical models (Ideker et al., 2000).

Schrödinger (1944), in discussing the question 'What is life?' foresaw a new principle, not alien to physics, but based on physical laws, or a new type of physical laws, prevailing inside the organism. These are the kind of laws that systems biology is after. The operator classification of Jagers op Akkerhuis is an important step because it emphasizes the continuity between physical systems and biological systems. However, the challenge of defining life is not in classification but in understanding the closure phenomenon by which life emerged from non-life.

Definitions of life are not only unnecessary, but they can do harm to understanding

Comments by Rob Hengeveld

In his paper, Jagers op Akkerhuis (this volume) refers to a list of almost 100 different definitions subsequently having been given in the literature to the phenomenon of life as we know it. These definitions may even have a more general application or meaning than that concerning life on earth only. That is, also to some form of life as we don't know it, even though we don't know it. Like other authors, he feels that all this activity messed things up. Thus, Jagers op Akkerhuis mentions authors emphasising "the seeming hopelessness of the situation", some of them adopting "a pragmatic/pessimistic viewpoint". Others would have suggested "that life cannot be defined, that its definition is not important for biology", or that "a comprehensive definition of life is too general and of little scientific use". Finally, only "living processes may be defined" which "cannot be reduced to physics".

His theory based on the criterion of hierarchically arranged operators would tidy up this mess a little. I feel, though, that the introduction of his own definition "life may be regarded as a special realisation of the evolution of material complexity" brings the 98 existing definitions even closer to 100. Worse, this theory and definition will confuse our biological issues even more by their circularity of reasoning. They are circular because his operator concept "emphasizes the autonomous activity of the entities involved, which 'operate' in a given environment without losing their individual organisation". How do we distinguish the autonomy of processes in early living systems or even in present-day molecular biological ones from those of non-living processes? Also, activity, operation, and organisation are concepts connected with living systems and their functioning. Furthermore, individual organisation smells of one of the criteria on which some earlier definitions have been based. Thus, recognising something as living depends on criteria derived from known, recent living systems; a bean is a bean because it is bean-shaped.

When, as a beginning ecologist, I was studying ground beetles, and later as a biogeographer, I never felt any need for a definition of life. Then, such a definition was clearly useless. More recently, being concerned with questions about the origin of life, that is concerned with processes ultimately having resulted in a beetle as a living system, I came to realise that most, if not all, of these definitions were designed particularly within this context of the origination of living systems. However, we don't need to define the moon to understand its origin either. Yet, they not only seem useless, they are even harmful. Adopting certain criteria on which to base the one or the other definition, authors easily force themselves to look into the wrong direction. Or even at the wrong

biogenetic phase, too late in the development of life. For example, not only is 'organisation' difficult to delineate objectively at a molecular level, and this without circularity, but depending on a subjectively chosen threshold level, it easily excludes initial phases from analysis, however significant these could have been. Continuing along such a misdirected road is fruitless.

Thus, the criteria used, such as a certain level of organisation, are always derived from present-day life forms, from processes or structures that may not have existed in the early biogenetic phases. One criterion, as one of many examples, points at macromolecules, although these will have developed from earlier oligomers (see, for a clear example, Eck and Dayhoff, 1966). Another, widely applied criterion derives from the present prevalence of carbon as a principal biochemical constituent. Yet, carbon forms very stable molecules, as do its neighbours in the Periodic table, nitrogen and oxygen, for example. They are difficult both to form as well as to break down again, which is therefore usually done by enzymes. These enzymes, plus the enzymatic apparatus they together form, must have developed earlier, before carbon could have been taken on board biochemically (see Hengeveld and Fedonkin, 2007). Moreover, in their turn, individual enzymes are often very complex macromolecules, which not only must have been derived evolutionarily from more primitive ones, but they have to be formed by and operate within an intricate biochemical apparatus in which DNA is pivotal. Yet, DNA itself requires the operation of a very complex system of repair enzymes, etc., plus the mediation of spliceosomes and ribosomes for the final construction of those enzymatic macromolecules. Clearly, carbon as an element must have been inserted into the biochemistry only at a later, evolutionarily more highly developed stage of biogenesis.

Personally, I prefer to abstain from using definitions in this context. This differs from asking what requirement is needed to form a molecular bond, of a system of molecules, etc., any form of organisation, biological or non-biological. This puts the problem within the thermodynamic realm. A basic requirement, one that can be met by several properties, therefore differs from a property, physical, chemical, biological, or socio-economic; instead, it defines both the process and the shape of molecules taking part in it (Hengeveld, 2007). It defines the properties. It's the resulting processes happening and developing which are of interest, for the understanding of which a definition of life is irrelevant. It does not add anything.

Formulating the study of biogenesis in terms of processes happening and developing precludes the design of definitions, which are more likely to be applied to static or stable situations. And which are, already for that reason only, to be shunned. Defining life is not a part of our scientific endeavour.

Explaining the origin of life is not enough for a definition of life

Reaction of Gerard Jagers op Akkerhuis to the comments and questions of Rob Hengeveld and Nico van Straalen.

I thank the commentators for their reactions, both positive and negative, giving me the opportunity to elucidate some important aspects of the presented theory.

As Van Straalen indicates, the operator hierarchy offers valuable innovations: Firstly, the hierarchy ‘... joins the objects traditionally studied by physicists, chemists and biologists into one overarching system.’ Secondly, ‘...it is strictly hierarchical’. I think that precisely these two aspects make the operator hierarchy a unique tool for defining life in a way that simultaneously addresses all the different organisational levels of living entities, e.g. prokaryotic cells, eukaryotic cells, pro- and eukaryotic multicellulars and neural network organisms, including future ones based on technical neural networks.

Further reactions of the commentators indicate that, probably due to the novelty of the operator theory, certain aspects require further explanation. I will discuss some essentialities in the following lines.

Hengeveld criticizes an asserted circularity in reasoning, in the sense that living operators are defined by means of concepts, which are derived from living systems. The confusion on this point results from my explanation in the paper. There I indicate that the name operator originates from the operating (in a very general sense) of individual entities. It may be reassuring to Hengeveld that the *origin* of the name ‘operator’ shows no direct relationship with the *definition* of the operators as system types. The entire set of all operators is defined as follows: based on the presumed existence of a lowest complexity operator, every system that belongs to the operator hierarchy resides at exactly one higher closure level than its preceding-level operator. Every closure level is defined by the occurrence of one or two first-next possible closures. Although this is a recursive definition in the sense that every operator in principle depends on its preceding-level operator, its hierarchical architecture precludes circularity of reasoning.

Hengeveld furthermore states in a general way that definitions of life ‘are always derived from present day life forms, from processes or structures that may not have existed in the early biogenetic phase’. This general criticism does not apply to the operator hierarchy. The reason is that both abiotic and biotic operators are all defined using first-next possible closure. In fact, the operator theory turns the argumentation of Hengeveld upside down, hypothesising that limited possibilities for reaching first-next possible closure have acted as a blue-print for the essential construction properties we recognise in abiotic elements and organisms.

I agree wholeheartedly with both Hengeveld's and Van Straalen's argumentation that we need to increase our understanding of the processes that have caused life. I strongly support the search for bootstrapping mechanisms allowing simple system states/elements to autonomously create more complex system states/elements (e.g. Conrad 1982, Martin & Russell, 2003, Hengeveld, 2007). In fact, every closure step in the operator hierarchy is the product of a specific (the first-next possible) bootstrapping mechanism. With respect to specifying the closure types resulting from such bootstrapping mechanisms, I consider concise and general definitions as indispensable tools, being helpful (instead of harmful!) in our search for the essences of the evolution of matter. Thus when Hengeveld advocates that he prefers '... to abstain from using definitions in this context.' I find his viewpoint surprising for two reasons. The first reason is that even a very thorough understanding of specific reaction mechanisms will not automatically result in a general definition of a meta-aspect such as the type of material organisation defining living entities. The second reason is that I think that accurate definitions are simply a way to improve the precision and communication of science: sloppy definitions lead to the development of sloppy theory and a lack of definitions leads to no science at all.

Referring to a demand for a mechanistic focus when defining life, Van Straalen states that 'the challenge is to understand how the transition from non-life to life can take place' as this can explain how the classification of operators comes about. Also in his last sentence Van Straalen writes that '..., the challenge of defining life is not in classification but in understanding the closure phenomenon by which life emerged from non-life'. Both statements being true, it is nevertheless impossible to construct an overarching theory such as the operator hierarchy if one limits his view to the mechanisms explaining one single step involved.

The warm interest of Hengeveld and Van Straalen for mechanisms that could explain the origin of life is understandable, because it frustrates the scientific community that science is not yet able to *de novo* synthesise life, not even in the form of a primitive cell. This general focus on the construction of life seems, however, to have caused a tunnel vision with respect the *definition* of life. Imagine that we would be able to explain the cell, and even construct it, would this then mean that we would have a proper definition of life in all its forms, including multicellular organisms and neural network organisms? The answer is a clear NO. If everything that is based on living cells would be life, then a donor organ and a fresh, raw steak would also be life. Moreover, any technical being, however intelligent, could never be called life, because it is not based on cells. This proves that a focus on cells alone is not enough. We need to broaden the scope and define all levels of organisation associated with higher forms of life. It is my personal conviction that, for the latter goal, the operator hierarchy offers a unique and unprecedented tool.

Getting the biggest part of the pie

Using resource dominance to explain and predict evolutionary success

“Without competitors there would be no need for strategy.”
(Keniche Ohnae)

Abstract

In this century, evolutionary biology has been successful in using fitness as a measure for evolutionary success. Although fitness has the intuitive association of "something which is better", a restricted definition in the form of "the number of successful offspring" is often used in biology. This definition is convenient because it is, in principle, easy to count offspring. Yet, the explanatory and predictive capacities of such fitness measurements are restricted and the method is restricted in its use to reproducing entities.

To better understand traditional fitness measurements, we suggest that more attention be paid to underlying factors. For this purpose we advocate to focus on "resource dominance". The idea is that any unit of evolution which is good at dominating the resources needed for maintenance, growth and/or reproduction will also show a high evolutionary success. We show that high resource dominance can be reached via different strategies. Additionally, we discuss how the capacity for resource dominance is related to the complexity and efficiency of the evolving unit.

Introduction

Ever since Darwin (Darwin 1859) and Wallace (Wallace 1855), evolution has been expressed as a struggle for life and survival of the fittest. Despite the general intuitive interpretation of a fit entity as being better in some respect, a more specific use of fitness has become generally accepted in biology (Frank 1997, Gavrillets 1997, Fear and Price 1998). This states that the fitness of an entity is proportional to the number of *successful* offspring. Using this definition, fitness is a convenient measure for evolutionary success, because it is, in principle, straightforward to measure the number of offspring. However, there is little predictive power in such a concept of fitness, and it is left open when it may be judged that an offspring has been successful. Additionally, fitness in this definition cannot be used as a criterion for the evolutionary success of units during periods in which they do not reproduce.

To improve on this situation we advocate the studying of the underlying factors which are responsible for the number and the quality of offspring. This, we claim, is done best by focusing on the capacity of organisms to gain dominance over resources, which we term their resource dominance.

In this study we will discuss different aspects of resource dominance as the basis for evolutionary success. We will present several important resource dominance strategies and pay attention to the interaction between resource dominance and the complexity of the evolving unit. By focusing on resource dominance it will become apparent that knowledge of the life history and ecological strategies of the different entities is critical in understanding the evolutionary processes.

To allow a broad covering of the resource use strategies and complexity of evolving units, we will apply the units of evolution approach. This has been used by several authors (Hamilton 1964, Lewontin 1970, Hull 1980) as a way to study evolution of units in relation to their position in the organisation of a system. Examples of such units and levels are the DNA in the cellular environment, mitochondria in the eukaryotic environment, endosymbiotic eukaryotes in other eukaryotes such as has been observed for example in the protist *Peridinium balticum* (Bardele 1997), individuals in populations, and groups of individuals, i.e. social insects in ecosystems.

By focusing on resource dominance as a criterion for evolutionary success, the concept can be applied to entities which evolve their structure without showing reproduction, such as companies and evolving neural networks. Additionally, evolutionary processes in different entities can more easily be compared.

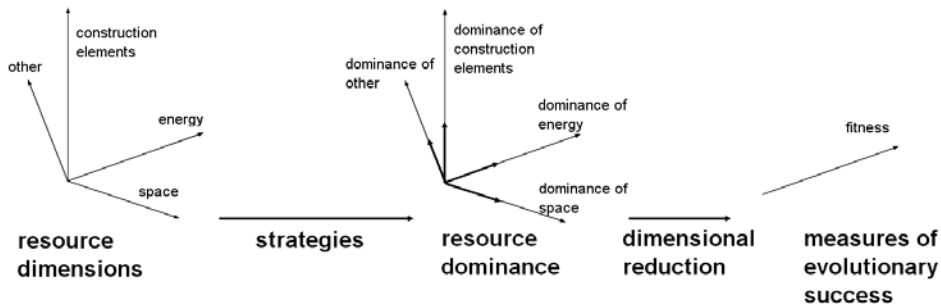


Figure 6.1. A dimensional comparison of resource space, resource dominance space, and fitness. The first part shows the space of all elements which, in principle, could act as a resource for evolving entities. The thick arrows in the second part show those parts of this space which are actually dominated by a particular evolving entity. The last part shows how the fitness of an entity as a measure for its evolutionary success can be obtained from resource dominance space via a fitness function. Note that the parameter reduction involved in obtaining fitness cannot be inverted to obtain information about the resource dominance strategies laying at the basis of fitness.

Resource dominance

The concept of resource dominance is based on the assumption that evolutionary success depends on the capacity to gain equal or larger dominance over limiting resources than competitors. Everything else being equal, a plant gaining access to the most light will grow fastest, and a small animal will lose more fights.

The focus on resources in the present paper is based on the necessity for organisms to use resources for their proper functioning, which minimally requires their maintenance. Under more favourable conditions resources can be converted into more biomass, leading to growth and/or reproduction. Fundamental demands for the use of resources during all these processes stem from the out-of-equilibrium state of organisms as dissipative systems which only can maintain and/or increase their internal organisation at the costs of entropy increase in the surrounding environment (Prigogine and Stengers 1984). The recognition that demands are fundamental to organisms forms, for example, the core of the 'supply-demand'-based models of Gutierrez (Gutierrez 1996, Schreiber and Gutierrez 1998).

Attempting to define resources in accordance with the above, we propose the following definition: resources are all entities that organisms, alone or as a group, can use for their functioning. This definition allows much freedom. It includes both consumables, which are degraded when used, and what could be considered as durables, for which the use does not markedly affect the state. It

also includes the information, the ideas, communicated in social interactions as shown by people and some animals.

As the second part of the resource dominance concept we have given preference to dominance over use, because the dominance by evolving units over resources may extend beyond the use. Examples of such dominance are allelopathy and territory.

Quantification of resource dominance

A measure for resource dominance of an individual or population has to be multidimensional with as many dimensions as there are different types of resources that play an essential role in the evolutionary success of the particular individual or population (Fig. 6.1). For each resource dimension the degree of dominance of the evolutionary unit has to be measured. The resulting measure can be compared with other evolutionary units that are competing for some or all aspects of the resource space. If two organisms compete for a common resource, for example space, their competitive ability may to a large extent depend on the access to non-overlapping, or 'external' resources. The more external resources can be used to increase their competitive ability, the higher their competitive capacity for any common resource will be.

The evolutionary success of a unit can now be measured directly as the increase in the degree of dominance over the resource space, but it is convenient to reduce the multidimensional resource dominance space to the one dimensional measure of evolutionary success: fitness (Fig. 6.1). The understanding of the function that reduces the multidimensional resource dominance space into the one-dimensional fitness measure will give valuable information about the underlying evolutionary processes, i.e. how much does the dominance of a specific resource contribute to the evolutionary success of an evolutionary unit.

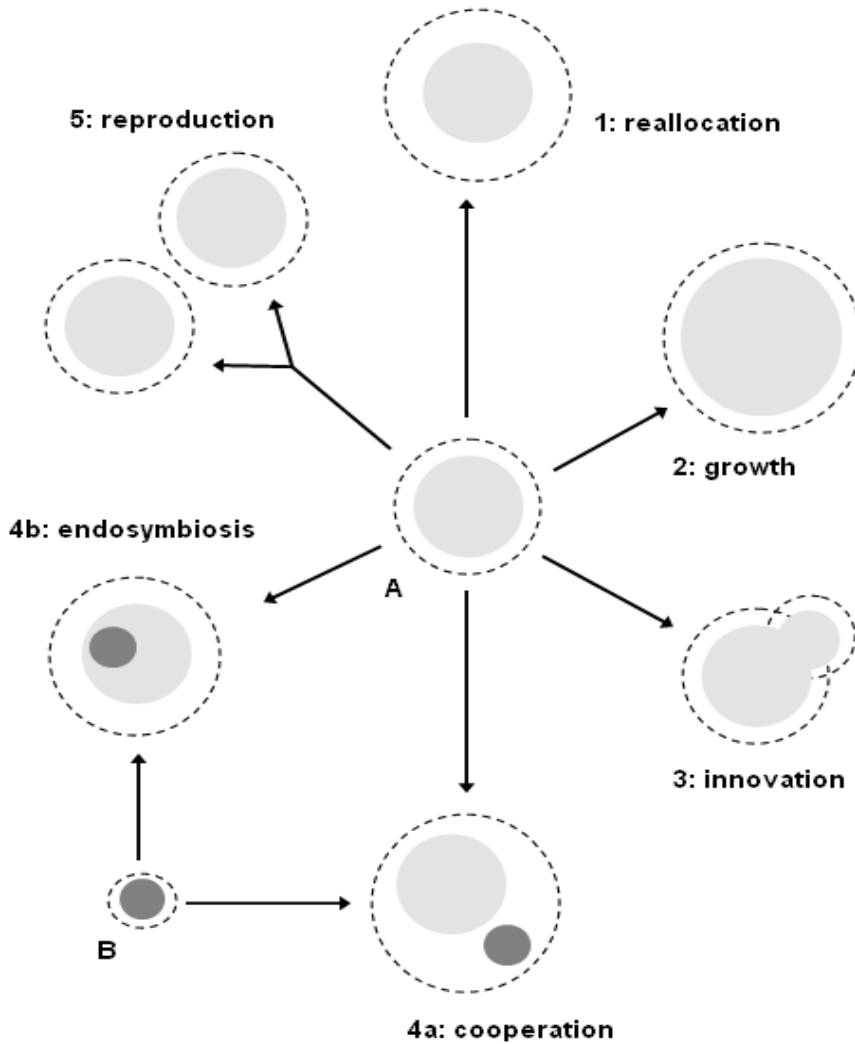


Figure 6.2. Different strategies for organisms and groups of organisms to increase their resource dominance. The physical size of the organism is shown as the inner, shaded circle. The outer, dotted circle represents the amount of dominated resources.

Resource dominance strategies

When talking about resource dominance, the question can be asked which strategies evolving entities can follow to increase this property. Some strategies are summarised in Fig. 6.2. We have ranked the options roughly in order of simplicity. The examples allow increased dominance through: 1) internal re-allocation, 2) larger size, 3) internal re-organisation and adaptation to new resources, 4) co-operative relationships, and 5) reproduction.

The first strategy in Fig. 6.2 refers to an increase in resource dominance by a 'smarter' or more aggressive strategy aiming at the same 'tasks', whilst the qualitative aspects of the internal organisation of the unit remain unchanged. This implies the reallocation of resources by means of phenotypic plasticity to expand certain existing internal/external processes. Examples of situations where this applies are internal reorganisation leading to induced production of an antibiotic chemical or to hormonal regulation of territorial aggression.

The second strategy realises an increase in dominance simply by an increase in size. In competitive environments a plant that is twice the size of another plant may grow more than twice as fast (asymmetric competition, Weiner 1990). Bigger animals win more fights. Larger brains, of the same quality, have a larger thinking capacity. Yet, size poses also evolutionary limits. The size of organisms puts increasing limits on internal transportation and large animals have to deal with small surface-to-volume ratios, with many consequences for physiology, food intake and mobility.

The third strategy is based on innovation, with which we refer to the gaining of access to new resources. This requires the incidental or deliberate development of new internal organisation. Examples of innovative events during evolution are the shift in metabolism that certain bacteria have shown from anoxybiontic organotrophs to phototrophs, the shift from multicellular life to neural networks, which allowed the emergence of co-ordinated mobility based on sensory inputs, and the shift from aquatic to terrestrial life forms. The first organisms possessing the above properties got access to a massive resource of sunlight to 'fuel' their chemistry, a much better escape or predation behaviour and the capacity to learn from experiences, and a large space for invasion with little competition, respectively.

The fourth strategy involves co-operation. It includes all situations in which any form of living together leads to an overall gain in resource dominance. The evolutionary success of such co-operations is convincing (Herre et al. 1999). Most markedly, this is illustrated by the presence of mitochondria in the cells of fungi and animals, and the presence of mitochondria and chloroplasts in the algae and the plants (Blackstone 1995). That mitochondria and chloroplasts are

symbiotic cells and not just organelles was first proposed by Margulis (1979) in the form of the 'endosymbiont hypothesis', which is now generally accepted. In addition to endosymbiotic symbiosis, there exist many other forms of co-operation between cells and/or organisms which are important in evolution (Margulis 1998, Michod 1999). These include symbionts dwelling in multicellular organisms, colonies of physically linked individuals such as in some corals, and colonies and other forms of symbiosis of freely moving individuals of the same or of different species. Behavioural co-operation may involve co-ordinated behaviour and the division of labour, for example during hunting and other activities by groups of social organisms.

The fifth strategy, reproduction, is an important characteristic of biological life, because it forms the basis for the 'tree of life', which represents the phylogenetic relationships connecting present organisms to past ancestors. Evolutionary units have been selected in different environments for different strategies of reproduction which locally assure a maximum number of offspring with high resource dominance, and consequently the highest evolutionary success. Annual plants and some fish reproduce only once, whereas other evolutionary units reproduce some or many times over a time span. Some produce many small offspring, which may be widely dispersed but have a small probability to obtain a similar resource dominance position as their parents; others concentrate resources and parental care in a few offspring with a larger probability of being successful.

Evolution will select for the best combination of strategies in a given environment

The different resource dominance strategies can be regarded as an evolutionary 'toolbox'. Organisms have access to different combinations of strategies for different circumstances. Not every tool is appropriate for every situation. Even though reproduction may be the strongest resource dominance strategy in the long term, every organism may experience periods during which it is difficult to raise young, and other resource dominance strategies are temporarily more rewarding. Also the use of size to increase resource dominance depends on circumstances. In competitive situations a large size is mostly an advantage. But for algae that are cultured in a stirred chemostat of which half the volume is replaced by fresh medium every 20 minutes, the situation is different. If their generation time equals 20 minutes, the algae have a chance of 50% that one of the offspring remains in the chemostat. This will maintain the culture. An increase in size, to increase resource dominance, will not work, because a large size generally requires a longer reproductive period, which dilutes the large algae from the medium. Instead, rapidly reproducing, small cells form the best dominance strategy.

Complexity and efficiency

When discussing resource dominance and resource dominance strategies, it is important to realise that organisms only can show resource dominance because they have a certain construction, which allows them to be active in the world. Resource dominance, therefore, depends on construction aspects of the organism. This is the reason that we advocate the integration of resource dominance theory with an analysis of major structuro-functional aspects of organisms. As will be explained presently, we have selected complexity and efficiency as the main aspects of the relationship between resource dominance and construction.

Complexity

There exist many viewpoints on complexity (Horgan 1995, Kot et al. 1988, McShea 1991, Jagers op Akkerhuis and van Straalen 1999, Sole et al. 1999). Most of these refer to the patterning in dynamic interactions or to a hierarchical layering of structural features and related dynamics. Here, however, we analyse complexity from a structuro-functional viewpoint, defining it as any form of internal and external functional diversity as can be supported by the internal organisation of an evolutionary unit. The overall complexity of an organism thus depends on the presence of specific physiology, eyes, limbs, etc. More in detail, the contribution to the organism's complexity of these different phenotypic aspects can be analysed by means of a multivariate summation. An eye may, for example, be judged for its capacity to observe different wavelengths, its resolution, e.g. pixel size, its speed of accommodation, its light sensitivity, etc.

Note that by using the above definition of structuro-functional complexity, we deliberately avoid discussions about the exact internal structure being responsible for a certain functional diversity. The reason is that both a large, badly organised structure and a minute, well-integrated structure may allow an entity to show the same functional diversity. Accordingly, the above definition recognises them as showing the same complexity. Yet, these systems will almost certainly differ in efficiency.

Efficiency

Efficiency is regarded here as the lowest resource use, when comparing two processes leading to a functionally similar product. Efficiency is an important aspect of resource dominance because it improves the performance of all resource dominance strategies. A high efficiency allows a larger dominance at the same size and a more economic use of the same resource for maintenance, growth and/or reproduction. Additionally, a high efficiency allows more organisational excess that may lead to innovations. Efficiency plays also a role in co-operation. New interactions involved in cooperation generally have their costs, but can cause a net profit typically because of the gain in overall efficiency

and resource dominance. A special aspect of efficiency is buffering, with which we refer to the creation of internal or external stores of certain resources when these are plenty, to be used in periods of shortage. When the times are hard, the evolutionary units showing the highest efficiency in their buffering will be able to continue their normal functioning the longest. The others will be less good competitors and experience a selective disadvantage.

We regard efficiency as logically independent from complexity and related resource dominance strategies. The reason is that efficiency can be an aspect of each of the different strategies. There are many situations in nature, however, in which complexity and efficiency occur in close association. For example, co-operation of entities will frequently increase the functional properties in close association with the internal complexity increase.

The close bonds between resource dominance, complexity and efficiency have to be integrated in evolutionary theory in order to explain, i.e., the competitive advantage of the 'fittest' entities during selection processes, and, over many generations, the apparent increase of complexity during evolutionary time in specific branches of the phylogenetic tree.

Discussion

Above we have presented a multivariate analysis of evolutionary success based on resource dominance, complexity and efficiency. The use of these factors for measuring evolutionary success makes a general approach possible, which includes reproducing entities as well as non-reproducing entities. This implies, however, that the traditional focus on fitness has to be accompanied by an analysis of the underlying resource space, in order to develop explanatory and predictive models for evolutionary success.

A special aspect of the present approach is that it integrates resource dominance and the complexity of the evolving units, either directly because high resource dominance in a competitive environment requires a high complexity, or indirectly when the forces of selection act against inefficiency. Yet, it remains the broad spectrum of environmental forces which determines in which direction the complexity of a unit can evolve.

At the one end of this spectrum we find the situation where competition is absent. This applies to environments in which resources are limited due to abiotic causes, whilst the organism experiences a random chance of mortality. An example hereof is the above discussed well-stirred chemostat with algae. The highest resource dominance in these situations is reached by the organism

reproducing fastest. It will be clear that this requirement acts as a severe constraint on complexity increase.

The other end of the spectrum is formed by situations in which the environment is experienced as relatively stable, or stable in its variability, and in which the availability of resources as well as mortality are mainly determined by competitive interactions. As the energy that an organism has to spend on competitive interactions is correlated with the frequency and extent of contacts, all competition based approaches are necessarily density dependent (Witting 1997, Heino et al. 1998). In a competitive environment the combination of a lower complexity, in the sense of less phenotypic possibilities, and lower efficiency necessarily causes lower resource dominance, and will be selected against. Accordingly, evolutionary disadvantage can only be avoided by any combination of changes in complexity and efficiency yielding a net increase in resource dominance of a unit. This leaves still much freedom to different strategies, such as 'specialists', which may trade complexity for efficiency, or 'generalists', which do not care much about efficiency in some aspects. It also allows for the coexistence within a population of different strategies for resource dominance. An example is the coexistence of dominant male deer with full-grown antlers, and male deer without antlers mating in secret with the female deer of a herd.

Although it may not be the most likely to occur, an especially favourable combination in the light of selection is that of complexity increase in combination with efficiency increase.

Rates of improvement

According to the above reasoning we can regard evolving units as being selected for a combination of complexity and efficiency which allows for a combination of resource dominance strategies which, in a given environment, yields the highest increase in resource dominance. Their success in these combined efforts, e.g. their evolutionary success, can be measured either in terms of their present resource dominance or in terms of the increase and the acceleration hereof. Focus on these different rates is of marked importance, because those which are best now may soon lose to those which get better all the time, whilst both these strategies will be beaten in the long term by units which can increase the rate of their improvement. The ecological importance of the acceleration of improvement has been stressed by Wagner and Altenberg (1996), who have asked attention for the evolution of evolvability.

Finally, we consider it a theoretical advantage that the resource dominance approach makes in principle no assumptions about the kind or combination of

resources which are used, about the kind of units of evolution involved, or about the combination of resource dominance strategies that is followed. Therefore, the competition of animals and plants for nutrients, light, etc., can be analysed in the same way as competition between companies on the basis of money, power, etc. This offers a common basis for the study of evolutionary processes in different disciplines, such as biology and economy, which is not offered when using fitness as the evolutionary measure. We consider this an exciting possibility for future study.

Acknowledgements

This study was performed within the framework of the programme of the Danish National Environmental Research Institute (NERI): 'Biotechnology: elements in environmental risk assessment of genetically modified plants'.

Definitions behind the operator theory

“Make everything as simple as possible, but not simpler.”
(Albert Einstein)

The operator hierarchy can be represented as a simple scheme. However, the reasoning behind this scheme is intricate and, involves many different steps and definitions. Because transparency is a major asset in science, the aim of this chapter is to explain and define the basic aspects of the operator hierarchy. First, some general aspects are defined, such as a 'system', a 'type' and a 'closure'. These general definitions form the basis for higher level definitions, e.g., the 'operator' and the 'operator hierarchy'. The definition process is not a goal in itself but is meant to sharpen the reasoning involved in the operator theory and to prevent confusion in situations where the operator theory uses certain concepts in a way different from other theories.

Most fundamental to the operator theory is the notion of a system itself. The word system dates back to ancient times and is derived from the Greek word *sunistanai*, which means 'together establishing'. Another fundamental concept to the operator hierarchy is that of 'type'. The use of types is helpful when referring to general properties of a group of systems without bothering about the organisational particulars of every individual system involved.

System

The system concept relates to entities that can be grouped by functionality because of past, present or future interactions and/or relationships. The entities that, by their relationships, define the group are considered the system's elements. Frequently, the elements and their interactions/relationships define, include or relate to some kind of system limit that reduces the number of elements being considered. With respect to natural systems, the system concept is limited to the universe or a subset of it. The latter includes thoughts and abstract concepts represented by oscillation states in networks of interacting neurons. Depending on the type of entities and interactions, different systems can be recognised, such as ecosystems, cybernetic systems, physical particles, welfare systems, logical systems, organisms, transportation systems, taxonomic systems, populations, systems for storing and retrieving objects or data, economic systems, etc.

The viewpoint that systems consist of elements and interactions is well covered by Von Bertalanffy (1950, 1968). Von Bertalanffy defines systems as 'a complex of interacting elements' where 'interaction means that the elements stand in a certain relation'. Hall and Day (1977) have expressed similar viewpoints. They state that 'Any phenomenon, either structural or functional, having at least two separable components and some interaction between these components may be considered a system'. De Wit (1978) describes a system as 'a limited part of reality, the elements of which show a certain relationship'. Mesarovic and Takahara (1975) propose an abstract interpretation as they define a system as a subset of the set of all possible input-output relations. Heylighen (1995) suggests another approach and defines a system as a constraint on variety,

where the constraint determines the invariant identity -- which allows us to distinguish states that belong to the system's limits -- in spite of a variety of appearances of the system.

In 1865, Claude Bernard indicated that defining a system represents a mental undertaking when he stated that 'Les systèmes ne sont pas dans la nature, mais dans l'esprit des hommes'. In other words, nature knows only phenomena while systems are our mental abstractions thereof.

Type

A type is used to group entities by a common property. Using types of types creates a type-hierarchy in which lower-level types show commonalities that can be grouped into higher-level types. For example, the higher-plant-type and the animal-type can be grouped within the multicellular-organism-type. In mathematical type theory, there exists a lowest type, the elements of which have no members. Such elements correspond to the 'ur-elements' of certain set theories. The following types are frequently used with the operator hierarchy:

- Process type: a comparable aspect that can be recognised in the dynamics of different entities. For example, catalytic activity is a common property of all enzymes, regardless of the specific reaction that they catalyze.
- System type (general): this type of a system is defined by comparable aspects with respect to (1) the rules for selecting elements, (2) the properties defining the elements and (3) the relationships that may exist between the elements.
- Closure type: a closure type is defined by the presence of comparable aspects with respect to the element and mechanism types causing the closure. Departing from the same system type, different self-organising processes may lead to different closure types. For example, if a bacterial cell is chosen as the start, one route leads to the closure type of the endosymbiont/nucleus while another route leads to the closure type of the multicellular.

Closing in on first-next possible closure

In addition to systems and types, two other concepts play an important role in the operator theory, namely that of a 'first-next possibility' and that of 'closure'.

In this study the definition process of a first-next possibility was started with a literature review that led to the concepts of the '*adjacent possible*', which is used in ecosystem theory, and the '*successor*', which is used in set theory.

The concept of the 'adjacent possible' appears in an interview with Kauffman in which he considers the existence of general laws in ecosystems. In the interview Kauffman states:

There is a chance that there are general laws. I've thought about four of them. One of them says that autonomous agents have to live the most complex game that they can. The second has to do with the construction of ecosystems. The third has to do with Per Bak's self-organised criticality in ecosystems. And the fourth concerns the idea of the adjacent possible. It just may be the case that biospheres on average keep expanding into the adjacent possible. By doing so they increase the diversity of what can happen next. It may be that biospheres, as a secular trend, maximise the rate of exploration of the adjacent possible. If they did it too fast, they would destroy their own internal organisation, so there may be internal gating mechanisms. This is why I call this an average secular trend, since they explore the adjacent possible as fast as they can get away with it.

The concept of the successor can be found in mathematics, where the successor of the number α is defined as the smallest number greater than α . When considering numbers, this is a sharp definition. In principle, we would like to obtain the same accuracy when translating the successor definition to the field of particle hierarchy and closure, for example, in the form of the following tentative definition: the successor of a particle $\underline{A}$ is the particle showing the least complex closure higher than $\underline{A}$. However, before one can regard the 'least complex closure higher than $\underline{A}$ ' as the 'successor closure', one must find a way to indicate the level of closure that is simultaneously simple enough and complex enough to be considered the successor closure.

Closure

General mathematical aspects of closure were already discussed in chapter one where it was also explained that the closure concept in the operator theory is used more specifically than it is in mathematical theory. In the operator theory, closure relates to a state of matter that results from a self-organisation process and that shows a closed topology for structure, called structural closure, or process, called functional closure, or the combination of both, called structuro-functional closure. When used in this way, closure always represents a finite set of relations, but as long as structural closure is absent, the relations may not define a physical system limit. Furthermore, the state and the process of closure are intimately related because a closure state is caused by underlying interactions.

Elementary closure

In real systems, closure may be embedded in complex interactions. If all details of these interactions were considered, it would become too complex to compare closures between systems. For this reason, the operator theory uses a methodology that reduces such complexity by identifying the minimum

complexity that still represents the system's closure type. The latter minimalistic representation is regarded as the elementary closure.

An elementary closure represents the lowest complexity realisation of its type for the system's structure, process, or when possible, the combination of both. The elaboration or repetition of the same closure type does not affect the elementary closure. For example, the closure by which a chain of carbon atoms creates a cyclic molecule (e.g., benzene, fullerene) is not regarded as creating a new elementary closure because the closure repeats the covalent binding of atoms; the covalent binding was already responsible for the self-organisation process that produced molecules from atoms. Accordingly, every molecule is a molecule, regardless of its construction. Similarly, the adding of electron shells to an atom and the presence of more than one nucleus in a multinucleate cell does not change the elementary closure. Finally, elaborating a catalytic cycle with shunts and connections between shunts will not affect the elementary closure type of catalytic closure.

A system loses its elementary closure when the construction and/or dynamics are reduced beyond the minimum situation required for a closed state, for example, an atom that is heated until it loses the last electron from its electron shells or an organism starving to the level where it cannot maintain autocatalysis in its minimum form and dies. To sustain elementary closure, a system must be capable of a minimum level of maintenance. In the context of chemical reactions, Dittrich and Speroni di Fenizio (2007) have specifically focused on maintenance by defining an 'organisation' as any 'set of molecules that is both closed and self-maintaining'.

First-next possible closure

First-next possible closure is defined as follows: given any system A that shows first-next possible closure, the *next* first-next possible closure creates the least complex system type above A that shows a *new type* of elementary closure based on A and, when required, any highest level system type possible below A that shows first-next possible closure. This definition is inherently recursive because a system showing first-next possible closure produces a more complex system showing first-next possible closure. Because a first-next possible closure is always built from systems showing a *preceding* first-next possible closure, the recursive definition does not lead to logical loops.

The above definition implies that any system showing first-next possible closure is produced by a system showing one lower level of first-next possible closure. Going down this 'staircase' either results in an infinite regression or suggests the existence of a least complex system that shows first-next possible closure. A regression *ad infinitum* represents an undesired perspective for real world systems because every step down the closure-staircase is accompanied by a

loss of organisational complexity and a reduction of the possibilities for closure. This regression strongly suggests that a least complexity system exists in nature that shows first-next possible closure without showing a substructure of lower level closed elements.

In general, the first-next possible closure of the system above A will be based on elements showing the same type of first-next possible closure as A. In certain cases, however, the construction of a higher level may also involve elements residing at more than one level below the newly formed element. For example, the atom is based on interactions between hadrons creating the nucleus, while the electrons of the electron shell show a lower closure level than hadrons. As the electrons are the highest complexity solution for creating closure nature allows, this situation still represents a valid first-next possible closure.

Exhaustive closure

The definition of first-next possible closure makes use a *new type* of elementary closure with respect to a hypercyclic process and/or its interfacing. To identify the new type of elementary closure, I suggest focusing on 'exhaustive closure' in the system at the one lower closure level. A system shows exhaustive closure, if there is no remaining potential for elaborating the structural and dynamic aspects of the elementary closure type, because any further development will cause the construction of a new elementary closure type. While the elementary closure of the system remains the same, the state of exhaustive closure allows for a new functionality.

Exhaustive closure can be applied at all the levels in the operator hierarchy. For example the transition to hadrons makes use of the relatively complex quarks and the transition from the multi-atoms to the autocatalytic sets makes use of three dimensional catalytic potential of complex molecules. With respect to the internal differentiation that forms the basis for the transition to the endosymbiotic/eukaryotic cell, exhaustive closure suggests that a cell should possess enough complexity to allow for the engulfment of an endosymbiont and/or the construction of internal membranes.

Exhaustive closure furthermore offers a guiding principle when defining the transition from a unicellular to a multicellular state. During this transition there are several not exhaustive configurations that could be classified as a next closure state. Firstly, two cells can mutually attach to each other by means of binding proteins. Secondly, the cells can develop a mutual dependency based on the diffusion of chemicals across their membranes. Thirdly, the membrane separating the cells could become perforated, connecting the plasma of the cells. Further unification would create a single cell with two nuclei. Of these four examples, the third option, where the soma of both cells is connected by pores, represents the most exhaustive closure situation. According to the demand of

exhaustive closure, the third option represents the preferred choice; the first two options are not exhaustive, and the fourth option implies a multinucleate cell, which repeats the closure represented by the nucleus. Based on exhaustive closure a strand of attached algae that do not show pores connecting the plasma, must be considered a multicellular colony, because they lack the prerequisites for the exhaustive multicellular closure state. The latter also implies that slight changes are required in the definition of life and of the organism as were given in the paper of Jagers op Akkerhuis (2010a). The reason is that the use of exhaustive closure demands that only cells connected by plasma strands represent multicellular operators.

System type of systems showing first-next possible closure

Two systems created by the same type of first-next possible closure are considered to be of the same system type. This definition creates subsets of the set of all systems that was defined above.

Closure dimension

The structural and/or functional properties of a system showing first-next possible closure can be grouped in relation to higher level types, named 'closure dimensions'. A system that results from first-next possible closure either shows a new closure dimension or shows an existing type of closure dimension. The assignment of closure dimensions depends strictly on the most recently realised first-next possible closure of the system and not on any other property. The following closure dimensions can be recognised:

The interface dimension

The interface dimension involves a first-next possible closure that causes a spatially closed topology acting as an interface separating the system's internal dynamics from the world. For elementary particles, the interface is assumed to be the only dimension that determines their structure. For the hadron, the atom, the cell and the memon, the interface dimension always represents an interface mediating the second-order cyclic processes that are associated with the hypercycle dimension.

The hypercycle dimension

In the operator theory, the word hypercycle is used in a general way. It refers not only to the catalytic hypercycle but also to other second-order cyclic processes resulting from first-next possible closures. The first time that a first-next possible closure results in a system showing the hypercycle dimension is when quarks and gluons form a second-order interaction cycle in quark-gluon soup. Other dynamics that show the interface dimension are the quark confinement, the electron shell, the cell membrane and the sensory interface of the memon.

The multi-state dimension

The multi-state depends on a first-next possible closure that creates recurrent interactions between systems sharing the same (one level lower) first-next possible closure. The multi-state dimension is introduced by the hadrons, where it depends on interactions between quarks. Other systems that are based on first-next possible closure and that show the multi-state are the hadron, the molecule, and the prokaryote and eukaryote multicellular.

The hypercycle mediating interface dimension (HMI)

This dimension marks the moment at which an interface is formed surrounding and mediating the interactions of a second-order interaction process (the hypercycle), while both interface and hypercycle result from first-next possible closure.

The structural (auto-)copying of information dimension (SCI)

This property states that a system's dynamics create physical copies of the elements responsible for the system's emergent hypercyclic process. The first system that shows this property as the result of first-next possible closure is the cell, where the molecules that allow for autocatalysis represent the cell's information that is autonomously copied by the cell's chemical reactions. So far, the cell is the only system with this closure dimension.

The dimension of structural auto-evolution (SAE)

This closure dimension is associated with systems that show the capacity to autonomously modify the structure of their hypercyclic interactions. This property is selectively present in organisms with a hypercyclic neural system with interface. Currently, SAE typically relates to animals.

Primary system

A system exhibiting/introducing a new closure dimension is regarded as a primary system. Accordingly, only the following systems showing first-next closure are primary systems: the elementary particles, the second-order quark-gluon cycles, the hadrons, the atoms, the prokaryotic cells and the memons.

Major transition

Any first-next possible closure creating a primary system is regarded as a major transition.

Minor transition

Any first-next possible closure creating a system, the closure type of which does correspond to an existing closure dimension, is considered a minor transition.

The sequence connecting first-next possible closures may split into different branches when a system allows for minor transitions belonging to different

closure dimensions. An example of this is the transition from bacterial systems to either eukaryotic cells or prokaryotic multicellular life-forms. The eukaryotic cells show an internal closure representing the hypercycle mediating interface dimension. The prokaryotic multicellulars show an interactive closure belonging to the multi-state dimension. Another example is the step from molecules to either autocatalytic sets or cellular membranes.

Complexity of a closure dimension

The complexity of a closure dimension is based on the number of major transitions that were required to construct it. Because closure dimensions occur in a strict sequence, their complexity level can also be numbered from 1 to 6, from the interface dimension to the structural auto-evolution dimension, respectively.

Pre-operator interaction systems

Systems showing closure dimension 1 or 2 are called pre-operator interaction systems.

Operator

An operator is defined as a system type showing a closure dimension of 3 or higher (Fig. 7.1). From a different perspective, operators can also be defined as those systems showing first-next possible closure that are not pre-operator interaction systems. The set of the operators unifies all particles whether they are physical particles or organisms. The following operators are currently known: the hadron, the atom, the molecule, the prokaryote cell, the eukaryote cell, the prokaryote and eukaryote multicellular and the neural network organism, called the 'memon' in the operator theory.

Operator hierarchy

The operator hierarchy is a conceptual ranking of all operators and pre-operator interaction systems. The structure of the operator hierarchy is based on an integration of the viewpoints of first-next possible closure and closure dimensions (Fig. 7.1). When discussing the operator hierarchy, I generally include the quarks, even though these are strictly no operators but pre-operator interaction systems.

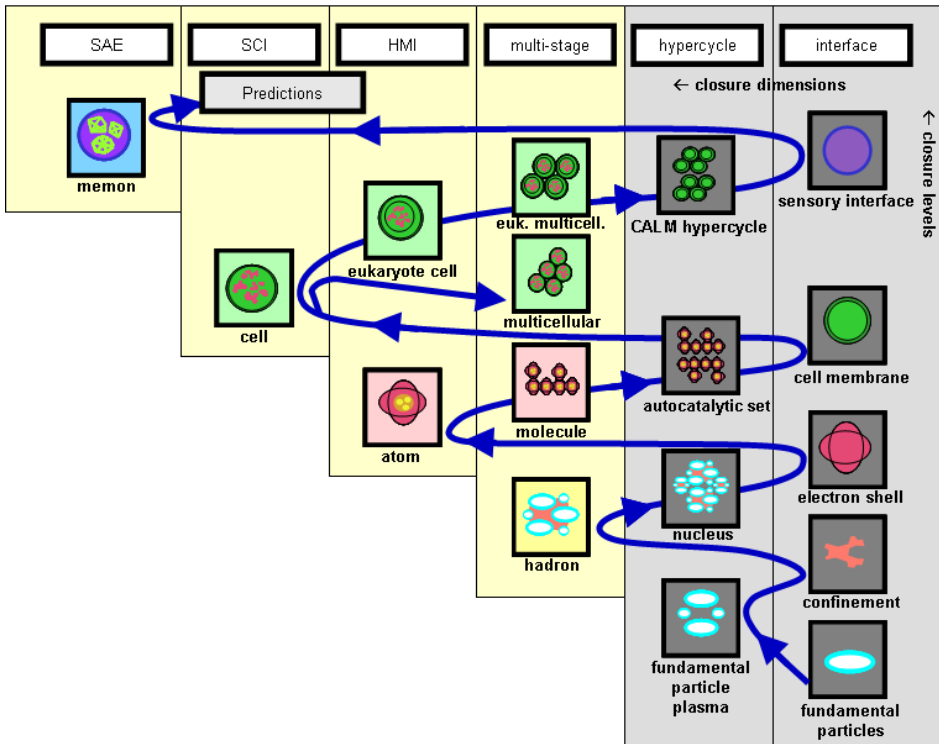


Figure 7.1. The figure shows the evolution of particles of increasing complexity as represented by the operator hierarchy. The black line shows the historical pathway by which first-next possible closures create the operators. The gray columns indicate pre-operator hypercyclic sets and interfaces. Explanation of abbreviations: SAE ('Structural Auto Evolution') = the property of an operator to autonomously evolve the structure that carries its information. SCI ('Structural Copying of Information') = the property of an operator to autonomously copy its information (genes, learned knowledge) by simply copying part of its structure. HMI (Hypercycle Mediating Interface) = a closure creates an interface that mediates the functioning of the hypercycle. Multi-state = operator showing closure between multiple units of exactly one lower closure level. Hypercycle = closure based on emergent, second-order recurrent interactions. Interface = closure creating an emergent limit to an operator. CALM (Categorizing And Learning Module) = a minimum neural memory.

Hierarchical layer

Operators and pre-operator interaction systems that are based on the same primary system and do not yet represent the next major transition are considered belonging to the same hierarchical layer. This means that the operator theory recognises as many hierarchical layers as there are primary systems.

Interaction system

An interaction system consists of operators that interact without that the interactions create first-next possible closure. The presence of first-next possible closure would make the interacting elements an operator.

Operator hypothesis

The operator hypothesis states that the fundamental limitations imposed by first-next possible closure act as a strict mould for particle evolution.

Operator theory

The operator theory is the theoretical framework that offers the context for the operator hierarchy and the operator hypothesis.

Centripetal science

Contributions of the operator hierarchy to scientific integration

“Meta-plumbing would concentrate on such questions as how to look as though you really understand what you are doing when the living room is several feet deep in water - instead of how to make a good joint, which is ordinary plumbing.”
(Jack Cohen and Ian Stewart)

Summary

The large number of discoveries in the last decades has caused a scientific crisis that is characterised by overspecialisation and compartmentalisation. To deal with this crisis, scientists need comprehensive approaches and unifying theories. A recent integrating theory, the operator hierarchy, connects the evolution of physical particles with that of organisms. In this chapter it is investigated what novelty the operator theory can add to a range of already existing integrating approaches. The following approaches will be discussed: the use of a cosmic timeline, the ranking of systems according to an 'ecological hierarchy', the use of periodic tables, the unification of evolutionary processes by regarding evolution as an artesian well, the generalisation of the evolution concept and a cross table plotting the applicability of unifying concepts against the different complexity levels that the operator theory recognises for ranking system types.

Introduction

The flow of scientific information is increasing daily and is causing what could be considered a knowledge explosion crisis (Sagasti, 1999). Dealing with this crisis requires not only methods that handle and make accessible huge amounts of information but also integrative theory that offers scaffolds to connect distant scientific fields. This text focuses on the role of the operator hierarchy as a scientific integration tool in the context of other integrative principles.

The knowledge explosion crisis is the result of science having a positive feedback on its own development. Science depends on our capacities as humans to observe the world, including ourselves, and to create mental representations of the observed phenomena. In turn, better representations increase our capacities to manipulate the world and to construct tools that improve our observations, which, in turn, accelerate scientific development. As the result of this process, scientific ideas have simultaneously developed extreme breadth and depth. They are not only frequently associated with overspecialisation and compartmentalisation but they are also moving towards the far reaches of major scientific integrations of a cosmic scale. At any level between these extremes, a concept is more valuable when it is efficient, pairing minimum complexity with maximum precision and elegance. Arbitrage by these aspects has become known as “Ockham’s razor”, cutting away the most complex and least elegant from any two theories explaining the same phenomenon. If theories describe different phenomena, arbitrage is less straightforward because different viewpoints may highlight different aspects of natural organisation. Considering the latter points, this paper analyses how the operator hierarchy may contribute to scientific integration while focusing on major integrative ideas, for example, the use of timelines, ecological hierarchy and evolution. The paper ends with an overview of existing integrating theories and the value of scientific integration.

Unification based on complexity and timelines

In history various theories have been developed to create coherence in the phenomena observed in the world. The structure of such theories has focused on the complexity of systems or has centered on timelines for historical ranking.

A classical example of a linear hierarchy ranking system complexity is the *Scala Naturae* of the Greek philosopher and naturalist Aristotle. In his approach, Aristotle ranks natural phenomena by decreasing perfection, from spiritual and divine beings to man, animals, plants and finally rocks and formless matter. This classification is also referred to as the Natural Ladder or the Great Chain of

Being and has influenced medieval Christianity and the thinking of well-known philosophers such as Descartes, Spinoza and Leibniz.

An approach that dates even further back in history is the ancient symbol of the Ouroboros, the snake swallowing its tail. This symbol represents the continuity and eternity of life and the world. A recent interpretation of the Ouroboros is shown in Figure 8.1. The left half of this figure shows how science has gained access to increasingly small systems, from large animals and plants, to individual cells, to molecules, to atoms, to nuclear particles and finally to fundamental particles. The figure's right half shows the scope of scientific research broadening towards increasingly large systems, from ecosystems, through planets, to solar systems, galaxies and finally the entire universe. When presented in this way, specific properties of the universe at large, such as the background radiation and its expansion in all directions, are connected with the universe's initial state. As the picture of the Ouroboros suggests, when the very large and the very small meet, the search for organisation in nature seems to swallow its tail.

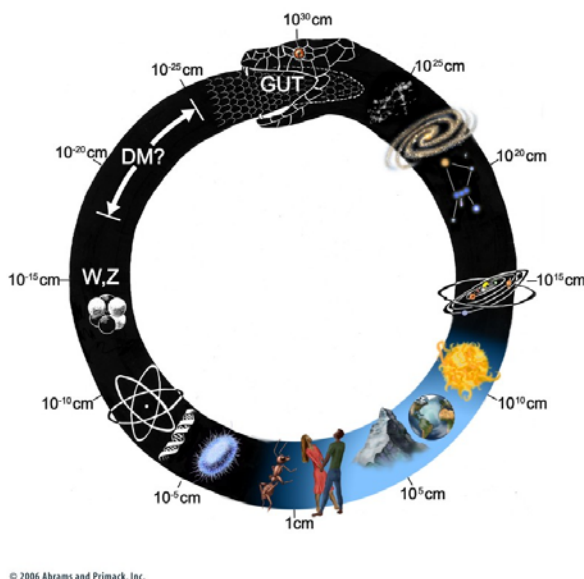


Figure 8.1. Historical expansion of scientific domains in the direction of the smallest systems and in the direction of the largest systems. GUT = grand unifying theory, DM = dark matter, W and Z indicate the particles conveying the weak nuclear force, cm = centimetre.

In addition to ranking systems by complexity, systems can also be ranked by the moment of their first formation and the historical time period in which they existed. When analysing system organisation in this way, timelines at different scales are created that refer to, for example, palaeontology, particle physics,

human history, the development of the automobile. These timelines also come in different forms, such as linear hierarchies, branching trees and circular approaches.

A modern timeline presenting a comprehensive overview of the organisation in nature is Big History (Spier, 1996; Chaisson, 2001; Bryson, 2003; Stokes Brown, 2007). This approach ranks all systems and processes by their occurrence in cosmic history. Big History is based on the scientific theory that the early universe was as small as a fundamental particle and obtained its present size following a rapid expansion, the Big Bang. The theory that the universe has a minute origin is supported by modern particle physics and by cosmological observations of the background radiation and the proportionality with distance of the speed at which galaxies recede from the Earth in all directions (Pagels, 1985; Weinberg, 1977). Based on these observations, it has been calculated that Big History started about 13.7 billion years ago (Fig. 8.2). During the universe's first three minutes, quarks formed and then condensed to form hadrons (such as protons and neutrons). During the following 17 minutes, the hadrons condensed to form simple helium nuclei (the combination of a proton and a neutron). After these initial minutes, it took about 70 thousand years before the dynamic balance of the transformation of matter and energy toppled to the advantage of matter. The matter in the rapidly expanding universe now aggregated under the influence of gravity. The aggregation process was slow because gravity is weak at large distances. The result was a universe with a sponge-like structure of concentrations of matter surrounding empty 'bubbles' of variable size that were almost devoid of matter. After 100 million years of aggregation, the first galaxies and stars were formed and their light started illuminating the universe. The nuclear reactions in stars supported the formation of elements heavier than helium. After approximately 9.1 billion years, the Sun was formed (4.57 years ago) and then planet Earth (4.54 billion years ago). Thereafter, it took about 1 billion years for the first life to emerge on Earth and another billion before cells gained the capacity of photosynthesis. Complex Ediacaran fauna has been found in rocks of about 600 million years old. Around 228 million years ago dinosaurs ruled the world. The first hominin fossils originate from approximately 7 million years ago. Human history dates back to several tens of thousands of years.

A universal timeline is a comprehensive integration tool. Its major strength is ranking all sorts of events simultaneously. Even though every event has only a single moment of occurrence, a timeline can flexibly adapt to variations in the moment of occurrence of similar events by indicating a first moment at which they occur and, assuming that such is known, a last moment. A universal timeline can thus be seen as a thickly woven cable of many threads representing local histories and developmental rates of different parts of the universe. (Fig. 8.2). Although all of these developmental threads unroll in different directions,

they result in similar histories. Stars are formed everywhere in the observable universe and their formation roughly started at the same moment. Stars of the same class also consist of similar particles and atoms, and stars the size of the sun are probably circled by planets everywhere in the universe. One may now ask why there is so much uniformity in the universe and whether such uniformity may be used to answer questions about the future of the universe.

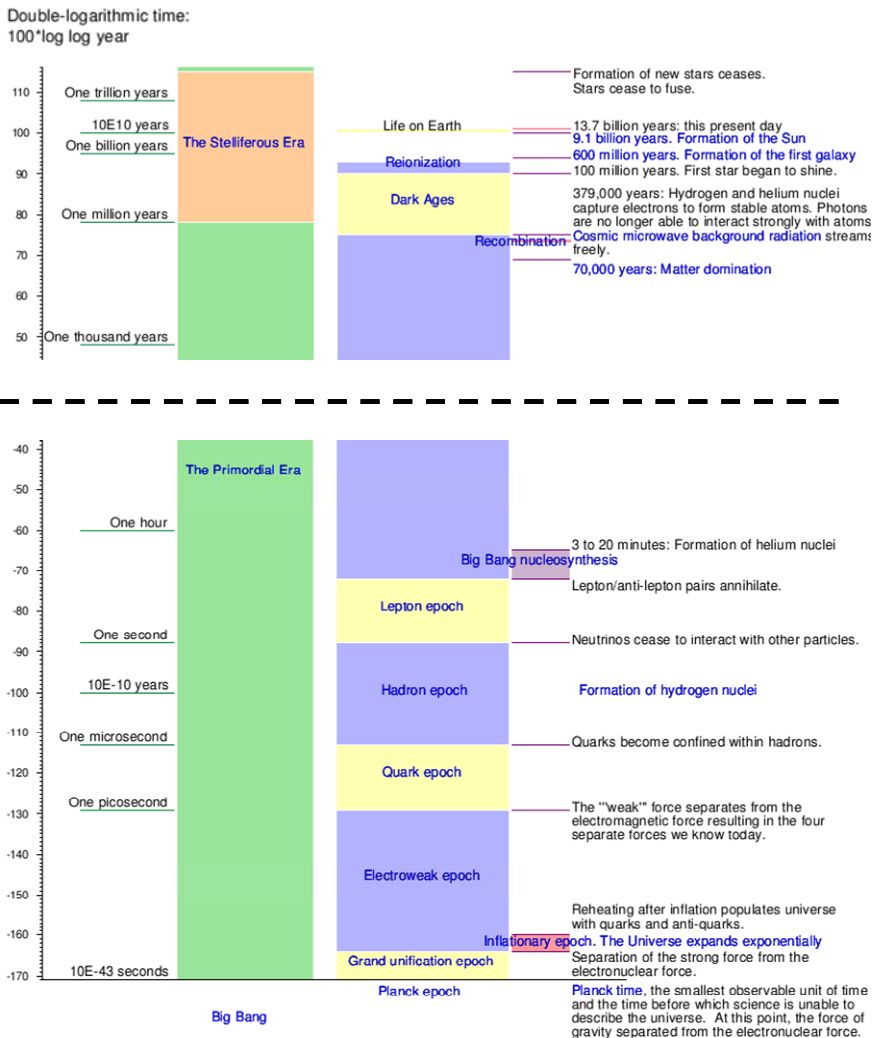


Figure 8.2. Universal timeline (modified from Wikipedia).

A methodology that may offer answers to the latter question is the operator hierarchy (Jagers op Akkerhuis and van Straalen, 1999, Jagers op Akkerhuis 2001, 2008). The operator hierarchy combines system complexity with a timeline of system formation. To explain this approach, it is useful to start with the basic

assumption that nature must be analysed according to three fundamental dimensions for structural complexity. As Figure 8.3 illustrates and taking a prokaryotic cell as a starting point, the first dimension involves the ranking from a single cell to a system with interacting cells. Systems like this, which consist of interacting organisms, were named ‘interaction systems’ by Jagers op Akkerhuis and van Straalen (1999). The second dimension involves the transition from the prokaryote cell to the eukaryote cell and then to the multicellular. By extending the ranking in this dimension towards systems of low complexity, such as molecules, atoms, hadrons and fundamental particles, it becomes clear that this dimension connects all physical particles and organism types. Because all elements in this dimension are regarded as ‘operators’ (Jagers op Akkerhuis and van Straalen, 1999; Jagers op Akkerhuis, 2008), their hierarchical ranking is called the operator hierarchy and the related theory the operator theory. As Figure 8.3 shows, transitions towards higher level operators may use interactions between lower level operators (e.g., from unicellular to multicellular), but they may also involve internal differentiations (e.g., the engulfment of an endosymbiont in a eukaryotic cell and the formation of a neural network in a multicellular). The third dimension involves the cell’s/organism’s interior organisation. Here the focus is on the elements, the elements in these elements, etc. The above dimensions capture *independent* directions for analysing natural organisation: a prokaryotic cell, a eukaryotic cell and a multicellular organism can all be involved in ecosystem interactions and each of them shows internal organisation.

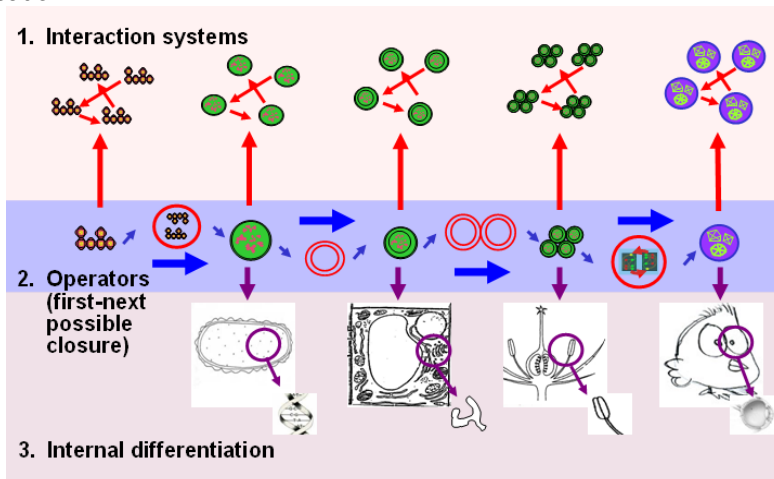


Figure 8.3. Three independent dimensions for hierarchy in the organisation of nature: (1) hierarchy in interaction systems (systems that consist of operators without being an operator), (2) hierarchy in the way how lower level operators create higher level operators, and (3) hierarchy in the internal organisation of operators. Only the hierarchical ranking of the operators is strict. All other hierarchies vary according to point of view, e.g., displacement, information, construction and energy.

Having explained how the operator theory recognises dimensions for organisation, it is time to return to the question of how these insights can assist in analysing cosmic development. The answer to this question rests on separating the events along the cosmic timeline into two parallel tracks: the track of the operators and the track of the interaction systems.

Starting with the Big Bang, the history of the universe can, in principle, be modelled as a container full of interacting particles. Particles exert forces on each other and interact. This interaction forms new particles and accompanying new forces. During the universe's early days, the initial quark soup rapidly transformed to also contain simple helium nuclei. Simultaneously, and on a larger scale, all matter aggregated due to the force of gravity. This aggregation created various celestial bodies, such as black holes and stars. Nuclear reactions in stars then fused helium to heavier elements, which were spread by stellar explosions. Under colder conditions the fused elements further condensed to form molecules that formed a basis for planets and comets. Models predicting the future of this process have been based on the total amount of matter, the gravitational constant, the expansion rate of the universe, and the life histories of celestial bodies. Although uncertainties exist about the values of certain parameters, such models generally predict the universe's heat death as the consequence of diluting matter in the vastness of an extremely large, cold space.

In comparison to the latter universal models, the operator theory (Jagers op Akkerhuis and van Straalen, 1999; Jagers op Akkerhuis, 2001, 2008) may seem to focus on minor details when it introduces a strict ranking of all operators, from quarks, through hadrons, to atoms and molecules, prokaryote cells, eukaryote cells, prokaryote and eukaryote multicellular organisms and neural network organisms (referred to as 'memons') (Fig. 8.4). Nevertheless, the first-next possible closure seems to strictly limit the structures of the operators such that there are important consequences for natural organisation, even at a universal scale.

Firstly, the operator hypothesis suggests that the limits set by first-next possible closure apply to all operators anywhere in the universe. Accordingly, the same classes of operators can be expected to exist anywhere in the universe as long as local conditions allow for their formation. In addition to uniform initial conditions in the universe during its early hours, first-next possible closure rules offer an explanation for the uniformity of the structural developments in unconnected local parts of the universe.

Secondly, the sequence of first-next possible closures and related operators is not only strict, but it also shows an internal regularity (Fig. 8.4). Based on this regularity, the operator theory now suggests that it is possible to extrapolate the

operator hierarchy towards future operators, the next of which is the memon (the generalised concept for operators with neural networks) that owes its intelligence to a programmed neural network (see Jagers op Akkerhuis, 2001). Because cosmology focuses on the universe at large, cosmological models offer no possibilities for predicting future operators.

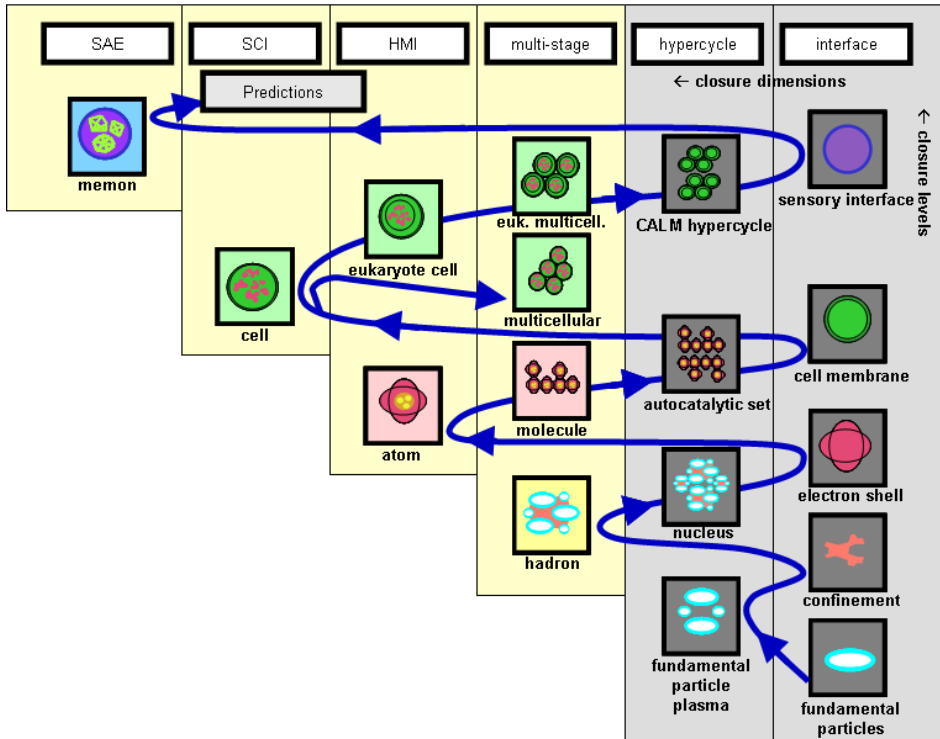


Figure 8.4. This figure illustrates the evolution of the operators. The black line shows the historical pathway of subsequent first-next possible closures and related operators. The gray columns indicate systems resulting from first-next possible closure but are not operators. Explanation of abbreviations: Memon = operator showing a hypercyclic neural network with interface, SAE ('Structural Auto Evolution') = the property of an operator to autonomously evolve the structure that carries its information, SCI ('Structural Copying of Information') = the property of an operator to autonomously copy its information (genes, learned knowledge) by simply copying part of its structure, HMI (Hypercyclic Mediating interface) = a closure creates an interface that mediates the functioning of the hypercycle, Multi-state = operator showing closure between multiple units of exactly one lower closure level, Hypercycle = closure based on emergent, second order recurrent interactions. Interface = closure creating an emergent limit to an operator, CALM (Categorizing And Learning Module) = a minimum neural memory.

Unification based on ecological hierarchy

An integration tool widely used in ecology, ecotoxicology and biology is ecological hierarchy. The logic behind this integration tool is that elements at lower levels in the hierarchy contribute to the systems at higher levels in the hierarchy. The general pattern of the ecological hierarchy is shown in Figure 8.5. With slight variations, comparable ecological hierarchies can be found in many basic textbooks and publications on ecological organisation (e.g., Odum 1959; Weiss, 1971; Koestler, 1978; Close, 1983; Kruijf, 1991; Haber, 1994; Naveh & Lieberman, 1994; Høgh Jensen, 1998; Korn, 2002). The ecological hierarchy's frequent occurrence in publications shows that this integration tool has worked so well that it has become a kind of dogma in ecology and biology. As a consequence, people seem to accept it unquestioningly. In the context of this paper, the ecological hierarchy is analysed in comparison with the three hierarchical dimensions of the operator theory explained above.



Figure 8.5: The classical ecological hierarchy

The application of the operator theory now dramatically impacts the ranking of the elements of the conventional ecological hierarchy (Fig. 8.6). What has happened?

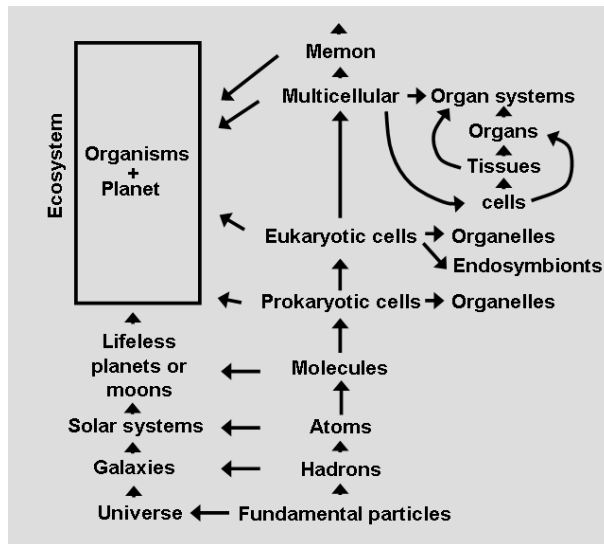


Figure 8.6. Ecological hierarchy following the ranking in three dimensions that is suggested by the operator theory

The most important cause of the observed differences is that the operator theory does not accept mixing hierarchal dimensions. This means that it does not allow switching between hierarchy rules when going from one level in the hierarchy to the next. For example, after the hierarchy of operators has been selected for analysis, e.g., atom-molecule-prokaryote cell, an organ or a community of cells can no longer be included as the next level. Including an organ would confound the operator dimension with the internal complexity dimension. Including a community of prokaryotic cells would confound the operator dimension with the dimension that is reserved for hierarchy in interaction systems. Interestingly, the conventional ecological hierarchy ends with the universe as the highest level, while the operator theory recognises the universe as the first occurring interaction system.

With the passing of time, and in close relationship with the formation of higher level operators, local parts of the universe change organisation and become identifiable as subsets with specific properties. The first subsystems that develop in the universe are concentrations of matter, parts of which further develop into primordial galaxies. Within such galactic concentrations of matter, gravity causes the atom nuclei that have formed to aggregate locally and form primordial solar systems. As a next step stars and planets may form. As soon as cells are formed on a planet, this planet changes from a chemosystem to an ecosystem. Subsequently, when memons arise on a planet, this development can be regarded as changing the planet into a 'memosystem'.

Finally, the operator hierarchy demands that the hierarchy of elements in an operator's interior be dealt with independently. In abiotic operators, such as atom nuclei, atoms and molecules, the internal differentiation directly results from interactions based on condensation (from hadrons to nuclei, from nuclei and electrons to atoms, and from atoms to molecules). For organic operators Turchin (1977) has formulated the law of the branching growth of the penultimate level. This law states that '*...after the formation, through variation and selection, of a control system C, controlling a number of subsystems Si, the Si will tend to multiply and differentiate*'. This law explicitly recognises that only after the formation of a mechanism controlling the subsystems Si is there a context that allows the variety of the subsystems to increase. Accordingly, nature has had neither a context nor the means to develop organelles before cells or to develop organs and tissues before multicellular organisms. For this reason, including sub-systems such as organelles, tissues, organs and organ systems in the conventional ecological hierarchy of systems is highly confusing.

Unification based on a periodic table of periodic tables

The most well-known periodic table is the periodic table of the elements. Mendeleev introduced this tabular display of the chemical elements in 1869. It organised the reactivity of atoms and indicated a number of missing elements. Mendeleev's discovery was so important that his table is still used as a basic tool in chemistry.

But chemistry is not unique when it comes to periodic tables. Various periodic tables of fundamental importance exist for other disciplines. Probably the most well-known is the 'standard model' used in particle physics. It categorizes the major classes of fundamental particles as either force carrying particles (bosons) or matter particles (fermions). The fermions are subsequently divided into leptons or quarks, both of which are partitioned over three groups of increasing mass.

Another fundamental periodic table used in particle physics is the 'eightfold way'. This table is used to organise the many ways by which quarks can combine into hadrons. Hadrons consisting of two quarks are called mesons while those made up of three quarks are called baryons, and a separate table exists for each of these types. The eightfold way was developed by Gell-Mann and Nishijima and received important contributions from Ne'eman and Zweig (Gell-Mann and Neeman 1964).

Furthermore, two tables can be considered the fundamentals of Mendeleev's periodic table: the 'nucleotide chart' and the charts showing which sets of electron shells are to be expected in relation to a given number of protons.

Finally, and even though it may be a bit unusual to regard this arrangement as a periodic table, there are also good grounds to include the “tree of life” in this overview of tabular presentations. The only difference with the other tables is that the tree of life also includes descent, a property that has no meaning in the other periodic tables discussed so far. In all other aspects, the tree of life has similar properties of creating a unique and meaningful overview of all basal types of operators, which enter the scheme as species.

Every single periodic table discussed above is central to its proper field of science. But the tables are not connected. The operator theory, however, shows that it is possible to connect the separate tables by focusing on the types of elements in every table. If this is done, the operator hierarchy can be used as a ‘periodic table for periodic tables’ to organise the elements of the existing periodic tables.

As Table 8.1 shows, the inventory of periodic tables offered a periodic table for almost every complexity level in the operator hierarchy. The inventory furthermore indicated the following gaps for which no periodic tables were found: the quark-gluon hypercycles, the quark confinement, the molecules, the autocatalytic sets, the cellular membranes, the cyclic CALM networks and the sensory interfaces. With the exception of the molecules, which may not have a periodic table because of the almost unlimited number of combinations that can be made from the various atom species, all the gaps involve hypercyclic sets and interfaces. One may now suggest that it is generally impossible to create periodic tables for hypercyclic sets or for interfaces, but this assumption is at least partially contradicted by the nucleotide chart and the classification of potential electron shells. A reason for the absence of tables for hypercyclic sets may be that the number of possible configurations is so large that it is impossible to classify them, in the same way that it is hard to classify molecular configurations. Such ideas, however, need to be worked out in more detail.

Table 8.1. Using the operator hierarchy for organising the periodic tables that exist for different types of operators. Shading indicates system types that are operators.

System type in operator hierarchy	Organisation in specific 'periodic table'
fundamental particles	standard model
quark-gluon hypercycle	??
quark confinement	??
hadrons	eightfold way
nuclear hypercycle	nucleotide chart
electron shell	types of shells
atoms	periodic table of the elements
molecules	??
autocatalytic sets	??
cellular membrane	??
cells	tree of life: prokaryotes
eukaryote cells	tree of life: eukaryotes
prokaryote multicellulars	tree of life: prokaryote multicellulars
eukaryote multicellulars	tree of life: eukaryote multicellulars
cyclic CALM networks	??
sensors (perceptive and activating)	??
memons (hardwired)	tree of life and technical hardwired memons
memons (softwired)	future tree of technical life

Unification based on organic evolution: the artesian well that is powered by cellular autocatalysis

Calvin (1987) describes evolution as a 'river that flows uphill'. Dawkins (1996) refers to it as a process that is 'climbing mount improbable'. Neither of these metaphors suggests the need for a force to realise the process. To clearly indicate that a driving force is needed to make water flow against gravity or to make evolution climb a mountain, the metaphor of an artesian well will be used. In an artesian well, the groundwater pressure makes the water flow naturally towards the surface allowing it to 'defy' gravity. But what exactly is the pressure that makes evolution flow towards increasing complexity, seemingly 'against' thermodynamic laws? As Russell (1960) and Pross (2003) have indicated, this pressure is a special form of the explosive, brutal power of autocatalysis. Taking Pross's insight as a basis, the following text places evolution in a thermodynamic perspective and invokes the operator hierarchy when appropriate.

Long ago Malthus (1798) and Verhulst (1838) realised that population growth leads to density dependent stresses. Darwin (1859) subsequently developed the idea that this stress, in combination with reproduction and heritability of parental properties, causes reproductive disadvantage of the least adapted individuals.

However, Darwin and contemporaries had no clear idea about what could cause the organisation of organisms. The laws of thermodynamics that were known at that time seemingly indicated that systems could not increase their organisation (Carnot, 1824; Clausius, 1865). A bit later, Bergson (1911) wrote about life:

Incapable of stopping the course of material changes downward (the second law of thermodynamics), it succeeds in retarding it ... Now what do these explosions (photosynthetic reactions) represent, if not a storing up of the solar energy, the degradation of which energy is thus provisionally suspended on some of the points (the plants) where it was being poured forth?

Later, ideas about non-equilibrium thermodynamics (Schrödinger, 1944; Prigogine, 1984) and hypercyclic catalysis (Eigen, 1979) offered the ingredients for a better explanation. Non-equilibrium thermodynamics solved the problem that growth and reproduction seemed to violate the laws of thermodynamics. What was new in open thermodynamic systems was the idea that the degradation of an external free energy gradient could power the dynamics required for self-organisation. For example, when a bathtub is unplugged, the self-organisation of the vortex is powered by the degradation of the potential energy stored in the height difference between the water in the tub and the drain at the bottom. But although non-equilibrium thermodynamics offered a general solution for the powering of self-organisation, it did not indicate what specific driving force powered evolution.

To analyse the processes that drive Darwinian evolution in more detail, evolution will be analysed as the combination of two processes: one process explaining the functioning of organisms, from single cells to animals, and the other process explaining selection. The functioning of unicellular organisms requires self-organisation and a membrane. Self-organisation is powered by transforming external energy gradients into work. As will be discussed presently, the operator hierarchy indicates that the organism receives the storage of heritable information for free as long as it uses hypercyclic autocatalysis as the basis for its energetics. The membrane is required to ensure that the information and other processes become individualised. The mechanisms behind selection depend on the capacity to produce offspring that receive variable heritable information, and on selective interactions affecting the phenotypes of the offspring differentially.

The basal self-organisation process responsible for the existence of organisms is autocatalysis. Autocatalysis in its basic form is the process in which a certain catalytic chemical, say A, transforms a substrate, which then leads to the production of A. Given sufficient substrate, autocatalysis leads to the doubling of catalyst molecules with every transformation step, from A, to 2A, 4A, etc. This process is referred to as exponential increase. The potential power of

exponential increase can be derived from the three dynamic states an autocatalytic process may attain (e.g., Lifson 1987; Dittrich and Speroni di Fenizio 2007): (1) when the influx of substrate is too low, the system decays; (2) when the inflow of substrate is high enough to let the autocatalytic production of catalysts equal their decay rate, the system is in (dynamic) balance; and (3) when there is a rich influx of substrate, the positive feedback causes a chain reaction that will let the process grow exponentially. While systems with decaying or balanced dynamics will go unnoticed, systems with exponential growth potentially possess the brutal force of an explosion.

The explosive power of autocatalysis is not sufficient to explain Darwinian evolution because autocatalysis lacks heritable information. The coupling of autocatalysis and information requires an additional step. In its simplest form this second step requires the coupling of two catalytic reaction cycles based on the molecules A and B in a second-order cycle in which A transforms substrate to B and B transforms substrate to A. The resulting reaction cycle is fully driven by an external free energy gradient and is a simplified form of Eigen's 'catalytic hypercycle' (Eigen, 1979). Eigen, who focuses on enzymatic reactions, has published various studies about the stability and thermodynamics of hypercyclic catalysis. In a catalytic hypercycle, every individual catalytic molecule can be regarded as carrying information for the overall process. The capacity of hypercycles to carry information has recently been discussed by Silvestre and Fontanari (2008). The hypercycle thus combines the explosive force of autocatalysis with the information function of the separate catalytic molecules.

Hypercyclic catalysis unleashes enormous powers while creating an informed process. However, these properties are still insufficient to cause evolution because the process does not yet include a spatial mediating boundary that allows the components to become a unit of selection. Without a boundary, the catalysts of an autocatalytic hypercycle float freely in the pre-biotic 'soup' and cannot be assigned to a specific group. They can dilute or mix freely with other sets. To end up with units that selection can act on, a physical system limit is required. This can be added quite easily as a fatty acid membrane. Vesicles naturally form by condensation in a watery solution containing fatty acids (Oparin, 1957; Claessens et al., 2007; Fanelli, 2008; Hernández-Zapata et al., 2009) and the process is well understood from the aspect of thermodynamics. The combination of a membrane with autocatalysis now defines the first primitive cell. In one of the more recent studies on the emergence of the first cells, Martin and Russel (2003) have discussed the simultaneous formation of autocatalysis and membranes based on the chemical reactions in pre-biotic submarine hydrothermal vents of volcanic origin.

Once primitive cells were produced, it was a relatively small step toward multiplication and heritability of information. Given a constant supply of substrate

molecules, autocatalysis automatically increased concentrations of the catalytic molecules in a cell. It also potentially produced fatty acids enlarging the membranous envelope. Increasing cell volume and envelope size will destabilise the cell structure and stimulate division, and the contents will then more or less be randomly distributed over the two 'offspring'. When this occurs, cell-based autocatalysis powers the motor of primitive cellular reproduction and only selective interactions have to be added before evolution occurs.

Despite their primitive state, the above cell-based reproduction and heritability immediately force the water in the artesian evolution well to flow upward. The reason is that cell-based cyclic autocatalysis implies the production of numerous individuals, that the individuals show interactions and that interactions are most detrimental for weak performers, which Darwin referred to as the 'less well endowed'. The latter processes result in selective interactions that scaffold the development of increasingly complex building plans (at least on average). Selective interactions, as used here, are not limited to competitive interactions but also include strategies based on cooperation.

Information, first in the form of the set of autocatalytic molecules and later in the form of RNA/DNA, plays an important role in evolution. A fundamental aspect of information is that it is hard to avoid random changes during its use and/or reproduction. As a consequence, the information in organisms naturally tends to change over generations. A negative result of this uncontrolled change is that offspring may suffer a lethal accumulation of deleterious mutations. This kind of mortality is referred to as Muller's ratchet (the name is derived from the random occurrence of deleterious mutations as discussed by Hermann Joseph Muller, 1890-1967). A positive result of this change is that every once in a while a given mutation will positively affect an organism's fitness. As long as the production of original types and mutants that fit equally well or better to their environment outweighs deleterious mutations, evolution will continue. The potential for genetic evolution has convincingly been demonstrated in experiments that investigated how the genetic material of viruses adapted over generations when it was subjected to different chemical stresses (Mills et al., 1967; Spiegelman, 1971).

The constant emergence and spread of favourable mutations unpredictably changes the ecosystem. To maintain one's fitness, units of selection must continuously adapt. The continuous need for adaptation has been simulated by Schneppen and Bak (Bak 1996) who in a group of competing species replaced the least fit species by one that is more fit (Bak, 1996). Their model showed that the resulting dynamics are inherently unpredictable. This was concluded from the fact that when plotting the number of species involved in one extinction event against the frequencies of such events, their model showed the fractal characteristic of a power law distribution. Such a power law accorded well with

the distribution of species' extinctions in the archaeological records, as van Valen (1973) observed. After changing the original Schneppen-Bak model to be more realistic, for example, by including genetic adaptation and random disturbances caused by meteorite impacts, the model was proven robust and relevant for the evolutionary process.

During evolution, selection acts not only in the direction of the capacity to evolve but also of the capacity to evolve evolvability (e.g., Wagner, 1996; Wagner and Altenberg, 1996). Once evolution has started, it becomes increasingly difficult to stop the process because selection will favour organisms that can exploit formerly inaccessible free energy gradients. Every new pathway implies a new kind of 'fuel' powering new autocatalytic processes and increasing the size of and/or the pressure under evolution's artesian well. Examples of switches towards new and larger free energy gradients are those from physico-chemical energy to solar energy (the development of photosynthesis), from physico-chemical energy to biochemical energy (the development of predation/herbivory), from anaerobic pathways to the use of oxygen (yielding a twenty-fold increase in available energy), from the exploitation of living biomass to the use of fossil biochemical energy, etc. Other examples are (1) the switch from depending on diffusion for energy transport to active transportation of energy-rich substrates through the cell and (2) the symbiosis with endosymbionts, generating energy throughout the cell.

From the above switches, the switch from physico-chemical energy to biochemical energy has especially affected the evolutionary process because the biomass of the early organisms suddenly became a degradable free energy gradient. Exploiting this gradient, viruses, parasites and consumers attacked the organisms. These attacks reduced the densities, which, in turn, increased growth rates. The chisel of selection was sharpened when indirect competition for abiotic resources was supplemented by organotrophic interactions. Afterwards, selective forces showed diversification towards searching for and digesting biotic resources and towards developing survival strategies to avoid becoming a resource.

Unification based on a general concept for evolution

Darwin's theory refers to evolution as a combination of two processes: (1) the production of numerous offspring with different combinations of heritable properties, and (2) the selecting away of individuals that are less well endowed; that is, in comparison to nearby organisms, their competitive and/or cooperative properties fit less well to the demands of the abiotic and biotic environment. The focus on these processes has linked the evolutionary process to heredity. In actuality, however, evolution requires nothing more than repeating a process

that combines the production of variation (a diversification step) with selection in relation to certain criteria (a selection step) (Fig. 8.7). As has been indicated by Popper (1972, 1999) and Campbell (1960, 1990) repeated diversification and selection steps offer a general basis for evolution of organisms. But the implications of diversification and selection may reach further, because these concepts are not limited to organisms.

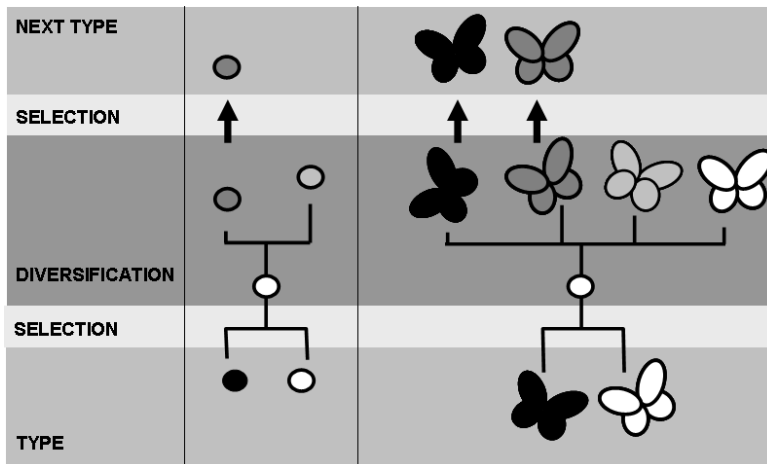


Figure 8.7. This figure illustrates the generalisation of the evolution concept Both the evolution of particles and the evolution of organisms can be regarded as consisting of steps combining the production of variation (diversification) and selection.

The production of variation may be based on genes but may also be based on abiotic particles or computer organisms. For example, when two fundamental particles meet, they may integrate and split again, or they may exchange a third particle, such that after the process, two new particle types are formed. And when a technical memon copies its brain structure through computer code, incidental or deliberate errors in the process may produce variation.

The selection process, too, is not limited to organisms. In Darwinian evolution, selection may occur at many points, including when two organisms choose each other as mates, when semen search for an egg cell, when an embryo develops in a uterus, when offspring are born and have to persuade their parents to feed them, etc. (Fig. 8.7). In particle evolution, selection depends on whether particles recombine and whether they produce new particles that are stable.

When examining evolution in the above way, the difference between Darwinian evolution and the evolution of particles fades and the principle of evolution becomes visible in its most basic and general form, which is based on diversification and selection. Of course, to apply this basic form to a given level in the operator hierarchy, the specifics of the diversification processes and the

selection processes that are typical for the selected operators and environment need to be filled in.

Unification based on unifying concepts

The above paragraphs have highlighted many grand unifying concepts in science and have shown how the operator hierarchy may contribute to these fields. The examples that were discussed represent a limited selection of the many larger and smaller unifying concepts that exist. To discuss all these in a single paper would detract from the major goal of this study: to analyse relationships between unifying concepts and to discuss the potential contribution of the operator hierarchy.

To analyse relationships between several unifying concepts while preventing endless elaboration, it was decided to create a cross-table at a high level of abstraction. On one axis the table shows an inventory of unifying concepts and on the other their relevance at different levels of the operator hierarchy. It was also decided to construct not one, but two cross-tables: one for unifying concepts relating to operators and one for unifying concepts relating to interaction systems (the systems that consist of operators but are not operators). In addition, it was decided to sort the unifying concepts *a priori* according to the four dimensions of the DICE approach (Displacement, Information, Construction and Energy, Jagers op Akkerhuis, 2008), such that unifying concepts dealing with similar subjects were gathered into these four classes. The outcome of these activities is shown in Tables 8.2 and 8.3. Undoubtedly, these two tables are not complete and the *a priori* assignment of a given unifying principle to one of DICE's four classes or the *a priori* assignment as being most important for operators or interaction systems may be disputed because many principles relate to more than one subject. It is furthermore recognised that some unifying concepts have a narrow scope, for example, the Pauli principle, while other principles, for example, the concept of evolution, could have been split up into a whole range of related unifying concepts, such as the selfish gene, the moving fitness landscape, game theory, etc. In relation to the latter remark, it has been attempted to combine *a priori* smaller concepts into overarching concepts. Concepts were separated if at least one aspect was important enough to justify this decision. Due to these considerations, Table 8.1 and Table 8.2 should be considered explorative tools for identifying interesting trends.

Table 8.2. This cross-table shows an inventory of unifying concepts ranked according to the operator hierarchy.

Main subject	Related subjects (it concerns states or dynamics within operators)	fundamental particles	hadrons	atom nuclei and atoms	molecules (prokaryote) cells	eukaryote cells	multicellular prokaryote	multicellular eukaryote	memon (hardwired)	memon (softwired)
Thermodynamics (energy)	Relativity, matter-energy	x								
	Thermodynamic laws	x	x	x	x	x	x	x	x	x
	Autocatalytic physiology, resource dominance, energetic demands				x	x	x	x	x	x
	Resource allocation and trade-offs, DEB-model				x	x	x	x	x	x
	Desire based activity and flows								x	x
Construction	FNP closure defining the operator types	x	x	x	x	x	x	x	x	x
	Functional limits irt levels of resources or (abiotic) stressors (Eyring, von Liebig, Paracelsus). Niche concept	x	x	x	x	x	x	x	x	x
	Selforganization and selforganized criticality	x	x	x	x	x	x	x	x	x
	Particle-wave duality	x	(x)							
	Schroedinger wave functions for electron shell			x	x					
	L-systems, gnomons (internal/external addition), fractals				x	x	x	x	x	(x)
	Constructal law				x	x	x	x	x	
	Growth and development, allometrics				x	x	x	x	x	x
	Life cycle during one generation (ontogeny and life stages), fitness, trade-offs				x	x	x	x	x	x
Information	Genes, genetic basis of ontology, of bodyplan, of phenotypic plasticity (response curves)				x	x	x	x	x	x
	Immune/self-other				x	x	x	x	x	x
	Genetic basis of neural network: mental traits, nature (instead of nurture)								x	x
	Neural based behavior, reflexes, memory, intelligence, consciousness, mental health, psychology, phychiatry, welbeing, satisfaction and brain-body-sensors interaction								x	x
	Memes								(x)	x
Displacement/dynamics	Zwitter-ion				x					
	Turing patterns inside operators				x	x	x	x	x	(x)
	Transportation inside organisms				x	x	x	x	x	(x)

Table 8.3. This cross-table shows an inventory of unifying concepts in science and the range of interaction systems to which the unifying concept apply. The interaction systems are arranged in order of the most complex operator in the system.

Main subject	Related subjects	fundamental particles	hadrons	atom nuclei and atoms	molecules	(prokaryote) cells	eukaryote cells	multicellular prokaryote	multicellular eukaryote	memon (hardwired)	memon (softwired)
Thermodynamics (energy)	Temperature dependence of interactions	x	x	x	x	(x)	(x)	(x)	(x)	(x)	(x)
	Thermodynamics of overall systems or flows	x	x	x	x	x	x	x	x	x	x
Construction	Grand Unification Theory (Theory of Everything)	x	(x)								
	Relativity, space-time	x	(x)								
	Electromagnetism	x		x	x						x
	Physical chemistry			x	x	(x)	(x)	(x)	(x)	(x)	
	Gravity	x	x	x	x	x	x	x	x	x	x
	Constructal law, patterning giving high access to flows (including interaction chains, such as foodchain), pseudo-fractal constrution.	x	x	x	x	x	x	x	x	x	x
	Selforganization and selforganized criticality (Pareto-Zipf-Mandelbroth, pseudo-fractal distributions)	x	x	x	x	x	x	x	x	x	x
	Alternative stable states/critical transitions	x	x	x	x	x	x	x	x	x	x
	Biochemistry				x	x	x	x	x	x	(x)
	Biotope					x	x	x	x	x	x

Table 8.3: Continued

Main subject	Related subjects	fundamental particles	hadrons	atom nuclei and atoms	molecules	(prokaryote) cells	eukaryote cells	multicellular prokaryote	multicellular eukaryote	memon (hardwired)	memon (softwired)
Information	Pauli principle	x	x								
	Evolution A (diversification via production, followed by selection)	x	x	x	x						
	Evolution B in moving fitness landscape ((selfish)-genes, diversification, reproduction (sex, populations), epigenetics, units of evolution, role neutral mutations, genotype-phenotype, defectors, game theory)					x	x	x	x	(x)	
	Group-against-group selection					x	x	x	x	x	x
	Habitat					x	x	x	x	x	x
	Stress ecology: targets, buffering and plasticity (phenotypic, population and community adaptation (PICT))					x	x	x	x	(x)	(x)
	Disease syndrome (viral, bacterial, multicellular causal agent)					x	x	x	x	x	(x)
	Social behavior: nurture, altruism, communication, moral, economy, politics, culture, science									x	x
	Lamarckian inheritance									(x)	x
	Evolution of memons (meme-to-network)										x
Displacement/dynamics	Quantum tunneling	x	(x)								
	Logistic map, Mandelbrot set, Julia set (stability, periodicity, chaos, bifurcations)	(x)	(x)	(x)	x	x	x	x	x	x	x
	Turing patterns and waves				x	x	x	x	x	x	(x)
	Spatial occurrence of organism interactions, neutral theory of biogeography					x	x	x	x	x	x
	Transportation (moving, phoresy, goods)					x	x	x	x	x	x

The inventory of unifying concepts in Tables 8.2 and Table 8.3 suggests two major trends. The first trend is that only a few concepts apply to many different levels of organisation and, in this sense, are truly unifying. One explanation for this lies in the fact that most theories mainly apply to either operators or interaction systems. Another explanation is that even within the separate lists of Table 8.2 and of Table 8.3, few theories can be found that apply to all different operators or to all different interaction systems.

Combining the information of both tables, the following unifying concepts are relevant for all material systems:

- Gravity impacts all systems.
- Thermodynamic laws have to be obeyed by all processes in systems (although minute disobediences due to chance effects are possible).
- The stability of all systems is limited to within a certain range of environmental conditions.
- Self-organisation and the constructal law connect thermodynamics with the formation of structural patterns.
- The concept of first-next possible closure allows the recognition of the operators and the operator hierarchy, hereby offering a “periodic table for periodic tables”.
- If systems show dynamics, these may show various patterns, such as alternative stable states, fractal behaviour or shifts between stable, periodic and chaotic behaviour.

The second trend that is suggested by the inventory is the divergence between non-dissipative or dissipative systems. Of course, there is a good reason for this: a dissipative organisation of an operator is intimately linked to properties that allow it to organise itself while using an external energy gradient. Examples of such properties are autocatalysis, a membrane, heritable information, growth, demand for food or energy, etc. More detailed subdivisions can be recognised for all levels of the operator hierarchy because every new emergent property of an operator introduces new properties. For example, memic closure introduces reflexes, learning and behaviour based on mental representations.

Discussion

The operator hierarchy contributes in different ways to scientific integration. Firstly, it allows the structuring of various fields of scientific theory by invoking the strict ranking of the operator hierarchy. Secondly, it establishes connections between other unifying concepts. The structuring capacity of the operator hierarchy results from using first-next possible closure, which allows a strict ranking of the operators. A strict ranking means that an operator cannot be included or excluded without disturbing the entire logic of the operator hierarchy. If a theory possesses such strictness, this can be regarded as a special kind of beauty. For example, Einstein said the following about his general theory of relativity that offered a strict framework for dealing with gravity, space-time and matter-energy: "The chief attraction of this theory lies in its logical completeness. If a single one of the conclusions drawn from it proves wrong, it must be given up; to modify it without destroying the whole structure seems to be impossible (from Weinberg: 1992). But while the relativity theory offers an abstract and *quantitative* framework for dealing with matter, energy, forces and space, the operator hierarchy focuses on complementary aspects by offering an abstract and *qualitative* framework for organising matter. That the operator hierarchy deals with qualitative aspects should not be considered a flaw of the theory, but its strength, because it addresses a blind spot in the scientific literature.

The general analysis of structural hierarchy is not a fashionable topic in science. Firstly, people may not think about a unifying ranking because they consider particles, such as hadrons, atoms and molecules, as incomparable with organisms. Secondly, people may have difficulty identifying a general ranking rule. When looking at the mechanisms, they look differently at every level. Only the use of first-next possible closure offers a principle that can be used across levels. Thirdly, people may consider it wrong to focus primarily on the operators because the universe is full of interaction systems, such as galaxies, stars, planets and at least one ecosystem. However, the operator hierarchy cannot be created or even recognised as long as interaction systems are considered to be part of its ranking. Fourthly, Teilhard de Chardin's early work dealing with a general ranking was confounded with religious statements. This may have led certain people to reject his early steps towards a general theory altogether. Finally, the focus of science on quantification and equations has drawn the attention away from structural analysis, which uses completely different concepts of quantity. These and other aspects may have contributed to the absence of the operator hierarchy in any form from the scientific debate.

As was discussed in this study, the operator hierarchy contributes in various ways to such fundamental topics as a cosmic timeline, an ecological hierarchy, a

periodic table for periodic tables, an organic evolution and an analysis of the scope of unifying concepts. The operator hierarchy adds to these topics a unique focus on the structural complexity of systems. This focus enables the logical integration of distant scientific domains. These achievements support the conclusion that the operator theory deserves a prominent role in science.

General discussion and conclusions

*"Der Philosoph ist nicht Bürger einer Denkgemeinde.
Das ist, was ihn zum Philosophen macht."
(Ludwig Wittgenstein)*

Introduction

The goal of this thesis was to contribute to unification in science by searching for rules that guide the development of structural complexity in the universe and that improve the analysis of hierarchical organisation in biology, ecology and system science. The major result of pursuing the above goal has been the discovery of the operator hierarchy. Various individual aspects of the operator hierarchy have been discussed in the above chapters. To place the conceptual framework of the operator hierarchy and its applications in a broad context, I will attempt to answer the following five questions: (1) what kinds of novel theoretical developments have accompanied the elaboration of the operator hierarchy, (2) what impacts may the operator theory have on science, (3) what aspects of the operator theory require discussion because of potential weaknesses, (4) how can the operator theory be evaluated, and (5) what routes are open for future development.

What is new?

Three principles are absolutely fundamental to the development of the operator theory. The first is the reduction of the complexity of the hierarchy problem to its minimum. The second is the identification of three major dimensions for analysing hierarchy. The third is the definition of first-next possible closure and its use as a tool to identify and to rank subsequent operators. To discover whether these principles can be considered new developments, they will be individually discussed in relation to existing theory.

Although biologists generally focus on details of a system's organisation, physicists quite generally solve problems by reducing the observed complexity to a minimum. The following citation from Bak (1996) presents an instructive caricature of the difference in attitude between biologists and physicists:

Thus, how would we physicists make a suitable model of, say, biological evolution? The biologist might argue that since there is sexual reproduction in nature, a theory of evolution must necessarily include sex. The physicist would argue that there was biology before there was sex, so we don't have to deal with that. The biologist might point out that there are organisms with many cells, so we must explain how multicellular organisms developed. The physicist argues that there are also single-cell organisms, so we can throw multicellularity out! The biologist argues that most life is based on DNA, so that should be understood. The physicist emphasizes that there is simpler

life based on RNA, so we don't have to deal with DNA. He might even argue that there must have been a simpler reproductive chemistry before RNA, so that we don't have to deal with that either, and so on. The trick is to stop the process before we throw out the baby with the bathwater.

That the concept of evolution can be reduced to a minimum shows the magnificence of the one-line programme developed by Harvey in 1996 (Harvey, 2001, 2009). The programme effectively mimics evolution, including rank selection, demes, recombination (via horizontal transmission), mutation and elitism:

```
for (t=0;t<T;t++) for (W=(e(A=P*r())>e(B=(A+1+D*r())%P)?A:B),
L=(W==A?B:A),i=0;i<L;i++) if ((r=r())<R+M) g[L][i]=(r<R?g[W][i]:g[L][i]^1);
```

Where: t = tournaments, T = max number of tournaments, W = Winner, L = Loser, e(i) is a problem-specific evaluation function returning fitness of ith member of population, g[j][i] is an array giving the ith gene of the jth member of population, A, B are members chosen for a tournament, to be labelled W(inner), L(oser) according to which is fitter, r() is a (pseudo-)random number 0.0<=r()<1.0, P is population size, D is deme-size, R is Recombination rate, M is Mutation rate.

Although the importance of the caricature presented by Bak and the minimalist model for a biological evolution process designed by Harvey are beyond discussion, the venom of simplification is in the tail because –as was stated above- the process should be stopped just in time to prevent the essence of the problem from being flushed down the drain. It is precisely in relation to this aspect that the use of first-next possible closure in the operator hierarchy does represent a major theoretical development; first-next possible closure indicates the line separating the situation in which the baby is saved from that in which it is being flushed down the drain. First-next possible closure indicates exactly the theoretical minimum complexity that is required to form a next level operator. It does this for all levels in the operator hierarchy, hereby guiding several situations where the trick is to stop the process of simplification just in time.

The difficulty of stopping the simplification process at the right moment is illustrated by the common belief that if we understood the origin of life, i.e., the origin of the first cell, we would solve the long standing problem of the definition of life. As Jagers op Akkerhuis (2009, in press) has shown, focusing on the first cells implies that the reduction process has been carried too far. The reason is that the most detailed insights into a cell's properties are vastly insufficient to define even the minimum aspects of all the other complexity levels of life, such

as eukaryotic life, multicellular life, memic life and, in the future, technical memic life. Using cells as a basis for a definition of life, especially technical life, is problematic because technical life does not even consist of cells. In the past the simplification process went wrong because it was continued to the simplest operator (the cell) and not to the simplest organisation that is typical for every type of living operator. As a result, all the properties that were typical for the organisation of complex organisms were lost during the simplification process, and this loss made it impossible to define life in a general way.

The second major principle advocated by the operator hierarchy was that organisation should be analysed on the basis of three dimensions for hierarchy. In principle, this realisation is not new. Around 1940 the idea had been discussed that when we analyse a system that controls several elements this system may itself be controlled by another system that resides 'above' it (Feibleman 1954). There are many examples of this three-level approach, for example, Koestler's Holon (Koestler, 1967) and Jaros and Cloete's Biomatrix (Jaros and Cloete, 1987). It is quite interesting that in many publications such three-level approaches to systems were placed one after another, such that a given system with its elements became itself an element in a larger system, etc. The resulting hierarchy had the effect of guiding the reader's thoughts towards a chain of interlocked systems. As a consequence, the initially independent three levels have now become hostage of a one-dimensional hierarchy. The operator hierarchy differs on this point because it recognises that hierarchies in these three levels (interior of a system, the system, and the world) point in different directions and that for this reason they are independent dimensions for hierarchy. According to this new perspective, one can analyse hierarchy in the internal organisation of a system, one can analyse the organisational differences between systems, or one can analyse how interactions between systems create hierarchy. Thus, even though the basal three levels of the classical system theory are retained, the operator theory recognises them as independent directions for hierarchy and not as levels.

Finally, the use of first-next possible closure in the operator hierarchy seems to be a truly original theoretical development. Except for Teilhard de Chardin's contribution (Teilhard de Chardin, 1969), no publications have been found dealing with first-next possible closure or related topics referring to "first-next".

What are the impacts?

The operator theory was developed to solve problems with the integration of toxicant effects at various levels of ecological organisation. Initially, the integration was based on the well-known 'ecological hierarchy', for example, from atoms to molecule, organelle, cell, tissue, organ, organism, population,

community and ecosystem, planet, solar system, galaxy and universe. But this hierarchy proved to be conceptually inconsistent and insufficient. Because no alternative was found in the literature, the only solution was to try to develop a new ecological hierarchy. This resulted in the discovery of the operator hierarchy. Later, it appeared that the logic of the operator hierarchy could be applied to solve many other problems that had their origin in the inconsistent use of hierarchy. Most notably, the operator hierarchy was applied to rearranging the classical ecology hierarchy. By using the operator theory, the original linear ranking of elements in this hierarchy could be transformed into three separate rankings: one for the hierarchies in interaction systems, one for the hierarchy of the operators and one for hierarchies in the internal organisation of the operators.

Furthermore, the operator hierarchy has a fundamental application in arranging a happy marriage between the particle concept used in physics and chemistry and the organism concept used in biology and ecology. Based on the operator hierarchy, the two concepts were united in a single ranking in which the word 'operator' was used as a common concept. Integrating all operators in one ranking also changes the way in which a particle is defined. Although the classical concept of a particle concentrates on minute physical entities (for example, see Falkenburg's review, 1993) one must now consider that the particle concept can be broadened to the operator concept and that demands for first-next possible closure should be part of a definition of physical and chemical particles.

Because it ranks abiotic and biotic operators, the operator hierarchy can also be applied as a periodic table of periodic tables because for every operator -- and for some interfaces or pre-operator hypercyclic sets -- a corresponding periodic table exists for the classification of all the known operators at that complexity level. In this way, the operator hierarchy connects the standard model for fundamental particles, the eightfold way for hadrons, the periodic table of the elements and the tree of life.

Another application of the operator hierarchy was the further development of complexity layers in the tree of life. In its most basal representation, the tree of life presents the historical divergence of species. Quite frequently, the time axis is supplemented with information about whether the organisms are prokaryotic, eukaryotic or multicellular. The operator hierarchy now suggests adding two other classes: multicellular prokaryotes (e.g., blue-green algae) and memons. The major advantage of introducing memons is that brains are no longer regarded as just another organ that can be found in multicellular organisms but as a different level of organisation altogether. The recognition of a level of memic organisation also has the advantage of fully merging neurobiology and technical intelligence.

The operator hierarchy also offers an interesting solution to the definition of life problem. Earlier attempts at a definition frequently focused on the origin of life, for example, on the properties that were typical for the minimum organisation of the most primitive prokaryote cell. The operator hierarchy indicates however, that minimum organisation is not typical for prokaryotes but exists at many levels, including those of the eukaryotes, the multicellulars, and the memons. Accordingly, a definition of life cannot be complete if it does not consider the different minimum organisations at all these levels. Using the ranking of the different operator types offered by the operator hierarchy, life is defined as matter with the construction of operators under the limitation that the operators should at least show the cellular operator's complexity. By focusing on operators and their minimal construction properties, the operator-based definition also solves problems with facultative aspects that plague many other definitions. For example, frozen cells are still life, according to the operator-based definition, even though they do not show physiology, behaviour, etc. Similarly, reproduction and growth are no longer requirements for life, although the production of offspring is, of course, required for evolution! Another implication of the operator-based definition is that technical memons must be regarded as life because it is irrelevant, for example, whether the structure of hardwired memons is based on organic cells or on technical devices.

A field of theory where the operator hierarchy has also been applied is that of astrobiology and extraterrestrial life. If it is assumed that the operator hierarchy correctly describes all the first-next possible closures that are possible in our universe, then the same operators will be formed anywhere in the universe for as long as ambient conditions allow this to happen. This assumption is supported by observations showing that atoms and molecules also exist in distant galaxies. Similarly, life, as defined by the operator hierarchy, may exist in the universe on other planets than Earth.

Yet another application of the operator hierarchy is that it offers a structured way to reason about the construction of future operators and hence about the future of evolution and, in particular, artificial intelligence (AI). Even when the outcome may be the same, using the operator hierarchy gives predictions a better basis than what is offered by observing trends in the robotic industry. Of course, the extrapolation of the operator hierarchy holds only as long as the sequence of the operators and their secondary structure are interpreted correctly. Under these assumptions, the extrapolation of the operator hierarchy can be used to predict the closures of a range of future operators. Although the operator hierarchy may well offer the only method science has ever had to predict future particles, the result remains, of course, an extrapolation and is burdened with various uncertainties. The most important uncertainty is related to how a closure dimension should be interpreted at a higher level. For example, the distance between multiatomarity and multicellularity is already enormous, but the distance

between multicellularity and multimemcity is even larger. Moreover, where it is already difficult to predict details of multicellularity as long as only bacteria are known, it will be much more difficult to predict details of multimemic life if the only known memons are animals. Of course, the smaller the predicted steps forward, the more likely it will be that a prediction is correct. The smallest step that can be predicted using the operator hierarchy is that from the hardwired memon (animals with 'brains', including human beings) to the softwired memon (a technical life form with modelled brains). The operator hierarchy predicts that a memic architecture is required if technical devices should show the emergent properties typical for memons, such as learning, association, creativity, intelligence, thinking and consciousness. These properties are all graded properties that increase in close correlation with the complexity of the neural network (e.g., size, connectivity, managing of weights of neural connections, hierarchy of feedback loops, etc.). In addition, a neural network has the advantage of efficiency because it does not have to store all past perceptions in files whose content has to endlessly increase over time with every experience (Baxter and Browne, 2009). Instead, a neural network stores new information by fine-tuning the structuring of one and the same network.

The operator hierarchy could furthermore be applied in the field of artificial intelligence to redefine the meme concept. The classical meme concept was introduced by Dawkins (1989). Dawkins defines the meme as a concept that "conveys the idea of a unit of cultural transmission or a unit of imitation". The meme has a deliberate association with the gene concept that represents the unit of heritable transmission. However, there is no proper parallel between the two concepts. Genes are material structures that code for organism properties. Memes are concepts of cultural transmission without a clear structural basis. The operator hierarchy suggests that the meme concept can be given a structural basis, if memes are defined as the coding that in technical memons (the softwired memons) contains the information about the number of neurons, their connections and the strength of these connections (Jagers op Akkerhuis, 2001).

The operator theory also offers a context for discussing the arrow of complexity hypothesis. On the arrow of complexity hypothesis, Bedau (2009) states the following:

We can distinguish three things: (i) a trend, which is simply a directional change in some variable; (ii) a robust regularity, which is a generic or non-accidental trend and which can be thought of as a statistical "law" of nature; and (iii) a mechanism which explains how a trend (whether accidental or robust) is produced. Now we can formulate the arrow of complexity hypothesis—the hypothesis that evolution inherently creates increasingly complex adaptive

organisations as life forms. Note that the hypothesis is about the increasing complexity of the most complex forms of life, not of all life forms. The hypothesis concerns not mere complexity but adaptive complexity. The arrow hypothesis should be understood as a robust regularity that has exceptions, and it holds for evolving systems only given certain constraints.

Assuming that both a trend and a robust regularity require a mechanism that explains their occurrence, confirmation of the arrow of complexity hypothesis requires an explanatory mechanism that, in a robust and regular way, increases the complexity of the most complex life forms. Demonstrating such a mechanism implies proof of the evolutionary advantages of complexity and a yardstick to measure it. The operator hierarchy solves the last problem by offering a strict yardstick as the number of closures a system shows and the elaborateness of a closure when present. Accordingly, plants are more complex than protozoa and single-celled blue-green algae are more complex than *Pseudomonas* bacteria.

An indirect proof for the evolutionary advantage of complexity can be derived from the fact that no system can organise itself in contradiction to the laws of thermodynamics. Accordingly, the fact that high complexity memic operators exist on Earth implies that complexity must have advantages that outweigh the costs. Other approaches to prove the advantage of high complexity may involve, for example, the economy and the competitive power of three-dimensional multicellular shapes compared to those of single-celled organisms. However, if it is assumed that the operator hierarchy correctly indicates the only closure situations that are possible, this assumption implies a fixed direction for the arrow of complexity because any evolution process either comes to a halt or proceeds along the pathway of the operator hierarchy.

What are potential weaknesses?

The operator hierarchy was constructed with great care. Every step in the hierarchy was checked to confirm if no other layer could be added or if a layer could be made superfluous. In addition, the internal logic of the operator hierarchy based on closure dimensions and complexity layers acts as a control mechanism because it leaves little freedom for manipulation. Its applications show that the idea is compatible with a whole range of other scientific ideas that could be supplemented or improved by relating them to the operator hierarchy.

Despite these positive aspects, it is important to remain critical and to continuously search for ways to falsify or improve the theory. The aim of this chapter is therefore to critically discuss various aspects of the operator hierarchy that may lead to questions or that require further research.

First of all, it must be said that the operator hierarchy has a strict and logical structure but that there is no clear explanation for the fact that every primary operator adds a new closure dimension. Although this may have something to do with the increasing conformational richness of every next hypercyclic configuration lying at the basis of every primary operator, it is still unclear how this mechanism works. It is easier to explain the observation that every primary operator shows transitions that recreate every existing closure dimension. The reason for this is that the transition cannot be made in another way (e.g., from quark to hadron, from atom to molecule) or that all possible pathways are in principle explored (e.g., from prokaryote unicellular to eukaryotic unicellular to prokaryotic and eukaryotic multicellular).

Secondly, the operator hierarchy is based on hypothetical closures that represent the least complex configurations. Consequently, the closures that figure in the operator hierarchy will generally have no parallels in real life. Even the simplest bacterial cell will most likely require more than two catalysts to perform autocatalysis while maintaining the cell membrane. This artefact results from the intention to minimise complexity in order to gain more insight into what are the essential aspects of every transition in the hierarchy.

Thirdly, it can be suggested that “there are more things in heaven and earth, Horatio, than are dreamt of in your philosophy” (William Shakespeare, *Hamlet*: Act 1. Scene V). In fact, this is a most interesting criticism. From science fiction stories, astrology programmes on television, biblical assumptions about resurrection and life after death, fairytales, ghost stories and the general scientific message that many things are still waiting to be discovered, most people are convinced that there is still much we do not know. The operator hierarchy offers a scientific way to discuss this point of view. The hierarchy's logic implies that the space for potential novelty is rather limited. The reason is that the operator hierarchy ranks all the operator types that have occurred since the beginning of the universe from the fundamental particles to the memons. Furthermore, for all operator types, science has created and continues to create increasingly detailed insight into what forms the operators may take, how they interact with their environment and what they may transform into (when they can). Moreover, assuming that the operator hierarchy ranks all possibilities for first-next possible closure, no other types of operators can exist elsewhere in the universe. Accordingly, the space that is left for truly unexplainable things has become small indeed. That the space for unexplainable things is limited has also been convincingly advocated by 't Hoofd (2000). Of course, a reasoning like that given above is not complete without indicating that science can say little about things that it has not measured or cannot measure. How much space is left for new discoveries depends in the end on whether a natural limit exists to the number of phenomena that can exist in our universe at the different levels of organisation and as the result of all possible interactions between elements.

Fourthly, it may be argued that the danger of a scientific Procrustean bed is lurking in the operator hierarchy. As an old Greek story goes, Procrustes was a blacksmith who invited people to sleep in his house. To a tall person he offered a small bed, and while the person slept, Procrustes hammered off his guest's extremities that extended beyond the bed. Similarly, a short person was offered a large bed, and Procrustes stretched his body by hammering on it until it fit the bed. In the context of debunking the operator theory, it is a legitimate question whether the notion of a rough blueprint of the operator hierarchy has not been a reason for formulating definitions that are fine-tuned to confirm the theory while a more general application of the principles would have led to a different outcome. This is an unlikely scenario because the definitions that describe the operator hierarchy were constructed so that the mechanisms involved are as general as possible to avoid manipulating definitions towards specific situations. Furthermore, any set of definitions that has been adapted to a Procrustean bed will fail to fit with other approaches that are free of such limitations. In this sense it can be regarded as positive circumstantial evidence that the operator hierarchy has led to useful applications in various scientific fields (e.g., ecological hierarchy, definition of life).

Fifthly, it must be concluded that the operator hierarchy offers no information about the average time that is required to reach any next level in the operator hierarchy. For this reason, the operator hierarchy lacks direct associations with time-related topics, such as evolutionary acceleration; it has a strict focus on structural transitions. The absence of time is not a unique property of the operator hierarchy. Time is not quantified in either thermodynamics or Darwinian evolution. But even though the operator hierarchy gives no information on this point, there are several reasons why an evolutionary process may speed up over time.

a. Development acceleration

If elements remain in the system once they have been formed, this will increase the possibilities for novel interactions. If we now postulate an evolutionary rate as the chance per time that new elements are formed, this rate will actually represent acceleration because the evolutionary rate creates new elements on the basis of the cumulated number of elements formed. The combination of both processes implies that the evolutionary rate (dimension time⁻¹) transforms into an evolutionary acceleration (dimension time⁻²).

b. Modularity and hierarchy

Assuming a system of k building block elements that shows a hierarchical structure with many layers, and assuming that on average s components have to combine to form the elements of any next level in the hierarchy and take the same time to do so, it can be deduced that the time for the evolution of the whole system is proportional to the logarithm to base s of k . Given any system that is structured in this way, the time required to develop from a

system with 1 element to a system with 1000 elements would be the same as for a system of 1000 elements to reach the size of a million elements (see also Simon, 1962).

c. The evolution of evolvability

Organisms are selected for a combination of complexity and efficiency that combines resource dominance strategies that, in a given environment, yield the highest increase in resource dominance. The organisms success in these combined efforts, e.g., their evolutionary success, can be measured either in terms of their present resource dominance or in terms of the increase and the acceleration hereof. A focus on these different rates is of marked importance; those that are the best now may soon lose to those that slowly improve and both strategies will be beaten in the long term by units that can increase their improvement rate. Early papers on the importance of the evolution of evolvability have been published by Wagner (1996).

d. The use of larger energy gradients in combination with increased efficiency

This aspect selectively applies to living operators. To maintain their organisation, organisms need energy. If there is a large quantity of energy available, the organism can afford a larger organisation. For this reason, increasing complexity requires increasing efficiency and/or an increase in access to energy gradients. In this sense, the changes from litho-chemical metabolism to photosynthesis, to the consumption and digestion of organic material from other organisms, to fossil fuel, nuclear energy and solar energy can be regarded as innovations that have sustained and/or accelerated the evolution process.

e. The evolution of concepts

Once the level of memons has been reached, new discoveries can be learned and/or documented. In this way, knowledge can be disseminated (also without reproduction) and be used to create new tools to further increase the rate of new discoveries and the development of knowledge. This acceleration mechanism must be considered the cause of the knowledge explosion crises.

Integrating the above and possibly other processes, Kurzweil (1999) has proposed the “law of time and chaos”, as follows: ‘In a process, the interval between salient events (that is, events that change the nature of the process, or significantly affect the future of the process) expands or contracts along with the amount of chaos’. Clearly, ‘time’ in this viewpoint is relative to the frequency of salient events. From this general viewpoint, two laws that are more specific can be derived, depending on whether one considers increasingly chaotic systems or increasingly ordered systems. For increasingly chaotic systems, like the overall universe, the ‘negative’ version of the above law – ‘The law of increasing chaos’ – reads as follows: ‘As chaos exponentially increases, time exponentially slows down; that is, the time interval between salient events grows longer as

time passes'. This fits well to the processes that can be observed in the overall universe, where most salient events, such as the formation of matter, occurred in the first seconds of the universe's existence. The 'positive' version of the above law – 'The law of accelerating returns'-- on the other hand, can be formulated as follows: 'As order exponentially increases, time exponentially speeds up; that is, the time interval between salient events grows shorter as time passes'. The latter fits well with the acceleration of evolution observed in local spots of the universe where initial self-organisation processes (e.g., chemistry, autocatalysis) lead to increasingly rapid self-organisation (e.g., cells, multicellulars, memons, etc.). Together these two laws describe that in the universe, the overall processes increase chaos and slow time, whilst in some local systems order has increased and continues to produce more order in an increasingly rapid way.

The law of time and chaos uses the word 'salient' events. I consider this formulation in perfect harmony with the operator theory because the operator hierarchy describes the occurrence of specific emergent properties that lead to the construction of new operators. The transitions leading from one operator to the next typically signify the most important 'salient' events in the universe.

Of course, the above examples of acceleration are simplified generalisations that could suffer from various disturbances. For example, certain newly formed elements may negatively affect the formation of new elements by disrupting the system. Moreover, adding higher level elements may block certain types of interactions with lower levels, hereby reducing the number of interactive combinations. It may also be argued that at any moment in evolution, the possibility of forming new elements from the prevailing elements has simply been zero (e.g., there is no life on the moon), which makes the evolutionary rate drop to zero. Yet, the long array of system evolution from quarks to neural networks shows that, at least in our part of the universe, a fatal blocking of the process has not yet occurred.

Sixthly, the question arises whether the operator theory represents a falsifiable construction, a construction in which experiments can be designed to prove or disprove the theory. The operator theory is, however, not a quantitative theory. It deals with the recognition and ranking of system configurations resulting from self-organisation processes. Is it possible to falsify such an approach? In this respect the following points may be considered to test the theory: (1) Is the ranking strict? (2) Is the second-order ranking by closure dimensions consistent? (3) Do any of the proposed transitions contradict thermodynamic laws? (4) Can the ranking be used to predict gaps? Although nothing indicates that the operator theory would violate the first three of these aspects, it is scientifically desirable to search for ways that can prove or disprove these aspects in a definite way. A difficulty with respect to the fourth point is that the theory cannot,

in principle, show gaps because it is designed as a strict ranking. If there were gaps, this would immediately require another ranking. The prediction of gaps is therefore limited to future operators that are not yet included in the ranking. Only the future will tell whether the predictions based on the operator hierarchy are correct.

From the above points it can be concluded that certain aspects of the operator theory need to be further developed. The identification of operators showing the same closure dimension would especially profit from a less intuitive conceptual methodology. On the other hand, no aspects have been found where the operator hierarchy can easily be proven wrong or insufficient.

How can the operator theory be evaluated?

When it comes to judging the value of the operator theory, certain evaluation criteria are needed. In a review of theories for worldview comparison, Vidal (2009) offers a set of three objective criteria to evaluate and compare worldviews: (1) the theory should exhibit internal and systemic consistency, (2) the theory should fit with all natural sciences, and (3) the theory should address and adequately resolve worldview questions. Vidal mentions the following worldview questions in his paper: What is? Where does it all come from? Where are we going? What is good and what is evil? How should we act? What is true and what is false?

Vidal's criteria offer guidance to objectively discuss the operator theory's value (Vidal 2009). First of all, the theory should exhibit internal and systemic consistency. In this respect, it may be judged as positive that all steps in the operator hierarchy are based on first-next possible closures and that a set of coherent definitions was used for its creation. A further indication for a strong internal consistency comes from the fact that no single operator can be taken from or added to the operator hierarchy without destroying the entire framework. Secondly, the operator hierarchy should fit all natural sciences. It should be stressed that the use of sound scientific criteria has always been the number one criterion for constructing the operator theory. All transitions and all system types have been checked – as much as possible – for being based on testable scientific concepts. Thirdly, the theory should address and adequately resolve worldview questions. Although I am not sure whether other people might suggest additional worldview questions, the operator theory addresses at least three of Vidal's questions. The question of "What is?" is addressed by the operator hierarchy, because the hierarchy hypothesizes that all structures in the universe are based on one of the system types in the operator hierarchy (including the pre-operator hypercyclic sets and the interfaces). While unifying theories such as the grand unification theory in physics address particles and

forces at one level of organisation, the operator hierarchy addresses particles at all levels of organisation. As it addresses more levels, the operator hierarchy can be used to suggest an answer to the questions of “What is life?” and “What is death?”. The question “Where does it all come from?” is partially addressed by the long sequence of operators illustrating the major organising principles that allowed the successive system types to come into being. Finally, the operator hierarchy offers a unique possibility to answer the question of “Where are we going?” because it predicts the major structural aspects of future operators, from which information can be gained about their interactive properties and thus, how they might become players in the world that we still consider ours. In fact, the operator theory can also be considered to address the question of “What is true and what is false?” because it has helped improve various definitions, including the definition of a particle, life, the organism, death and ecological hierarchy.

Future development

I am convinced that the most promising routes for future development lie in finding explanations for the second-order structure of the operator hierarchy. Insights into this structure will test the validity of the operator hierarchy. If the operator hierarchy’s basic structure can be consolidated and our understanding deepened, I see three exciting routes for future development. The first is to increase insight into the lowest levels of organisation. The second is to apply the operator hierarchy’s structure to solving long standing problems related to hierarchical organisation. The third is to increase both the detail and the reach of predictions of future operators.

In conclusion

Originally, the search for order that is described in this thesis started with an integration problem in ecotoxicology. But the direction of the project changed when the first ideas about the operator hierarchy emerged; it suddenly became possible to pursue the much broader goal of contributing to the unification in science by searching for rules that guide the development of structural complexity in the universe. As was demonstrated in the different chapters of this thesis, the operator hierarchy holds a central position in the organisation of matter. The strict ranking of the operators based on first-next possible closure offers a basis for several important applications, including the definition of life, the restructuring of the classical ecological hierarchy, the prediction of future operators and the offering of a scientific integration tool in the form of a periodic table for periodic tables. In this way, the operator hierarchy improved the analysis of organisation in biology, ecology and system science. Given its central position in natural organisation and its broad range of fundamental

applications, the operator hierarchy can be regarded as a unique step forward towards Von Bertalanffy's dream of a '*general theory of hierarchic order*' (Von Bertalanffy, 1968) .

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Summary

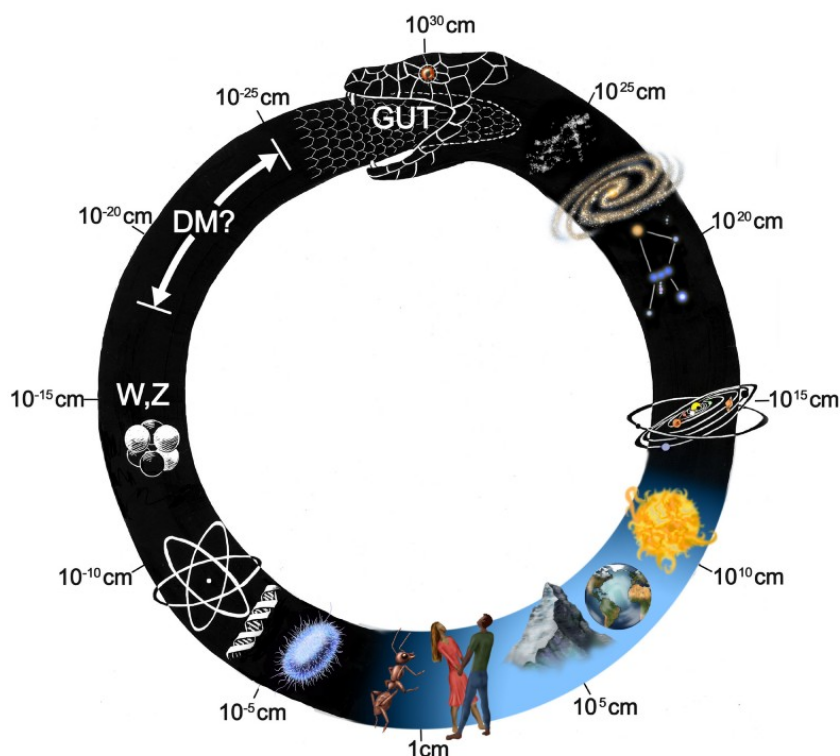
“To confine our attention to terrestrial matters would be to limit the human spirit.”
(Stephen Hawking)

It has been estimated that more discoveries have been made in the past 30 years than in the rest of human history. This explosion of knowledge has caused a crisis in science that is accompanied by overspecialisation and compartmentalisation. Scientists face the challenge of overcoming this crisis by constructing comprehensive and integrating concepts. This thesis presents a new method for creating bridges between disciplines and fighting the knowledge explosion crisis.

In human history various theories have been developed that aim at creating coherence in the phenomena observed in the world. An ancient approach is that of the Ouroboros, the snake swallowing its tail. This symbol represents the continuity and eternity of life and the world. Later, in his *Scala Naturae*, the Greek philosopher and naturalist Aristotle ranked natural phenomena by decreasing perfection, from spiritual and divine beings to man, animals, plants and finally rocks and formless matter. Aristotle's vision is also referred to as the Great Chain of Being. The Great Chain markedly influenced medieval Christianity, and, in turn, this chain influenced several well-known philosophers such as Descartes, Spinoza and Leibniz.

A current, comprehensive approach to the organisation of nature is Big History. Big History ranks all systems and processes by their occurrence in cosmic history. The approach rests on the scientific theory that the early universe was as small as a fundamental particle and obtained its present size after an explosive expansion: the Big Bang. Although the question about the universe's origin remains unanswered, the Big Bang theory is firmly supported by modern particle physics and cosmological observations.

Sometimes old structuring attempts are given a new interpretation, such as the Ouroboros in Figure 1. The left half of the figure shows how science has gained access to increasingly small systems, from large animals and plants, to individual cells, molecules, atoms, nuclear particles and finally quarks. The right half of the figure shows the scope of scientific research broadening towards increasingly large systems, from ecosystems, through planets, to solar systems, galaxies and finally the entire universe. When presented in this way, specific properties of the universe at large, such as the background radiation and its expansion in all directions, are connected with the universe's initial state. As the Ouroboros picture suggests, where the enormous and the miniscule meet, the search for organisation in nature seems to swallow its tail.



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Figure 1. This figure shows the historical expansion of scientific domains in the direction of the smallest systems and in the direction of the largest systems. GUT = grand unifying theory, Z and W indicate fundamental force carrying particles that are responsible for the weak nuclear force, DM = dark matter, cm = centimetre.

Evolution beyond Darwin

Despite all efforts aimed at unification in science, a general theoretical framework connecting the many fields of science has yet to be found. Many regard the lack of such a framework as a major deficit because it reduces our abilities to counteract current centrifugal trends in the knowledge explosion. This thesis aims to tackle this problem by systematically exploring unifying principles in science that may allow us to connect various scientific domains such as particle physics and evolution.

Darwin's theory of evolution offers a good starting point to explain how this thesis has approached the goal of developing unifying concepts. Darwin stated

that selection acts against offspring that are less well adapted to their environment. A white butterfly living in an ecosystem full of dark volcanic rocks is not well adapted to its environment because predatory birds can easily spot it. Consequently, it will suffer more predation than its darker relatives. As the genes of the dark parents code for dark offspring, the percentage of dark butterflies will increase with every generation. This example shows that the theory of evolution uses two processes. Firstly, the parents produce offspring with unique combinations of heritable properties and then the environment selects against less well-performing individuals.

Butterflies and other organisms are not the only things that evolve. Particles evolve, too. Of course, the evolution of particles does not involve heritable variation. However, if particles collide, the product may be a new particle or a range of new particles. Just like reproduction, such processes produce new variation, and the particles that are produced also experience selection. For example, the hot gaseous environment of a star continuously produces various atomic “species”, while only a few of these are stable in the hot environment. We may regard this as a form of evolution where the process of diversification is based on *production* instead of on *reproduction*.

Productive and reproductive evolution processes became active at different moments in cosmic history. The early universe had only physical particles and only production could create diversity that selection could act on. Much later, the emergence of organisms introduced the possibility of reproductive creation of diversity.

The difference between the productive and the reproductive production of diversity coincides with the conceptual separation of physics and biology. To close this gap, this thesis suggests using a general definition of evolution based on diversification (the production of variation) and selection, and the modification of these aspects by circumstances. In relation to given contexts, diversification can relate to the chemical production of variation, to organic reproduction and, in the future, to the technical construction of offspring. Similarly, selection can change in relation to the system types that are considered. This approach allows the evolution concept to be applied to all operators in the universe, from fundamental particles through living organisms to future robotic life forms.

Levels of complexity

The difference between evolution based on production and reproduction is, however, not the only reason why the fields of physics and biology seem to resist integration. There is another barrier. In physics, researchers usually have a clear picture in mind when referring to levels of complexity, such as nuclear

particles, atoms and molecules. The formation of these particles is generally attributed to condensation reactions and not to evolution. In biology, Darwin's theory of evolution is broadly accepted, but this theory ignores the complexity levels of organisms.

Darwin knew, of course, that bacteria, protozoa, plants and fungi, and animals existed. But he did not need the differences in complexity between these groups to define what was later coined the "struggle for life" and "survival of the fittest". Although genetics has contributed much to the understanding of evolutionary mechanisms, its development has not helped much with understanding the complexity levels of organisms, with the exception of the difference between organisms without or with mitochondrial genes.

That it pays no attention to structural complexity represents a serious flaw in Darwin's theory. Because of this flaw, the theory of evolution cannot answer an apparently simple question such as "Is it possible to predict what the next step in the evolution process will be?" It also cannot answer a question such as "Are endosymbiotic/eukaryotic cells the only logical successors of bacteria?" To answer these questions requires a comprehensive theory that accounts for structural complexity and its levels.

Dimensions for hierarchy

Levels in the organisation of nature are frequently represented as a sequence of increasingly complex system types. The literature contains many examples of such sequences. Generally, these sequences exhibit marked similarity to the following example: atom, molecule, organelle, cell, tissue, organ, organism, population, community, ecosystem, planet, solar system, galaxy and universe (Fig. 2). What is very interesting about these kinds of hierarchies is that, at face value, they seem useful tools for organising complexity, whereas on closer consideration it is easy to show that they are actually based on an inconsequent use of hierarchy rules.



Figure 2. A typical example of the much used ranking of complexity generally indicated as 'ecological hierarchy'

To solve problems with existing approaches, Figure 3 introduces a new vision to analyse hierarchy in nature. It is based on three fundamental directions: (1) the hierarchy from a particle to a system of interacting particles, (2) the hierarchy ranking particles of different complexity, and (3) the hierarchy in the interior of a particle. This thesis proposes that these three directions represent three dimensions for hierarchy.

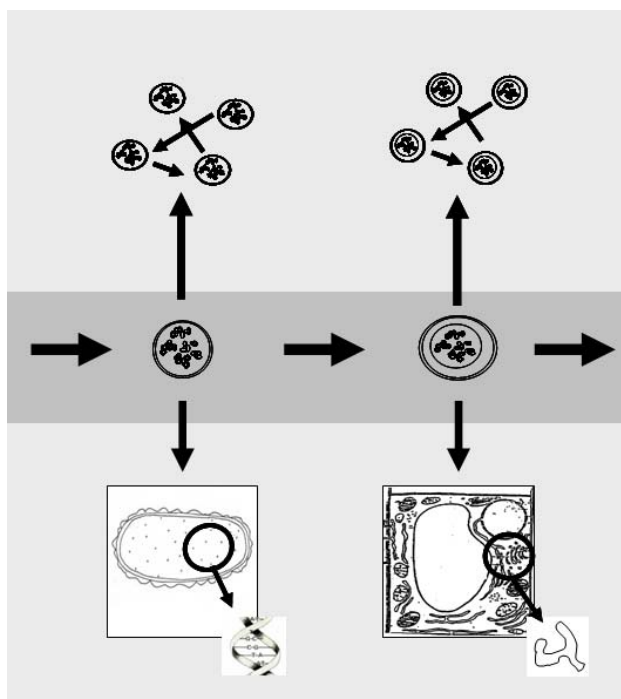


Figure 3. The figure represents the three fundamental dimensions for hierarchy in the organisation of nature Upward pointing arrows indicate increasing complexity in systems of interacting particles. Arrows pointing to the right indicate how lower level organisms create higher level organisms. Downward pointing arrows indicate increasing complexity in the internal organisation of an organism.

The idea that there are three dimensions for hierarchy in nature is illustrated in Figure 3. For simplicity reasons, the figure is deliberately limited to prokaryotic cells and eukaryotic cells. Based on the same principle, the figure can be extended in the direction of fundamental particles and in the direction of more complex organisms. The figure shows that it is important to use dimensions in a systemic manner. It is, in principle, not allowed to switch between dimensions when analysing hierarchy. In relation to the latter rule, Figure 4 shows what an ecological ranking looks like that respects the three dimensions for hierarchy. The left column of this figure shows that local areas in the universe display an ongoing development and differentiation from vague aggregations of matter, to galaxies, solar systems, planets and ecosystems. On the opposite side, the right column illustrates how hierarchy can be analysed in the interior of a particle. The column in the centre shows that specific forms of aggregation or the formation of internal structures can give rise to more complex particles.

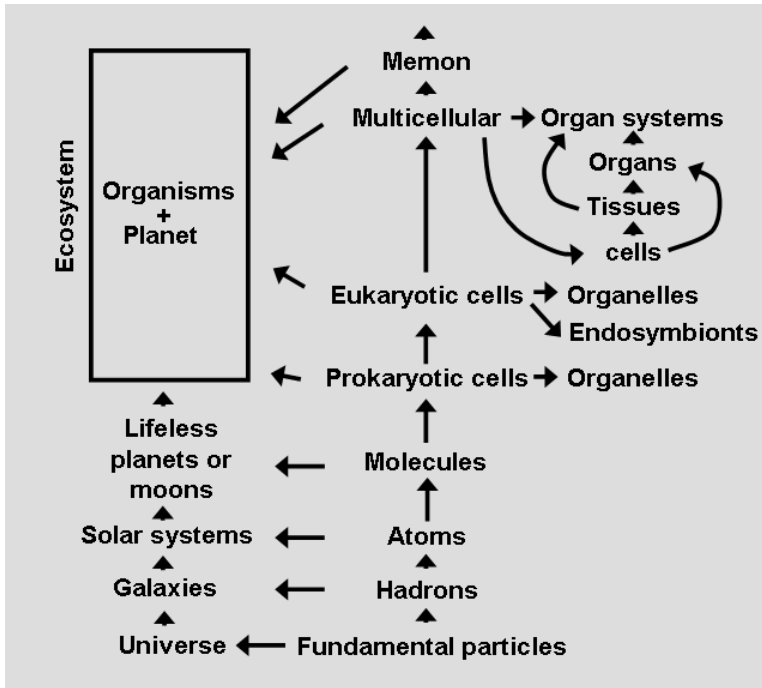


Figure 4. Ranking of systems that accounts for three dimensions for ecological hierarchy

Towards a strict ranking

The particle hierarchy in the central column of Figure 4 forms the core of the theory discussed in this thesis. In this hierarchy, every step results from a self-organisation process. This self-organisation automatically causes a new cyclic process (a functional aspect) and a new circular shape (a structural aspect). A concept generally used in system science to indicate cyclic interactions is 'closure'. As the result of the functional and structural closure, the interactions form a new unit.

The theory in this thesis now focuses on situations in nature in which a next particle type and associated closures are realised as the first possibility nature allows. This logic was named the principle of 'first-next possible closure'. The use of first-next possible closure allows the creation of a strict hierarchy that is based on self-organisation steps, a property that is fundamental to the theory presented in this thesis. Whereas most theories apply a rather loose and intuitive classification of stages or levels of complexity, our objective is to develop a systematic version that explains why the next level was both possible and inevitable.

The definition of first-next possible closure allowed the identification of all systems in the universe that comply with this demand. These systems form a highly special and strictly hierarchical subset of all the systems in the universe. This subset includes the quarks and hadrons, the atoms, the molecules, the prokaryotic cells, the eukaryotic cells, the multicellulars and the animals. Searching for a logical name for all the systems in this subset, I realised that, due to their closures, these systems can be considered as *individual operational units*. This was the reason why I named them 'operators'. Thus, by first-next possible closure, an operator type at one particular level of complexity transforms to an operator type at the next level.

The introduction of the operator concept can be regarded as a major tool for bringing physics and biology closer by bridging the gap between abiotic and living systems; the operator concept shows that both spheres of existence are ultimately guided by the same organising principles such that, at a high level of abstraction, both physics and biology are studying the same kind of systems: the operators. The word operator has various meanings in other contexts, such as mathematics and the operation of machinery. In the context of the theory proposed in this thesis, the concept always refers to the system types that are related to each other by first-next possible closures.

The dark line in Figure 5 shows how subsequent first-next possible closures connect all the operators. This hierarchical organisation has been named the "operator hierarchy" and represents an important result of the present study. In comparison to other approaches to hierarchy in nature, the operator hierarchy possesses the special property that it is strict; that is, it is impossible to delete a single operator from the scheme or add one to it without destroying the scheme's entire logic. Another aspect that is unique to the operator hierarchy is that it introduces a new name for animals: memons. This adaptation is needed to distinguish between the organisms that do and the organisms that do not show neural network structure. Accordingly, a human being is an organism and a memon, but a plant is only an organism. The concept of the memon is also more practical than the concept of an animal when it comes to classifying future intelligent technical beings.

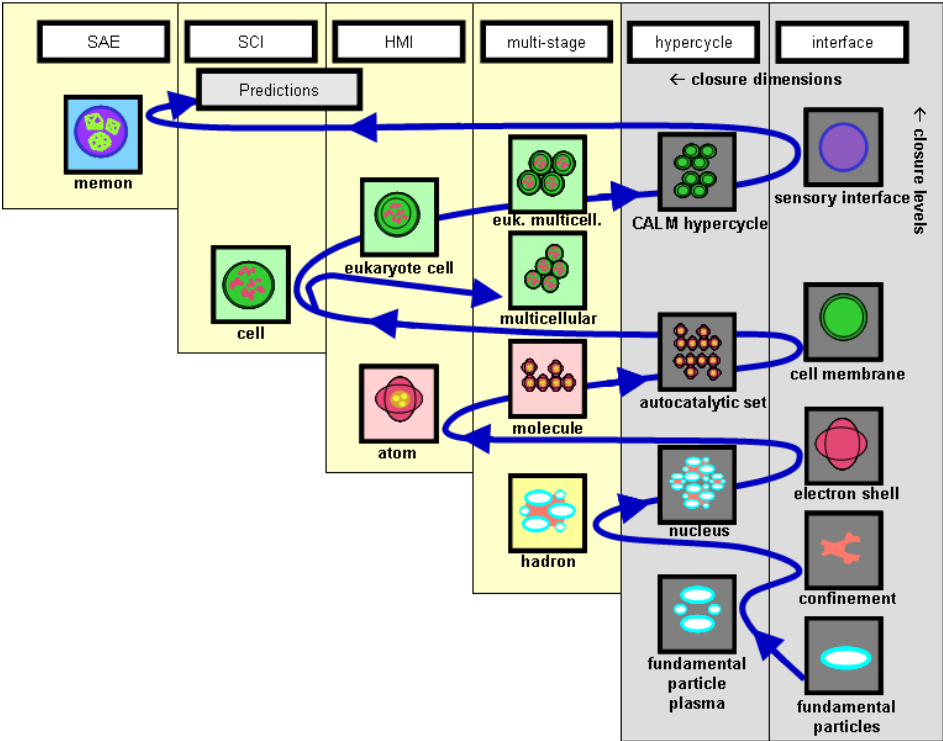


Figure 5. The evolution of the operators

The dark line shows the historical pathway by which first-next possible closures created the operators. The gray columns indicate systems resulting from first-next possible closure that are not operators. Explanation of abbreviations: SAE ('Structural Auto Evolution') = the property of an operator to autonomously evolve the structure that carries its information. SCI ('Structural Copying of Information') = the property of an operator to autonomously copy its information (genes, learned knowledge) by simply copying part of its structure. HMI (Hypercycle Mediating interface) = a closure creates an interface that mediates the functioning of the hypercycle. Multi-state = operator showing closure between multiple units of exactly one lower closure level. Hypercycle = closure based on emergent, second-order recurrent interactions. Interface = closure creating an emergent limit to an operator. CALM (Categorizing And Learning Module) = a minimum neural memory.

A new natural order that connects scientific disciplines

The goal of this thesis was to systematically explore unifying principles in science that may allow us to connect various scientific domains such as particle physics and evolution. How does the operator hierarchy contribute to this goal?

As an answer to this question, I have summarised the ways in which the operator hierarchy can be applied to various scientific integration topics:

- The operator hierarchy allows ecological hierarchies to be improved by taking into account the following three dimensions for hierarchy: (1) the hierarchy of the operators, (2) the internal organisation of the operators, and (3) the interactions between operators, giving rise to hierarchy in large systems of interacting operators. Uncontrolled mixing of these three aspects disturbs the logic of any hierarchical ranking.
- Conventional definitions of Darwinian evolution are based on heredity, reproductive diversification, and selection. The operator hierarchy now adds levels of complexity to this list of aspects that are relevant to evolution.
- The operator hierarchy offers a periodic table to which other periodic tables can be linked, such as the periodic table of the elements, the standard model, the eightfold way of the hadrons, and the tree of life.
- The operator theory offers a completely new viewpoint for defining life, the organism and death. Life was defined as matter with the operator structure and an equal or even higher complexity than that of the cellular operator. In a strict sense, an organism can be defined as an operator that agrees with the definition of life. Death occurs when irreversible deterioration causes the loss of the level of closure that is typical for the organism.
- If the operator hypothesis correctly predicts that the possibilities for constructing all operators are guided by closure as a fundamental rule for organising matter, the operator hierarchy would be valid in the entire universe. If this is the case, extraterrestrial life will show the same fundamental closures as life on Earth. Of course, the actual size, shape, physiology, molecular construction, colour, etc. may differ.
- First-next possible closures may form and disintegrate. Given the existence of a long sequence of operators, closure must represent a thermodynamically favourable situation. Consequently, the arrow of complexity moves towards complex operators, unless ambient conditions block the process.
- The operator hierarchy offers a framework that, possibly for the first time in scientific history, allows essential construction-properties of future operators to be predicted. The operator theory predicts that technical memons are the next step in operator evolution. The use of the operator hierarchy gives much more weight to the resulting predictions than can be given to extrapolations based on existing trends in technological development. In addition, the operator hierarchy opens up possibilities to look much further ahead.
- The operator hierarchy offers a structured scheme for discussing the things between heaven and earth that are known to science and to speculate about the possibilities for things still undiscovered.
- Because a memic architecture represents just another operator in the sequence of the operator hierarchy, there are no scientific reasons for considering human beings as some kind of final stage in evolution or as a crown on a reputed creation.

- The operator theory indicates that it may be practical to introduce a novel interpretation of the meme concept. A meme currently stands for a cultural replicator without any structural parallel with the gene, which stands for a molecular replicator. By creating a meme concept that refers to the neural network structure of a memon, the analogy can be improved. A structural meme would take the form of a code-string coding for the number of neurons in a network, the connections of these neurons and the inhibitory or excitatory strengths of the connections. The new meme could actually code for all the knowledge in a given neural network and would reintroduce Lamarckian inheritance.

The operator theory: a new approach?

The operator theory is an innovative approach, but it is not an entirely new concept. Around 1950, the French palaeontologist, philosopher and Jesuit Pierre Teilhard de Chardin was working in the same direction. His attempt aimed at integrating system theory with Christianity. In his work Teilhard de Chardin distinguished the systems that are 'formed' and 'centered' from all the other systems that do not show these properties. He was convinced that only the formed and centred systems were relevant in creating an evolutionary hierarchy. Teilhard de Chardin's work is not generally accepted in the scientific community. One reason for this may be that several important organising principles that could have supported his approach still had yet to be discovered. Another reason may be Teilhard de Chardin's prediction of the unification of man and God, called Point Omega, as a final level in the hierarchy.

The concepts of structural and functional closure and the use of operators in the present approach show connections with the work of Teilhard de Chardin. The operator theory extends the approach, however, with modern self-organisation theory, with the concept of first-next possible closure and with the recognition of the secondary structure of the operator hierarchy. In contrast to Teilhard de Chardin's work, the operator hierarchy strongly suggests that the evolution of the operators has no end.

A detailed approach describing the evolution of particles and organisms comparable to the operator hierarchy was not found in the literature. Because this viewpoint is new, many of its aspects are still open to further research. I consider it especially interesting and rewarding to increase our understanding of the rules defining the operator hierarchy's internal structure (Fig.5). Now that the operator hierarchy offers a fundament for understanding the evolution of the operators, the next challenging goal is to predict future operators as accurately and as far ahead as possible.

Samenvatting

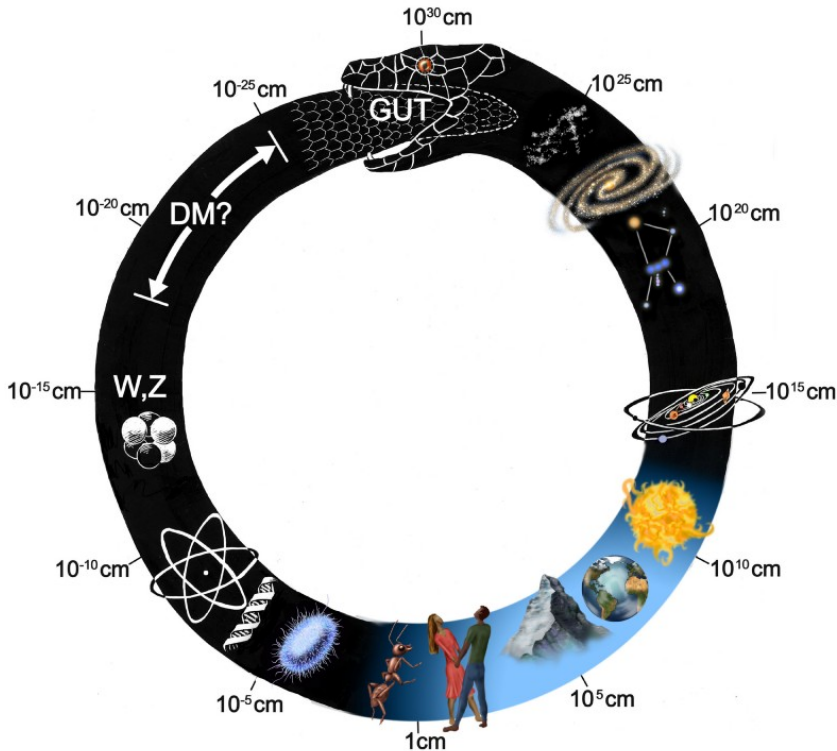
*“When I’m working on a problem, I never think about beauty.
I think only how to solve the problem.
But when I have finished, if the solution is not beautiful, I know it is wrong.”*
(Buckminster Fuller)

De laatste dertig jaar zijn meer ontdekkingen gedaan dan in alle eeuwen daarvoor. Deze kennisexplosie heeft geleid tot een crisis in de wetenschap. De afstand tussen verschillende disciplines neemt toe en het onderlinge begrip neemt af omdat wetenschappers zich steeds meer zijn gaan specialiseren. Dit proefschrift biedt een nieuw raamwerk dat samenhang creëert tussen wetenschapsdisciplines en zo deze kenniscrisis te lijf kan gaan.

Door de eeuwen heen zijn verschillende theorieën ontwikkeld die zich richten op het ordenen van fenomenen in de ons omringende wereld. Een voorbeeld uit de verre oudheid is de Ouroboros, de slang die zijn eigen staart verzwelgt. Deze slang was het symbool van de continuïteit en de eeuwigheid van het leven en de wereld. Later, in zijn *Scala Naturae* stelde de Griekse filosoof Aristoteles een indeling voor van de natuur op basis van afnemende perfectie, namelijk de heilige en bovennatuurlijke zaken, mensen, dieren, planten en levenloze dingen. Deze theorie speelt ook een rol in het middeleeuwse christendom en is terug te vinden in het werk van bekende filosofen uit de gouden eeuw, zoals Descartes, Spinoza en Leibniz.

Een recent voorbeeld van een ordening van de natuur is Big History. Big History streeft naar een omvattende weergave van de ontwikkelingen in het heelal sinds het allereerste begin. Het gaat ervan uit dat het vroege heelal zo klein was als een fundamenteel deeltje en dat het tot zijn huidige grootte is uitgedijd na een explosieve beginfase: de oerknal. Zowel de moderne deeltjesfysica als de kosmologie leveren onderbouwing aan de oerknaltheorie.

Soms wordt aan oude symbolen van ordening een nieuwe inhoud gegeven, bijvoorbeeld aan de Ouroboros in Figuur 1. Hier is aan de ene kant weergegeven hoe de wetenschap inzicht heeft gekregen in steeds kleinere systemen (van dieren, naar cellen, naar moleculen, atomen en quarks) terwijl ze aan de andere kant steeds grotere systemen is gaan onderzoeken (van ecosystemen, via planeten naar sterrenstelsels en uiteindelijk het hele heelal). Deze manier van presentatie verbindt enkele bijzondere eigenschappen van het heelal in zijn geheel, zoals de reststraling van de oerknal en de uitdijning in alle richtingen, met de begintoestand van een mini-heelal, die de oorsprong was van deze eigenschappen. Hierdoor lijkt het of het onderzoek naar de kosmische ordening in zijn eigen staart bijt zoals bij de Ouroboros.



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Figuur 1: Historische uitbreiding van de reikwijdte van wetenschapsvelden in de richting van steeds kleinere en steeds grotere systemen. GUT = grote unificerende theorie, DM = donkere materie, Z en W staan voor twee fundamentele deeltjes die verantwoordelijk zijn voor de zwakke kernkracht, cm = centimeter.

Darwin als startpunt

Ondanks al deze pogingen tot ordening is het nog niet gelukt om een algemeen geaccepteerd raamwerk te ontwikkelen dat alle wetenschappelijke disciplines met elkaar verbindt. Dit wordt vooral in de systeemkunde en de filosofie als een gemis ervaren. Dit proefschrift beschrijft een nieuw ordenend principe met als doel daarmee bruggen te kunnen bouwen tussen de verschillende wetenschapsvelden.

Bij het realiseren van dit doel is de evolutietheorie van Darwin als startpunt genomen. Darwin stelt dat de natuur selecteert op nakomelingen die zijn aangepast aan hun omgeving. Een witte vlinder die leeft in een omgeving met

veel donkere rotsen, is slecht aangepast en vogels zullen hem snel herkennen. De witte vlinder wordt eerder opgegeten dan zijn donkere soortgenoten. Op deze wijze selecteert een donkere omgeving op donkere vlinders. Deze zullen vervolgens via hun genen de donkere kleur doorgeven aan hun jongen en generatie na generatie zal het percentage donkere individuen toenemen. Dit voorbeeld laat zien dat de evolutie gebruik maakt van twee processen. Eerst produceren ouders nakomelingen met een unieke mix van overerfbare eigenschappen en vervolgens selecteert de omgeving in het nadeel van de slechtst presterende individuen.

Vlinders en andere organismen zijn niet de enige zaken die evolueren. Ook deeltjes evolueren. Natuurlijk is er bij deeltjes geen sprake van erfelijke variatie. Maar als deeltjes samensmelten en soms weer opsplitsen zijn niet alle ontstane deeltjes gelijk aan de oorspronkelijke deeltjes. Er ontstaan nieuwe varianten. En ook deeltjes staan bloot aan selectie. Bijvoorbeeld in de hete gassen van een ster worden voortdurend verschillende atoomkernen geproduceerd, terwijl slechts sommige typen atoomkernen stabiel zijn in dit hete milieu. Ook hier is sprake van evolutie, maar hierbij is de variatie in gevormde deeltjes het resultaat van *productie* en niet van *reproductie* zoals bij de vlinders.

Deze twee vormen van evolutie hebben op verschillende momenten hun intrede gedaan in het heelal. Eerst waren er alleen fysische deeltjes, zoals atomen en moleculen en was productieve evolutie de enige mogelijkheid. Pas veel later werd reproductieve evolutie mogelijk, namelijk nadat organismen met erfelijke eigenschappen waren ontstaan.

Het verschil tussen evolutie op basis van productie en reproductie valt samen met de scheiding tussen de fysica en de biologie. Om deze kloof te dichten, gaat dit proefschrift uit van een algemene definitie van evolutie die de productie van variatie combineert met selectie. De productie van variatie is breed toepasbaar en kan opeenvolgend het resultaat zijn van chemische productie, van biologische reproductie en zelfs, in de toekomst, van technische constructie van nakomelingen. Het begrip selectie is eveneens bruikbaar in zowel de fysica als in de biologie.

Niveaus in complexiteit

Het verschil tussen productieve en reproductieve evolutie is niet de enige hinderpaal die in de weg staat bij integratie van fysische en biologische wetenschapsvelden. Er is nog een barrière. In de fysica heeft men een helder beeld van niveaus van complexiteit, zoals kerndeeltjes, atomen en moleculen. Voor het ontstaan van deze niveaus denkt men gewoonlijk niet aan een evolutieproces. In de biologie is de evolutietheorie van Darwin algemeen

geaccepteerd, maar deze besteedt echter geen aandacht aan de complexiteit van organismen.

Darwin kende zeer zeker de verschillen tussen bacteriën, protozoën, meercelligen zoals planten en schimmels, en dieren. Maar hij had de verschillen in complexiteit tussen deze groepen niet nodig om het mechanisme van 'struggle for life' en 'survival of the fittest' te bedenken. Diepgaande genetische experimenten om de evolutietheorie van Darwin te onderbouwen hebben evenmin bijgedragen aan een beter inzicht in niveaus van structurele complexiteit.

Dit nu blijkt een tekortkoming van Darwin's theorie. De evolutietheorie kan namelijk in zijn huidige vorm geen antwoord geven op de simpele vraag "Kunnen we de volgende stap in de evolutie voorspellen?" Ook andere vragen zoals: "Zijn in de evolutie eukaryote cellen de enige logische opvolgers van bacteriën, of zijn er andere mogelijkheden?" kunnen niet worden beantwoord. Voor het oplossen van dergelijke fundamentele problemen is een theorie nodig die inzicht geeft in het ontstaan van verschillende niveaus van organisatie in de natuur.

Dimensies voor hiërarchie

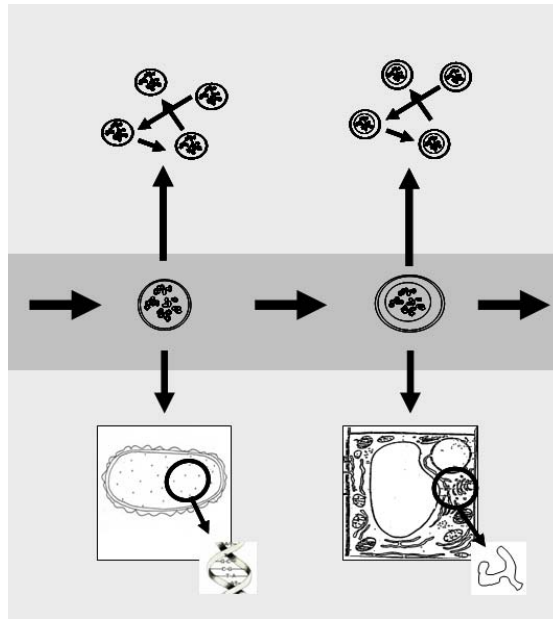
Het ontstaan van organisatieniveaus wordt vaak weergegeven als een hiërarchische volgorde van systemen. De literatuur geeft hiervan talrijke voorbeelden. De gepresenteerde opeenvolgingen van systemen zijn op het eerste gezicht heel logisch, zoals atoom, molecuul, organel, cel, weefsel, orgaan, organisme, populatie, gemeenschap, ecosysteem, planeet, zonnestelsel, sterrenstelsel, heelal (figuur 2). Een dergelijke benadering van de hiërarchie in de natuur heeft breed opgang gedaan in de exacte wetenschappen. Echter, bij nadere bestudering blijkt deze hiërarchie niet consequent.

In Figuur 3 wordt een nieuwe benadering geïntroduceerd voor het analyseren van hiërarchie in de natuur op basis van drie fundamentele richtingen. Ten eerste bestaat er een hiërarchie die loopt van individuele deeltjes naar groepen van deeltjes. Ten tweede bestaat er een hiërarchie die loopt van fysische deeltjes naar organismen. Ten derde bestaat er een hiërarchie die de interne organisatie van de deeltjes ordent. Dit proefschrift stelt de term dimensies voor voor deze drie manieren van ordening.

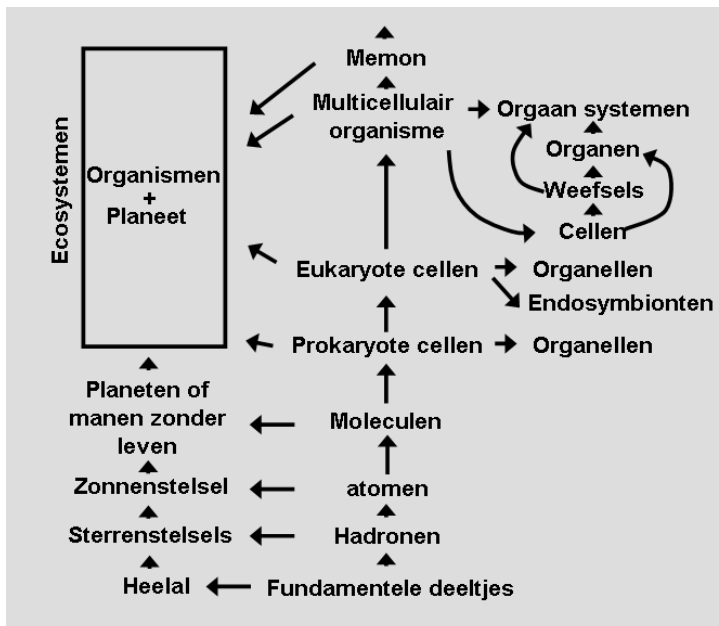


Figuur 2. Een typische weergave van de veel gebruikte ordening van complexiteit die meestal wordt aangeduid als de ecologische hiërarchie.

In het voorbeeld van Figuur 3 staan alleen bacteriën en eukaryote cellen, maar het is niet moeilijk om dit schema uit te breiden in de richting van fysische deeltjes en in de richting van meer complexe organismen. Het voorbeeld in figuur 3 laat ook zien dat het na de keuze voor het volgen van hiërarchie in een bepaalde dimensie niet mogelijk is om naar hiërarchie in een andere dimensie over te stappen. Deze manier van denken is gebruikt om Fig. 2 zo aan te passen dat de nieuwe ordening wel rekening houdt met hiërarchische dimensies. Het resultaat staat in Fig. 4. De linker kolom laat zien dat in het heelal steeds deelgebieden ontstaan met toenemende differentiatie, te beginnen met sterrenstelsels, gevolgd door zonnestelsels, zonnen, planeten en ecosystemen. In de rechter kolom is voor enkele deeltjes aangegeven hoe de complexiteit toeneemt door interne differentiatie. De middelste kolom toont dat samenwerking of interne differentiatie de basis kan vormen voor een toename van complexiteit van fysische deeltjes tot complexe organismen.



Figuur 3. Drie fundamentele richtingen voor hiërarchie in de natuur. Pijlen naar boven wijzen van organismen naar toenemende complexiteit in ecosystemen. Pijlen naar rechts wijzen in de richting van organismen met toenemende complexiteit. Pijlen naar beneden wijzen in de richting van hiërarchie in de interne organisatie van organismen.



Figuur 4 Een herschikking van de systemen in een ecologische hiërarchie waarbij is uitgegaan van drie dimensies.

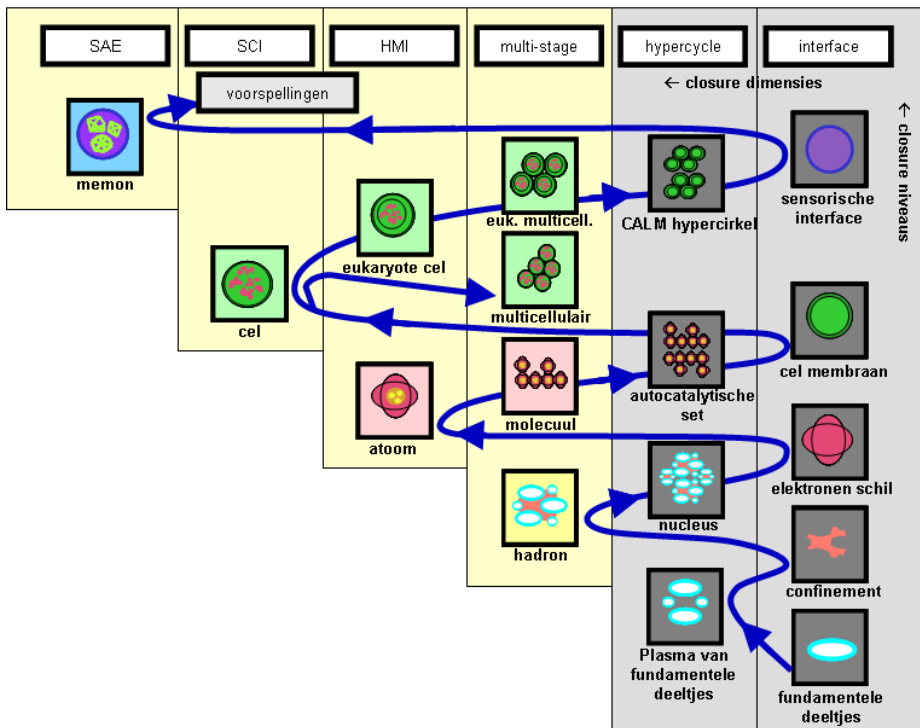


Figure 5. De evolutie van de operatoren. De donkere lijn volgt het historische pad waarlangs door middel van first-next possible closures de opeenvolgende operatoren zijn gevormd. De systemen in de grijze kolommen zijn wel het gevolg van eerstvolgende mogelijke closure, maar zijn strikt genomen geen operatoren omdat ze alleen een cyclisch proces of een cyclische structuur (de 'interface') vertegenwoordigen en niet een combinatie van beide.

Verklaring van afkortingen Fig. 5:

SAE (Structural Auto Evolution) - de eigenschap dat een operator zelfstandig het deel van zijn structuur dat de informatie bevat, kan evolueren

SCI (Structural Copying of Information) - de eigenschap dat een operator zelfstandig de in zijn hypercyclus vastgelegde informatie kan kopiëren door eenvoudigweg hiervan de structuur te kopiëren. Deze informatie is vastgelegd in de elementen van de katalytische hypercyclus of in de neurale hypercyclus.

Hypercycle - de first-next possible closure die is gebaseerd op cirkels bestaande uit cyclische processen

Interface - een first-next possible closure die een nieuwe ruimtelijke grens creëert.

CALM (Categorizing And Learning Module) - een minimale eenheid voor neurale geheugen.

HMI (Hypercycle Mediating interface) - een first-next possible closure veroorzaakt een interface die selectief interacties afschermt tussen de hypercyclus en de buitenwereld.

Multi-state - een operator gebaseerd op structurele en functionele first-next possible closure op basis van operatoren van een closure-niveau lager.

Een strikte rangorde

De hiërarchie van deeltjes in de middelste kolom van Figuur 4 vormt de basis voor de theorie in dit proefschrift. In deze hiërarchie is in iedere volgende stap een zelforganisatieproces te herkennen. Deze zelforganisatie leidt automatisch tot een nieuw cyclisch proces en een nieuwe cyclische vorm. Door het sluiten van deze cirkels ontstaat een nieuwe eenheid. Een kringvorm van dergelijke interacties wordt in de systeemkunde algemeen aangeduid met het begrip 'closure', wat daarom ook in de hier ontwikkelde theorie is gebruikt. Closure betekent in het Engels afronding of geslotenheid.

De theorie in dit proefschrift is gebaseerd op situaties in de natuur waar een nieuw type deeltje en daaraan verbonden volgende closure automatisch wordt gerealiseerd als de eerstvolgende mogelijkheid die de natuur toelaat. Deze opeenvolging van twee deeltjes wordt hier aangeduid als 'first-next possible closure' (eerstvolgende mogelijke closure). Het gebruik van dit begrip maakt een strikte ordening mogelijk en is daarom onmisbaar voor de hier uiteengezette theorie. Het kijken naar de combinatie van gesloten processen en gesloten vormen in combinatie met het principe van first-next possible closure leidt er toe dat slechts één bijzondere groep systemen in het heelal aan dit principe voldoet. Al deze systemen blijken via de eis van first-next possible closure met elkaar te zijn verbonden in een grote afstammingsboom en vormen daarmee een strikt hiërarchische deelverzameling van alle systemen in het heelal. Deze deelverzameling omvat de fundamentele deeltjes, de hadronen, de atomen, de moleculen, de prokaryote cellen, de eukaryote cellen, de pro- en eukaryote meercelligen en de dieren.

Ieder element van deze verzameling is op basis van zijn closures van de omgeving te onderscheiden als een individuele operationele eenheid. Dit is de reden dat de verzameling van alle elementen in de hiërarchie in dit proefschrift de naam 'operatoren' heeft gekregen.

De introductie van het concept operator biedt een belangrijke bijdrage aan het samenbrengen van verschillende natuurwetenschapsgebieden. Het blijkt namelijk dat in al deze wetenschapsgebieden een zelfde type bouwsteen, deze zogenaamde operator, de basis vormt van de onderzochte systemen. Hiermee krijgt het begrip operator een extra betekenis naast bestaande betekenissen in het Engels, zoals een wiskundige bewerking of iemand die een apparaat bedient, bijvoorbeeld een telefonist(e).

In Figuur 5 is met een donkere lijn de familiestamboom van de opeenvolgende operatoren aangegeven. Deze hiërarchische ordening van alle operatoren is de

‘operatorhiërarchie’ genoemd en is het resultaat van deze studie. De operatorhiërarchie heeft, in tegenstelling tot alle eerder ontwikkelde hiërarchische benaderingen van de natuur, de bijzondere eigenschap dat het niet mogelijk is om één operator aan de hiërarchie toe te voegen of er uit te breken zonder dat de hele structuur uiteen valt. Wat ook nieuw is aan de operatorhiërarchie is dat de groep dieren een nieuwe naam heeft gekregen, namelijk ‘memon’ (meervoud memons). Deze aanpassing maakt een helder onderscheid mogelijk tussen organismen zonder en organismen met neuraal netwerk. Zo is de mens bijvoorbeeld een organisme en een memon, terwijl een plant alleen een organisme is. Bovendien is het woord memon in de toekomst ook te gebruiken voor levende wezens die zijn gebaseerd op technische neurale netwerken (de robot-achtige systemen of ook wel ‘technische memons’).

Nieuwe ordening verenigt disciplines

Het doel van dit proefschrift is om ordenende principes in de natuurwetenschappen te vinden en deze toe te passen bij het bouwen van bruggen tussen de disciplines. Hier volgt een beschrijving van de fundamentele bijdragen die de operatortheorie kan leveren aan een brede integratie van de exacte wetenschappen.

- De operatortheorie maakt het mogelijk om bestaande ecologische hiërarchieën te verbeteren door rekening te houden met drie aspecten: de hiërarchie van de operatoren, de interne organisatie van operatoren en interacties tussen operatoren (zie Fig. 4). Het gemengd toepassen van deze drie aspecten in hiërarchische benaderingen verstoort de logica daarvan.
- Gangbare definities van Darwiniaanse evolutie zijn sterk gefocused op erfelijkheid, reproductieve diversificatie en selectie. De operatortheorie maakt het mogelijk om de complexiteit van organismen toe te voegen aan de evolutietheorie.
- De operatortheorie biedt een periodiek systeem voor de koppeling van alle andere periodieke systemen (voor zover deze betrekking hebben op operatoren).
- De operatortheorie biedt een nieuwe context voor het definiëren van leven. Leven kan worden gedefinieerd als materie met de structuur van een operator en met de minimale complexiteit van de (prokaryote) cellulaire operator. Als consequentie hiervan zal ook de definitie van een organisme als volgt moeten worden aangepast. Een organisme is een operator die voldoet aan de definitie van leven. Sterfte treedt op als een irreversibel vervalproces dat de organisatie van een organisme aantast, leidt tot het verlies van de voor dit organisme kenmerkende meest complexe first-next possible closure.
- Als mag worden aangenomen dat het principe van first-next possible closure algemene geldigheid heeft in heel het heelal, dan moeten buitenaardse

levensvormen op dezelfde first-next possible closures zijn gebaseerd als het leven op aarde.

- De operatorhiërarchie laat zien dat first-next possible closures kunnen worden gevormd en ook weer uiteen kunnen vallen. De lange keten van operatoren toont daarnaast aan dat het optreden van zelf-organisatie in de vorm van first-next possible closure in thermodynamisch opzicht een gunstige toestand moet zijn. Dit betekent dat de ontwikkelingen daarom altijd voort zullen snellen in de richting van de volgende operator, tenzij lokale omstandigheden het zelforganizatatieproces niet faciliteren.
- De operatorhiërarchie biedt een nieuw raamwerk dat gerichte voorspellingen mogelijk maakt van essentiële constructie-eigenschappen van toekomstige operatoren. De operatortheorie voorspelt dat memons gebaseerd op technische neurale netwerken de volgende stap vormen in de evolutie van de operatoren. Onderbouwing door middel van de operatorhiërarchie geeft aan een voorspelling een veel zwaarder gewicht dan aan extrapolaties gebaseerd op bestaande trends in de ontwikkeling van robots. Bovendien kan op basis van de operatorhiërarchie veel verder vooruit worden gekeken.
- De operatorhiërarchie biedt een raamwerk om op een gestructureerde manier de discussie te voeren of er meer is tussen hemel en aarde dan waar de wetenschap zicht op heeft door aan te geven waar onbekende zaken zich met grote waarschijnlijkheid niet bevinden.
- Omdat de memon gewoon een willekeurige operator in de operatorhiërarchie is, zijn er geen wetenschappelijke redenen om mensen te beschouwen als het eindpunt van de evolutie of als een kroon op een vermoede schepping.
- De operatortheorie laat zien, dat het wenselijk is om het begrip 'meem' voor een idee in een informatiedrager zoals de hersenen (de "meme" senu Dawkins) en daaraan verwante culturele replicatoren (melodieën, text, etc.) aan te vullen met een extra interpretatie die wél een structurele parallel vertoont met het begrip gen (Engels: gene). Dit kan door de meem ook te laten verwijzen naar de structuur van het neurale netwerk van een memon. Een meem krijgt dan de vorm van een serie codes die weergeeft welke neuronen worden verbonden, welke verbindingen er bestaan tussen de neuronen en welke sterkte de verbindingen hebben. In principe kan met een dergelijke meem en de bijbehorende interface alle kennis van een memon worden overgebracht op eventuele nakomelingen.

De volgende uitdaging

De operatorhiërarchie is een sterk vernieuwende theorie, maar desondanks niet een volledig nieuwe benadering. De Franse paleontoloog, filosoof en Jezuiet Pierre Teilhard de Chardin heeft halverwege de vorige eeuw een serieuze poging ondernomen in dezelfde richting. Hij was op zoek naar een methode om het christelijk geloof in overeenstemming te brengen met de evolutietheorie. In

zijn benadering maakte hij onderscheid tussen enerzijds systemen die hij 'gevormd' en 'gecentreerd' noemde en anderzijds alle systemen zonder deze eigenschappen. De aanduidingen 'gevormd' en 'gecentreerd' vertonen veel gelijkenis met de structurele en functionele closures die bepalend zijn voor operatoren. Teilhard de Chardin was er sterk van overtuigd dat alleen het ordenen van gevormde en gecentreerde systemen inzicht in de evolutie kon opleveren. Hoe bewonderenswaardig ook, de theorie van Teilhard de Chardin was te weinig onderbouwd om wetenschappelijk geaccepteerd te worden. Bovendien werd zijn benadering door onderzoekers gewantrouwd omdat zijn hiërarchie eindigde met de eenwording van de mensheid met god in het zogenaamde punt omega. De operator theorie gebruikt kernen uit het gedachtegoed van Teilhard de Chardin en breidt deze uit met moderne inzichten en een gedetailleerde systeemkundige onderbouwing. Bovendien maakt de operatortheorie aannemelijk dat de evolutie van operatoren juist geen vast eindpunt heeft.

Omdat de operatortheorie nieuw is, zijn er nog veel uitdagingen om deze theorie verder te verfijnen. Eerst en voor alles is het noodzakelijk om de regels die de basis vormen voor de kolommen in Figuur 5 beter te leren begrijpen. Een beter begrip van deze regels zal het namelijk mogelijk maken om voorspellingen over de volgende stadia in de evolutie aan te scherpen en op basis hiervan nauwkeuriger uitspraken te doen over toekomstige operatoren. Dit zal wetenschappers en filosofen nieuwe mogelijkheden bieden om op verkenning te gaan in een domein waarvan men tot voor kort dacht dat het ontoegankelijk was voor een natuurwetenschappelijke benadering: de toekomst van de evolutie.

History and acknowledgements

“We rarely forget that which has made a deep impression on our minds.”
(Tryon Edwards)

The evolution of an idea

The operator hierarchy started developing while I was working as a postdoc at the Vrije Universiteit from September 1992 to August 1993 after my PhD in ecotoxicology. The project was initiated by the “Netherlands Integrated Soil Research Programme” and involved writing an integration study of 21 PhD projects on soil pollution. The project started with writing fact sheets for all 21 projects. Based on this and other information, a proposal for theoretic integration entitled “Ecotoxicology across the levels of ecological organisation” was sent to the advisory committee in mid-1993. This draft already hinted at using dimensions as an organising principle, stating that *“all stress on ecological systems is a combination of the effects on the creation and destruction of ‘matter’ and ‘information’ in systems”*. Around this time Bas Kooijman allowed me to read a first draft of his book “Dynamic energy budgets in biological systems”. Near the end of 1993, the project’s advisory committee received a second draft report. Later that year I read Kauffman’s book “The Origins of Order”, and the basic idea for the operator hierarchy was born during the winter of 1993-1994. Developing the operator hierarchy required studying many new things ranging from quarks to neural networks, which took a while. Around this time Bart Happel introduced me to the astonishing world of technical, modular, recurrent neural networks and the fractal inner space they show. Figure 1 shows one of the first drawings of the operator hierarchy and illustrates just how much work had yet to be done.

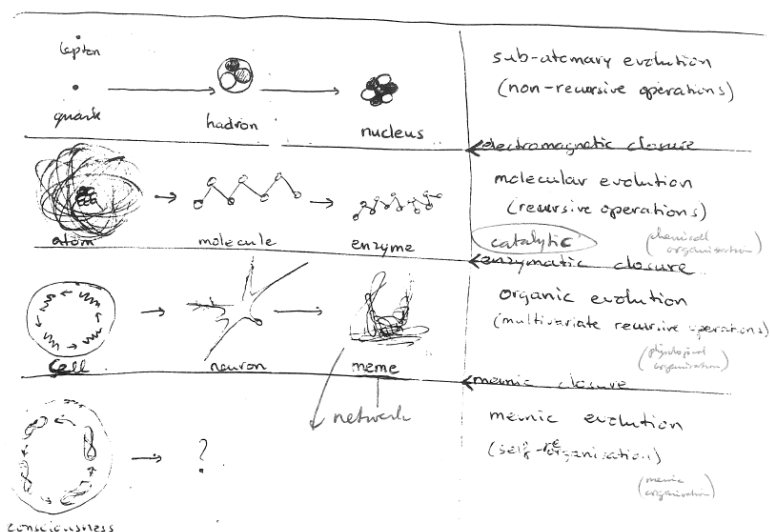


Figure 1. This figure illustrates one of the first drawings of the operator hierarchy (spring 1994). Note that every level shows the same number of elements.

In August 1994, a final report on the integration project was sent to the advisory committee with the title *"Application of a hierarchical concept of ecosystem organisation in ecotoxicology"*. The report included a part about the dynamic balance of toxicants in organisms and a part about targets, buffering and plasticity and the processes of assessment, diagnosis and prognosis. The advisory committee responded with disappointment because they had hoped for indications of "What is an acceptable toxin level?". Instead, the report dealt with: When, Why, How, Related to what, and even So What? The report introduced the basic ideas of the 'operator' and 'closure': *"Using closure of operations as a borderline between two hierarchical levels in the information evolution, the organisation shows four levels: the sub-atomary level, the level of atoms and molecules, the organic level, and the level of the consciousness"*. Importantly, it was concluded that *"... the repeating of an evolutionary pattern within the hierarchical levels appeared to be so eminent, that we have given the resulting hierarchy a central position in this study"*. It was a great help to discuss the operator hierarchy with Cajo ter Braak in January 1995. His comments included a list of 92 suggestions and questions in the manuscript's margins. By this time, the operator hierarchy had evolved into the scheme in Figure 2.

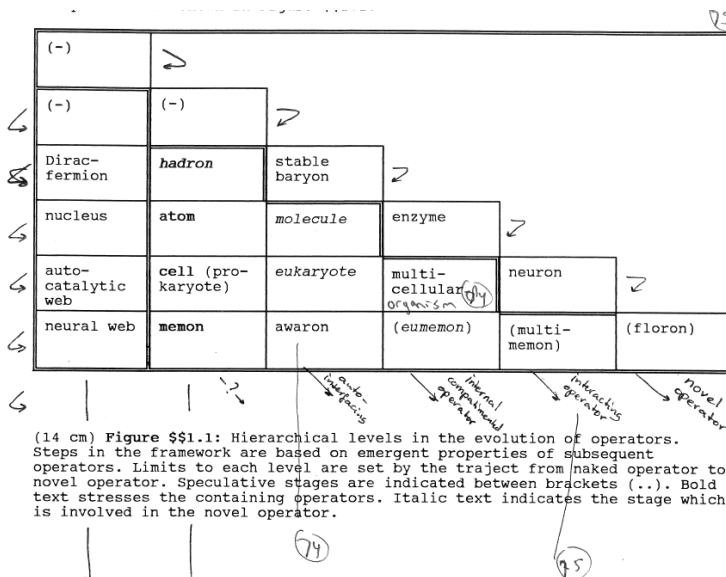


Figure 2. The operator hierarchy as it looked in January 1995. The numbers in circles refer to Cajo ter Braak's remarks. Note that the scheme now assumes a variable number of steps per level, but that complexity increase is still linear within levels.

In 1996, while working at NERI (Denmark,) I submitted the Lego-bricks paper. After two years it was sent back unreviewed. Klaus Skovbo Jensen then introduced me to Eigen's hypercycles. In 1997, I was inspired by Lars Witting who kindly gave me a draft of his book "A General Theory of Evolution". In 1998, Hans Løkke gave me the green light for three months of writing time to restyle the ecotoxicology manuscript. But after these months of hard work -- during which I stayed in a NERI guesthouse -- it appeared that I had again underestimated the complexity and quantity of the work. In 1999, the paper about the Lego bricks was published in *World Futures*, the journal of general evolution. And later that year, a new job came along at Alterra as the head of the functional biodiversity team.

During the last months of 2001, Diedel Kornet introduced me to her idea of "slots in state space" and gave me an interesting scheme of the natural levels including elementary particles, atoms, molecules, free-living cells, multicellular organisms and interbreeding communities. This scheme also contained the principle of internal organisation. In 2001, the *Acta Biotheoretica* paper was published. The prediction of future operators then awoke the media's warm interest because of the question: "Will robots dominate humanity?" This resulted in a range of interviews for local and national newspapers and for radio and television. Suddenly, living in two worlds proved too complex. I decided to create more time for the operator hierarchy. This proved a fruitful strategy. The *Analysing Hierarchy* paper was published in *Biological Reviews* in 2008. In 2009, the 'definition of life paper' was accepted by *Foundations of Science* (to be published in 2010). In June 2009, Rolf Hoekstra invited me to a meeting in his office with Eörs Szathmáry. After a short presentation of the operator hierarchy's major ideas, Eörs made two very valuable comments. As far as he knew, the idea of first-next possible closure was a unique approach. He also indicated that using only interactions as a basis for first-next possible closure in the 'three dimensions picture' was presumably too restrictive. This was a wise remark. I immediately adapted the figure. Based on the accepted publications, I considered the possibility of a PhD. When speaking to Nico van Straalen about this plan, he advised me to contact Hub Zwart of the Radboud University Nijmegen. This resulted in a very pleasant contact and two month of writing time to finalise the project.

"Without friends no one would choose to live, though he had all other goods."
(Aristotle)

At the National Environmental Research Institute in Silkeborg (NERI, Denmark), numerous people have supported the development of the operator hierarchy and have become dear friends, notably Hans Løkke, who arranged three months of writing time, Jorgen and Lisa Axelsen, Christian and Mette Kjaer, Christian Damgaard and Inger Møller.

At Alterra I am most grateful to Henk Siepel for many years of practical and theoretical support of the project. Jeff Baldwin critically read the concept text of the hypercycle website and Wiert Dijkkamp made it accessible on the internet. Rob Hengeveld helped me organise and submit my book manuscript “The Modular Evolution of Matter”, which, unfortunately, was rejected. Hans Peter Koelewijn offered new insights into genetics and suggested various excellent books with up-to-date theories.

For commenting on various drafts of papers, I thank Henk Siepel, Herbert Prins, Hans Peter Koelewijn, Leen Moraal, Ton Stumpel and Dick Melman. Rolf Hoekstra has been involved in the operator hierarchy project in various ways, most notably in supporting the Analyzing Hierarchy paper and by inviting me for a meeting with Eörs Szathmáry. Clément Vidal and John Smart are thanked for organising the Evo-Devo conference in Paris. I thank Peter Winiwarter, who died all too early, for his friendship, his inspiring website and his plan to include the operator hierarchy in his book. Furthermore, I would like to thank all members of the Blauwe Kamer Koor for their much appreciated and warm friendship, and especially Albert Ballast, Marnix van der Meer, Peter Schippers and Marjolein Kikkert, all of whom contributed to the operator hierarchy through discussions and valuable insights.

I thank Claire Hengeveld for the challenging job of improving the English of the Biological Reviews paper. Liewien Koster contributed by commenting on the definition of life paper. I thank Palmyre Oomen and Ronny Desmet for information about Whitehead. During the preparation of the thesis, Hub Zwart of the Radboud University Nijmegen contributed by arranging two months of writing time, by offering inspiring new points of view and excellent suggestions on the style of the final texts. Peter Griffith's corrections of the English have greatly improved the texts of the unpublished chapters of this thesis. Reena Bakker-Dhaliwal helped improve the English of the ‘stellingen’. Last but not least, I am grateful for the assistance of Desiree Hoonhout at the Vrije Universiteit Amsterdam, Birgit Sørensen at the NERI and Nelja Schöenthal, Suze Landman, Liesbeth Steenhuisen and Leona van Eck at Alterra. Florentine Jagers op Akkerhuis greatly improved the quality of the draft text of the summary, the readability of which was subsequently tested by Ivo Laros and Leen Moraal. The craftsmanship of Henny Michel transformed my plain texts to a nice ‘Alterra Scientific Contribution’, the cover of which was given shape by Martin Jansen.

Of course, this thesis would never have been produced without all the moments of joy shared with family and friends. I would need many more pages to thank everyone who enriched our lives at home, in the Floriade, during Christmas dinners and the Ekocup, at the Koninginnemarkt, during different swampeturene, on Livø, in Gammel Ry and on Westerbakken, in the Gorges du Tarn, in Death Valley, Las Vegas, San Francisco, at meetings and conferences in Warsaw,

Odense, Paris, Winchester and Budapest, during the coffee breaks, during rehearsals and weekends with the BKK, while having our yearly Roghorst barbeque, during the City of Insects festival, in Xanten, while listening to the 'wiew wiew' of stone owls, when counting deer in de Kop van Schouwen, during the World of Music Festival, etc.

Above all, I am grateful to Florentine, Marrit, Stijn and Inge. You have been and still are the best friends I could ever wish for. Thank you for your practical and mental support, for tolerating my periods of absentmindedness and for never giving up teasing me about 'het evolutie gedoe' ('the evolution stuff').

Curriculum vitae

*“We are the accidental result of an unplanned process ...
the fragile result of an enormous concatenation of improbabilities,
not the predictable product of any definite process.”*
(Stephen Jay Gould)

My work involves using system approaches and evolutionary theory to analyse practical problems in biology, ecology and ecotoxicology. My work has contributed to studies concerning the effects of agricultural practices on biodiversity, the modeling of insecticide side-effects, the biodiversity impacts of climate change, invasive species, forest biodiversity, the biodiversity of the soil ecosystem, advisory work in relation to the habitats directive and birds directive, biodiversity monitoring, trait-based ecology, etc. As a general basis for the understanding and analysis of systems, I developed the operator, which is explained in this thesis and on my website hypercycle.nl.

Period	Degree	Locations and topics
1978 - 1986	MSc (Cum Laude)	Wageningen Agricultural University: Entomology, Nematology, Animal physiology
1988 - 1993	PhD	Wageningen Agricultural University: Ecotoxicology (Prof. J.H. Koeman)
1992 - 1993	Post Doc	Vrije Universiteit Amsterdam: Ecotoxicology (Prof. N.M. van Straalen,)
1995 - 1995	Researcher	Centrum voor Landbouw en Milieu
1996 - 1999	Guest scientist	NERI, Silkeborg, Denmark (Dr H. Løkke)
1999 - 2010	Senior scientist	Alterra, Wageningen UR, Nederland (Prof. H. Siepel)
2009	Senior scientist	Radboud University, Nijmegen, (Prof. H. Zwart)

Publications

First author (related to the operator hierarchy)

- Jagers op Akkerhuis G.A.J.M. (2010, in press). Explaining the origin of life is not enough for a definition of life. *Foundations of Science*.
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Glossary

“Accurate definitions improve the precision and communication of science.

Sloppy definitions lead to the development of sloppy theory.

A lack of definitions leads to no science at all.”

(Gerard Jagers op Akkerhuis).

The operator theory represents a new point of view. This implies that a number of new concepts had to be introduced and defined. Furthermore, as a consequence of the logic of the operator theory certain existing concepts were re-evaluated and sometimes had to be re-defined. Additionally, there exist various concepts in science that play a more general role in the context of the operator hierarchy and for which it is useful to have a short description at hand. For all these reasons it was considered appropriate to offer the readers of this thesis an overview of concepts that play an important role in the context of the operator theory.

Analogy: Analogy implies a mapping of knowledge from one domain (the base) to another (the target) such that a system of relations that holds among the base objects also holds among the target objects (Gentner & Jeziorski 1993)

Building block: I sometimes use the word 'building block' or 'unit systems' for indicating the particles that in the operator hierarchy are named operators. I always have in mind a system in which the elements create a physical and functional unity on the basis of first-next possible closures.

Catalytic hypercycle: see Hypercycle

Closure: In the context of the operator hierarchy, closure relates to a state of matter that is the result of a self-organisation process and that shows a closed topology with respect to structure, process or the combination of both. Closure as a state shows a close association with underlying mechanisms because it also is used to refer to the closing process producing the closed state.

Closure level: In the context of the operator hierarchy, every first-next possible closure adds one closure level.

Closure, structural and functional: Functional closure is defined as a closed cycle of processes that does not cause a physical mediating layer. Specific forms of functional closure are the catalytic reactions involved in an autocatalytic set, the pion exchange between protons and neutrons in the atom nucleus and the plasma strands connecting the cells of multicellulars. In contrast, the definition of structural closure demands that interactions create a physically closed topology. In the operator hierarchy, the focus is on a special form of structural closure, namely the structural closure that creates a physical boundary mediating a contained, first-next possible, hypercyclic process. Specific examples of structural closure in the operator hierarchy are the electron shell around the atom nucleus, the cell membrane of a single cell, and the connected cell membranes of multicellular organisms and the sensory interface of the memon.

Closure dimension: A closure dimension focuses on similarity in structural closure, functional closure or, when present, a combination of both. The naming of a closure dimension is directed after the most complex organisational property of the system as allowed by structural or functional closure or, when possible, the combination of both. The following closure dimensions are acknowledged in the operator hierarchy: 1. the interface dimension, introduced by the fundamental particles, 2. the hypercyclic dimension, introduced by the quark-gluon plasma, 3. the multi-state dimension, introduced by the hadrons, 4. the hypercycle mediating interface dimension (HMI), introduced by the atoms, 5. the structural copying of information dimension (SCI), introduced by the cell, 6. the structural auto-evolution dimension, introduced by the hardwired memon

Complexity (functional): I regard as the functional complexity of an entity 'all forms of internal or external interactive processes that are supported by the internal organisation of the entity'. Both a large, badly organised structure and a minute, well-integrated structure may allow an entity to show the same functional complexity.

Complexity: Complexity is a concept that refers to our inability to give a straightforward description of the properties of an entity. Complexity relates to the number and inter-relatedness of the elements of an entity and to the patterns and sub-patterns in its states and dynamics.

Complexity of a closure dimension: The complexity of a closure dimension is based on the number of major transitions that were required to construct it. According to the operator theory, the complexities of the closure dimensions that are known to exist are: 1 for the fundamental particles, 2 for the first-next possible closure creating hypercyclic interaction systems, 3 for the hadrons, 4 for the atoms, 5 for the cell and 6 for the memon.

Complexity of operators: The operator hierarchy measures the complexity of an operator by means of the number of first-next possible closure levels that underlie its construction.

Confinement: Confinement binds quarks in hadrons in a condensation-like process. It is the result of the strong force, also called the color force, which is conveyed by the exchange of gluons between quarks. At higher temperatures/energies the quarks become increasingly heavy and the confinement relatively weaker, which is referred to as the asymptotic freedom of the quarks.

Corrupt hierarchy: If, in any hierarchy, one or more steps/layers do not comply with the hierarchy rule used for creating the ranking, I consider this a corrupt hierarchy. For example the hierarchy 1, 2, 4, 5, 6 ... is corrupt in relation to the

rule that for every N , the next element in the ranking must be exactly $N+1$ (it lacks the 3). For the same reason the ranking 1, 2, 3, 3.2457, 4 ... is a corrupt hierarchy (the 3.2457 is superfluous).

Dissipative system: The organisation of a dissipative system results from selforganisation processes caused by the degradation of free energy gradients in the environment. Examples of dissipative systems are waves (degrading wind energy), whirlwinds (degrading a pressure gradient in the atmosphere) and organisms (degrading a chemical and/or radiation energy gradient). As a thermodynamic equilibrium implies a random distribution of elements and interactions, the organisation of elements in a dissipative system is regarded as to be 'far from equilibrium'. Dissipative systems do not contradict with the laws of thermodynamics, because any increase in organisation inside a dissipative system (which implies a decrease in entropy) is driven by a free energy gradient and causes at least as much entropy in the system as is lost during the organisation process.

Efficiency: I regard efficiency as the lowest resource use, when two processes are compared leading to a functionally equivalent product or achieving a functionally equivalent goal.

Elementary closure: An elementary closure represents the lowest complexity realisation of its type with respect to the system's structure, process, or when possible, the combination of both. Elaboration and repetition of the same closure type does not affect the elementary closure.

Elementary particle: In physics, the concepts of elementary particles and fundamental forces are used to indicate matter particles and force carrying particles of the standard model, respectively. The operator hierarchy suggests that one may also regard all operators as elementary particles with respect to their highest level first-next possible closure. Defined this way, only the particles of the standard model are truly elementary (which I prefer to consider fundamental) in the sense that they presumably show no substructure of smaller particles.

Emergent property: An emergent property is a group-property that results from interactions between entities that individually do not show this property. For example water flow and waves are emergent properties of interacting water molecules (a single molecule cannot form a wave). Used in this general way, emergent properties arise from almost any interaction between separate elements.

Entropy: Entropy is the opposite of free energy. Because in a closed system the average free energy can never increase, the entropy can only increase. An

increase in entropy corresponds with the natural pathway of systems from a high to a low energy state. Examples are the reaction of chemicals to low energy products, the transformation of light to heat, the falling of particles in a gravitational or electric field and the change of a system towards the state that shows the highest number of possible microstates. For closed systems Boltzmann has shown that the chance on a decrease in entropy becomes infinitesimally small for systems consisting of many elements. It is an important aspect of nature that in local parts of open systems entropy may decrease, the local system becoming more organised. This does not violate the laws of thermodynamics, as long as the entropy decrease in the local system is driven by a free energy gradient.

Evolution: Any process based on the following aspects: 1. the production of entities the structure of which differs from that of their precessors (productive diversification), and 2. structure-dependent performance of the entities causing a gradient in their evolutionary success (the cause of selection). Evolutionary dynamics can be observed at all levels of the operator hierarchy (e.g. elementary particles, prions and viruses, organisms, technical memons) but also things that are not operators may show evolution, e.g. strings of computer code, bee colonies, or neuron states produced in relation to the invention and weighing of different scenarios in a decision making process. The evolution of neuron states precedes that of tools (cars, windmills and the like) with which it co-evolves.

Evolutionary success: Evolutionary success is a measure that depends on the relative performance of entities with respect to: 1. the stability of their internal organisation, 2. the stability of their functioning in interactions with other entities and/or forces, 3. their capacity for productive diversification, which in relation to operators ultimately includes the capacity to produce the following first-next possible closure. Without the latter, evolution cannot proceed towards higher level operators.

The evolutionary success of dissipative systems, such as living beings, is related to the relative success with respect to resource dominance, when compared to other systems that take part in the process. The longer an organism exists and the better it functions (which may include reproduction), the more resources it (and its offspring) will use/dominate. Organisms which at a given moment are the best resource dominators, may rapidly lose from others which get slowly better over time, whilst both strategies will be beaten by organisms that can increase the rate of their improvement, especially if they can increase the acceleration of this rate. Strength in competition as well as strength in cooperation may increase evolutionary success. The duration of observations determines which of the above aspects of evolutionary success can be observed.

A higher evolutionary success not necessarily implies a more complex structure. For example, in dynamic environments with a high random mortality, simple, rapidly reproducing entities will prevail.

Exhaustive closure: To assist in identifying the new type of elementary closure, I suggest identifying the 'exhaustive closure' in the system at the one lower closure level. A system shows exhaustive closure, if there is no remaining potential for elaborating the structural and dynamic aspects of the elementary closure type, because any further development will cause the construction of a new elementary closure type. While the elementary closure of the system remains the same, the state of exhaustive closure allows for a new functionality.

First-next possible closure: First-next possible closure is defined as follows: given any system A that shows first-next possible closure, the *next* first-next possible closure creates the least complex system type above A that shows a *new type* of elementary closure based on A and, when required, any highest level system type possible below A that shows first-next possible closure. This definition is inherently recursive because a system showing first-next possible closure produces a more complex system showing first-next possible closure. Because a first-next possible closure is always built from systems showing a *preceding* first-next possible closure, the recursive definition does not lead to logical loops.

Force: A force is the result of an interaction. For example the repulsion between electrons (electromagnetism) is caused by the interaction of two electrons by means of the exchange of virtual photons. Likewise, the exchange of gluons causes the attractive force between quarks. In principle the equating of force and interaction works at all levels of the operator hierarchy. For example the interaction between a predator and its prey can be regarded as a 'predation force'.

Fundamental particle: A physical particle that shows no substructure of smaller particles. In the operator hierarchy: the system showing the lowest level first-next possible closure (see also elementary particle).

Hardwiring: This concept is used to describe a neural architecture that is based on physical 'wires' between neurons, for example in the shape of dendrites. The difference with 'softwiring' is that softwired connections between neurons do not exist as physical wires, but as entries in computer memory telling which neuron is connected to which other neurons and what is the strength of the connection.

Hierarchy: Hierarchy assumes a ranking of entities. Formally, elements in a hierarchy meet the following two demands (Simon 1973): *Irreflexivity*: A can never hold a hierarchical position below itself. *Transitivity or non-transitivity*: if A

has a lower hierarchical position than B, and B has a lower position than C, then A does have, or does not have a lower position than C. From irreflexivity and (non-)transitivity follows *Antisymmetry*: if A has a lower hierarchical position than B, then B cannot hold a lower position than A. An example of a transitive hierarchical relationship is: A is ancestor of B, B is ancestor of C. In this case A is also ancestor of C. An example of a non-transitive hierarchy is: A is a child of B, B is a child of C. In this case A is not a child of C.

Bottom-up hierarchies arise when the behaviour of lower level elements integrates them in larger assemblies (e.g. when atoms create a molecule). Top-down hierarchies may have different origins, for example 1. when social agreements define a top figure (marshal/manager) and allow it to direct groups of (now) lower level figures (soldiers/workers) or 2. when after the formation of a functional unit, internal differentiation leads to internal hierarchies of functional relationships (see also 'Penultimate level').

Hierarchical layer: Operators and pre-operator interaction systems that are based on the same primary system and do not yet represent the next major transition, are regarded as to belong to the same hierarchical layer.

Hypercycle: The use of this concept in the literature generally refers to the enzymatic hypercycle as discussed by Eigen and Schuster (1977). With respect to the operator hierarchy, the concept is used for any second order cyclic process that is related to a first-next possible closure.

Information and complexity: Information has a structural and a semantic aspect. The structural aspect relates to the number of elements and the different states they can code for (e.g. Shannon 1948). The semantic aspect relates to the interpretation of a coding. In principle, there is no limit to the semantic complexity of a message, because even a simple coding may relate to a highly complex interpretation. The functional elements of a coding (the 'bites', 'characters', 'genes', 'symbols', etc.) normally show an intermediate complexity. Too low complexity would allow too little differences between the elements. Too high complexity would make the coding/decoding difficult.

Intelligence: In the context of the operator theory intelligence is an emergent property brought about by the functioning of an operator with a complex enough memic architecture. Intelligence is associated with the autonomous capacities to observe, learn, make internal representations, predict, evaluate and act. Intelligence requires sensors for contacting the world and a neural network for creating internal multiple-channel representations, the latter offering a natural source for association and creativity. Intelligence shows a gradual increase with increasing neural complexity. For intentional behaviour, the representations must be available for the evaluation of which actions are most effective for

reaching the mental concept of a certain goal. Intelligence, therefore, has much to do with the art of choosing appropriate aspects for evaluation in multi-factorial problems.

Interaction: An interaction is an event that involves at least two entities and causes a change in one or more parameters of both systems. This excludes as interactions all events in which one element remains unchanged. For example, if someone listens to a radio program, this seems an interaction between the person speaking on the radio and you. But the person speaking is not affected in this process, and therefore it is not an interaction according to the above definition.

Interaction system: An interaction system consists of interacting operators but lacks the closure(s) that would allow it to be regarded as an operator. The world is swarming with interaction systems, including footballs, stars, cars, water, populations, society, companies, etc. Of course also operators consist of interacting elements. Yet, like Orwell made his pigs advocate that 'all animals are equal, but some are more equal than others', I advocate that all systems are interaction systems, but that the operators show such special interactions, that it is wise to regard them as 'more equal than others'. Accordingly I assign them to a special subset. Although they play an important role in the operator hierarchy, the pre-operator hypercyclic sets and interfaces are not operators, but interaction systems.

Life; as a state of matter: Life is a concept that relates to all matter that shows the construction of operators, and that has the minimum complexity of the cellular operator. Subsets of living entities can be defined as autocatalytic life (uni- and multicellular plants, fungi, sponges, protozoa, etc.) or memic life (including all memic operators, regardless whether they are based on a cellular or a technical construction).

Life; meaning of: The meaning of life is in the first place a personal subject. Besides this, the operator theory offers two general ways of thinking about the meaning of life. The first meaning is associated with the functioning of organisms as individual operators. Every organism has to stay alive and memic organisms additionally care about their daily satisfaction. Survival is a quite objective criterion. The validation of daily satisfaction depends on the individual judgment of what is 'satisfying'. The second meaning of life is associated with the contribution of all operators to evolution. On the one hand, this implies an involuntary act. Whatever you do, you are always part of the large process that is driven by entropy production. On the other hand, increasing insight in the overall structure of evolution may have the implication that a person decides to realise a directed contribution to evolution, for example by constructing a technical memon

Living: Living can be defined as the dynamic activity of systems that comply with the definition of life. A bacterium, for example, may or may not be living, depending on whether it is active or frozen/dried.

Major transition: Any first-next possible closure creating a primary system is regarded as a major transition (not to be confused with the major evolutionary transitions of Maynard Smith and Szathmáry, 1995a, 1995b)

Meme: Dawkins (The selfish gene, 1976) defines the meme as: '... new replicators, which I called memes to distinguish them from genes, can propagate themselves from brain to brain, from brain to book, from book to brain, from brain to computer, from computer to computer.' Dawkins' memes are not structural analogues of genes, because any pattern of replicable information in brains, books, etc. could be a meme, whilst not any pattern of replicable information in cells is regarded a gene. To solve this, I propose the use of different meme concepts: 1. Abstract meme (A-meme): abstractions communicated between memons (melodies, stories, and theories), 2. Physical memes (P-meme): physical models of thoughts (written language, artwork, buildings), 3. Functional meme (F-meme): the actual neural network, or part of it, harboring information, 4. Coding meme (C-meme): C-memes code for neural network architecture just as genes code for catalytic molecules.

Minor transition: Any first-next possible closure creating a system that shows an already existing closure dimension, is regarded a minor transition.

Model: I regard as a model any entity that represents another entity. This may involve mental models that represent parts of our environment, scaled physical models that represent larger or smaller physical or mental originals, and simulation models that represent aspects of real world systems.

Modularity: Modularity refers to the construction of larger systems from small functional and/or structural subassemblies or 'modules'. Herbert Simon illustrated the evolutionary merits of modularity in the parable of the watchmakers Tempus and Hora, making watches consisting of 1000 parts each. Tempus made his watches bit by bit. When disturbed, he had to redo the entire assembling process. Hora put his watches together from subassemblies of 10 parts each. 10 subassemblies were put together in a larger subassembly and 10 larger subassemblies constituted the whole watch. Hence, when Hora was disturbed he only lost the specific subassembly-job he was involved in. Simon calculated that if customers disturbed Hora and Tempus on average once in hundred assembly operations, Tempus would need about four thousand times longer to assemble a watch.

Natural systems: I regard as natural systems all elements of the universe of which the physical existence allows us to interact with it and describe static and/or dynamic properties (qualities and quantities) in a consistent way. More/better measurements should lead to an increasing detail of our representation of the system. Kragh (Aktuel Naturvidenskab 1999) has said this in the following way. 'It is difficult to understand, how measurements of important scientific parameters normally can become more and more precise, and how knowledge shows a general consolidation and refining, if these measurements and knowledge do not concern something that really exists in nature'. In the context of the operator theory, natural systems include the neural configuration and neural dynamics that 'carry' a thought, for example of the number pi, but do not include the word 'thoughts' or the number 'pi'.

Operator: An operator is defined as a system type that shows first-next possible closure with a closure dimension of at least 3. This implies that operators can also be defined as those systems showing first-next possible closure that are not pre-operator interaction systems. The set of the operators unifies all particles, irrespective whether these are physical particles or organisms. All operators that are currently known to exist are: the hadron, the atom, the molecule, the (bacterial) cell, the eukaryote cell, the bacterial and eukaryote multicellular and the neural network organism, called the 'memon' in the operator hierarchy.

Operator hierarchy: The operator hierarchy is the structuring of all operators and pre-operator interaction systems on the basis of first-next possible closure and closure dimensions.

Operator hypothesis: The operator hypothesis states that the fundamental limitations imposed by first-next possible closure act as a strict mould for particle evolution.

Operator theory: The operator theory is the theoretical framework that offers the context for the operator hierarchy and the operator hypothesis.

Penultimate level (Law of the branching growth of the ...): This law by Turchin (1977) states that: '...after the formation, through variation and selection, of a control system C, controlling a number of subsystems Si, the Si will tend to multiply and differentiate. The reason is that only after the formation of a mechanism controlling the Si it becomes useful to increase the variety of the Si.

Pre-operator interaction systems: Systems, caused by first-next possible closure, that selectively create an interface or a 2nd order cyclic interaction (the 'hypercycle') as closure dimension, are called pre-operator interaction systems.

Primary system: A system showing a new closure dimension is regarded a primary system.

Quanta of evolution: Quantification normally involves simple variables such as length, weight, color (wavelength), etc. A more complex variable to quantify is the evolutionary complexity of a system, for which quanta of evolution have been proposed (Turchin 1995, Heylighen, Joslyn and Turchin 1995). The operator hierarchy uses first-next possible closure steps for creating a strict system of quanta of organisation.

Recursion of definition: A definition is recursive if it explains some entities X_n in terms of X . The operator hierarchy is recursively defined, because lower level operators are used to define higher level operators. Note that a recursive definition does not suffer from a logical loop.

Resource: A resource is something a living operator needs to enable certain aspects of its existence.

Resource dominance: Resource dominance is defined as the capacity of organisms to gain dominance over resources. There are different aspects of resource dominance that are of evolutionary importance. First, there is the amount of resources that an organism can dominate by degrading them. After degradation they are no longer available for other organisms. Second, there are resources that an organism may dominate, without that it uses them. Again they are no longer available for other organisms. There exist various resource dominance strategies by which an operator can increase its evolutionary success.

Softwiring: In softwired memons, the neural network is based on computer files that keep track of the neurons involved, the interactions they show with other neurons, and the types and connection strengths of the interactions.

System: The system concept relates to entities which can be endowed group-wise functionality because of past, present or future interactions and/or relationships. The entities that by their relationships define the group are considered as the elements of the system. The system concept applies to the universe or a subset of it (the latter including mental states and via these, all aspects of our imagination). Frequently, the entities and their interactions are chosen in such a way that they define, include or relate to some kind of physical system limit.

System type of closed systems: Two systems that are created by the same first-next possible closure are considered to be of the same system type.

Tool: In the context of the operator hierarchy I define as a tool 'any idea or physical object that a memic operator may use to help it manipulating the world to its liking'. Consequently there are mental tools, such as mathematics, and physical tools, such as a stick, a hammer, a car, a house, a factory and a computer. It is interesting to realise that the operator hierarchy predicts that the next level memons are not based on cells but on technical hardware. Consequently, the process of reproduction (giving birth), that is so important for the evolution of organisms based on one or more cells, will be replaced by the process of producing an 'offspring-tool'.

Topology: Topology studies qualitative aspects of geometrical structures. In stead of asking how big a certain thing is, it focuses on other aspects, such as: does it have any holes in it; is it connected together, or can it be separated into parts.

Transition: If a system changes from state A to state B this can be regarded as a transition of the system between these states. For any particular transition the property that is going to be looked at as well as the states that can be recognised have to be defined.

Type: A type is used as a grouping of entities according to a common property. Using types of types leads to the creation of a type-hierarchy in which lower-level types show properties that are grouped into higher-level types. For example the higher-plant-type and the animal-type can be grouped within the multicellular-organism-type. Frequently used types in relation to the operator hierarchy are: 1. process type: a comparable aspect that can be recognised in the dynamics of different entities. 2. System type (general): the type of a system is defined by comparable aspects with respect to a. the rules involved in the selection of elements, b. the properties defining the elements and c. the relationships that may exist between the elements, and 3. Closure type: a closure type is defined by the presence of comparable aspects with respect to the type of elements and the type of mechanisms causing the closure.

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