Analysing hierarchy in the organization of biological and physical systems

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ABSTRACT

A structured approach is discussed for analysing hierarchy in the organization 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 organization. At the end, the paper discusses practical implications of the proposed method for the analysis of system organization and hierarchy in biology, ecology and physics.

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I. 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 organization 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 organization 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 organization 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 organizational 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 organization, 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 modeling energy budgets of communities, which in turn are the elements for modeling 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 organization, which also shows hierarchical aspects. For example in bacteria, this includes mainly molecules, whilst in multicellular eukaryotes this may include tissues, organs, specialized 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 organization by means of a stepwise procedure that recognizes different aspects of hierarchy and can be summarized 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 organization. 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 organization, 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 analyze. 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 organization 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 nucleid acid molecules, but also in relation to its functioning in a cell. The fourth step can then be used to further analyze the organization of elements in the selected system. This implies that the parts and their interactions are studied to create a picture of the internal organization of the system. If necessary, iteration of the fourth step can be used to further analyze the internal organization 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 summarized 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.

II. 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 discus 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 emphasizing the importance of circular interaction patterns for recognizing elements and hierarchy. Such publications include discussions of the hypercycle (Eigen & Schuster, 1979; Kauffman, 1993), emergent organization (Laszlo, 1996; Ponge, 2005), major transitions (Smith & Szathmáry, 1999), meta-system transitions that are regarded as the quanta of the evolution of complexity (Turchin, 1977), relational closure (Heylighen, 1989, 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 recognized 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 organization 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 organization (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-organization of systems in response to certain attractor states. Self-organization implies that interactions between systems autonomously create patterns. The most important aspect of self-organization 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 organization of systems, a special approach is used that recognizes 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 organization allowing them to operate as individuals and produce effects in their environment. The name operator was chosen, even though it was realized 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. 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 hyper-cyclic 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 multi-particle 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. 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. 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. 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 organization in systems. As an example, let us discuss the simple situation of a system (S) that contains a water
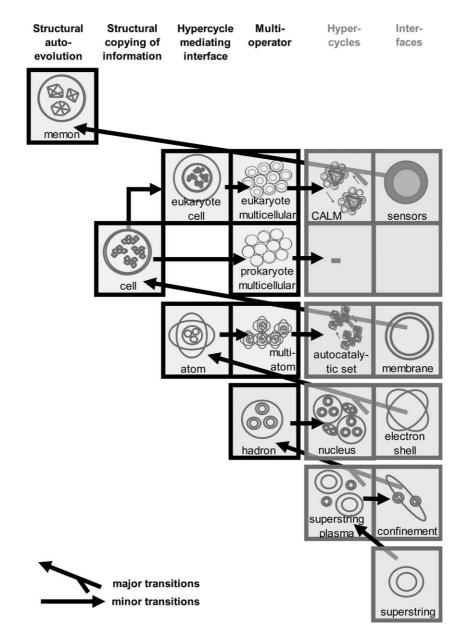
Fig. 1. The ranking of system types according to the operator hierarchy (Jagers op Akkerhuis & van Straalen, 1999; Jagers op Akkerhuis, 2001). Grey boxes indicate non-operator systems that play an important role in the operator hierarchy as intermediate closure states. Black upward arrows represent major 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. Titles above the columns indicate closure types. '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.

molecule ($\underline{M}$) and a water droplet ($\underline{D}$) (Fig. 3). The operator hierarchy regards the water molecule an operator and the droplet and system $\underline{S}$ 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 $\underline{D}$. The system $\underline{S}$ also represents an interaction system, because it contains elements the interactions of which do not show first-next closure.
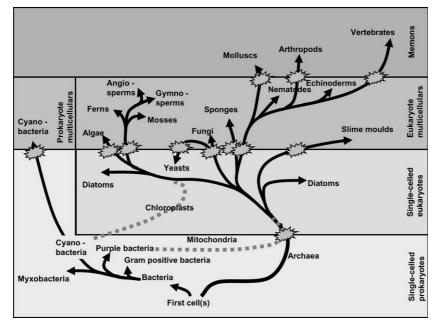
Fig. 2. A schematic representation of the phylogenetic tree. Organisms are ranked according to speciation patterns, at the same time indicating when a specific lineage passes through one of the major levels of structural organization recognized by the operator hierarchy.

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 fibers 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 organization, they have all evolved from operators and may respond to changing conditions by a change in organization 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 characterized as a compound object in air, but not in water.

It is recognized 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 organizational 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 organization of both operators and interaction systems. The
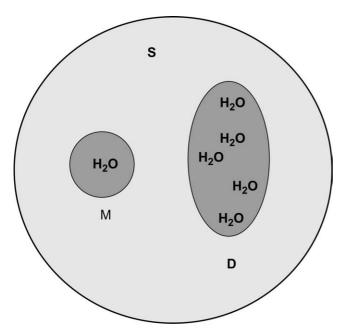
Fig. 3. A system $\underline{S}$ containing a water molecule $\underline{M}$ and a drop of water $\underline{D}$ and water molecules (H_2O).

internal organization of these systems can be looked at from two perspectives: that of the elements and that of the interactions.

(a) Elements

A general analysis of system organization 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 organization of a dog (an operator of the memon type) includes interaction systems, such as organ systems, organs and tissues, and operators, such as many specialized 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 'organizational dimensions'.

For example, a focus on the relationship '$\underline{a}$ causes the displacement of $\underline{b}$' 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 '$\underline{a}$ has genes that are used by $\underline{b}$'.

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 '$\underline{a}$ eats $\underline{b}$' is an example of an energetic viewpoint. Other aspects of the energetic dimension may include behaviour aiming at maximizing 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 emphasized 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 summarized 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 organization of any system is principally incomplete.

To summarize 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 specialize 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 organization 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).

III. 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 organization 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. Although in Fig. 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 Figure 4) may contain large parts in which cellular life has not yet emerged and where the analysis of system organization does not have to take into account the activities of organisms. Furthermore, the scheme shown in Fig. 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 characterization 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 organization 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 organization is that of the individual and is limited by intercellular connections.

(3) Mediating influences

The third step involves a further characterization 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 organization 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 organization

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 organization 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 II.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 organization 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

Fig. 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($\underline{X}$-$\underline{Y}$) indicates all possible interaction systems containing type $\underline{X}$ as the highest-level operator in a succession stage of the universe that contains $\underline{Y}$ 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($\underline{Y}$) is used to indicate all possible operators of type X in a stage of the universe that contains $\underline{Y}$ as its highest-level operator.

communities, which finally are parts of ecosystems. Instead, this hierarchy only involves abstract subsets, and not structural elements. Fig. 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.

IV. APPLICATIONS OF THE NEW METHOD

The application of conflicting hierarchy rules and the inclusion of ill-defined systems flaws many existing analyses of hierarchy in system organization. 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 organization use an organism concept that covers all types of organism and link this to an internal organization 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 organization. To avoid such problems, the present approach uses the operator hierarchy to determine (and rank) the complexity level of the organism before analysing internal
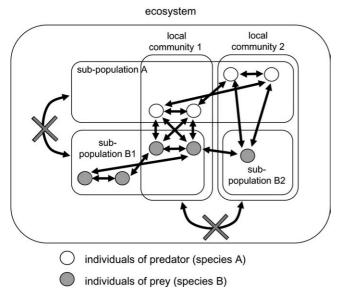
Fig. 5. The partitioning of individuals into subsets of an ecosystem. Black arrows indicate interactions between individuals. Arrows marked with a cross indicate sets that do not interact as entities, such as populations and communities. The figure shows that it is always the individual (or a physically connected colony of individuals that acts as one individual) that interacts in the ecosystem, regardless of the subset it is assigned to.

organization. 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 $\underline{C}$, controlling a number of subsystems $\underline{S}_i$, will these $\underline{S}_i$ 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 specialized cells in multicellulars.

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

Analyses of the organization 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 organization 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.

(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 organization 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. 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 organization of elements in the organism. Considering the organism as just another operator, this part can also be generalized to relate to the internal organization 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 recognized.

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 organization '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.

V. CONCLUSIONS

(1) The literature shows a controversy about the usefulness of hierarchy in analysing the organization of biological/physical systems. On the one hand, it is postulated that hierarchy is the most general organizing 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 organization. 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 organization.

(3) The present method of identifying contributes in three ways to the analysis of system organization: (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.

VI. ACKNOWLEDGEMENTS

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