

ASPECTS OF COMPLEXITY IN LIFE AND SCIENCE

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ABSTRACT

A short review of complexity research from the perspective of history and philosophy of biology is presented. Complexity and its emergence has scientific and metaphysical meanings. From its beginning, biology was a science of complex systems, but with the advent of electronic computing and the possibility of simulating mathematical models of complicated systems, new intuitions of complexity emerged, together with attempts to devise quantitative measures of complexity. But can we quantify the complex?

1. Introduction: The metaphysics of complexity in science

A common idea of complexity is that complex things have a long complicated history, and that complexity must be understood in the context of processes in Nature generating systems with more parts, different parts, and special relations between various kinds of parts, forming a structure which must be described on several distinct levels of organization and as involving entities with emergent properties. These terms — complexity, system, part, relation, structure, levels, emergent — are problematic and should in principle be defined first, but for the present it is sufficient to let the context fix their meaning. In this note I will address some questions about evolution of complexity and the attempts to measure complexity from the perspective of the philosophy of biology and the cross-disciplinary field of Complex Systems research (including the study of non-linear dynamical systems, chaos theory, Artificial Life, cellular automata, etc.).

General concepts about life, organization and complexity have a peculiar status within philosophy of science. In a sense, they reveal that

one cannot draw clear demarcating lines between natural science and metaphysics taken as general ontological assumptions about our world. Indeed, this can be done analytically, but in practice the everyday life world of people in a modern society is perfused with the products of science and technology and moreover with ideologies and world views that are at least historically dependent upon the development of science. Still we can distinguish between phenomenological areas of experience (that are common to all and non-scientific) and specific scientific ways of exploring and explaining the everyday world. There is little doubt that we can talk about a more or less shared everyday notion of 'complexity', vague, ill-defined, and fuzzy as it may be, which belongs to this phenoworld, and which scientists bring with them in their mental baggage into their respective disciplines, and which, however, for most of the time have been considered uninteresting and irrelevant for study in the exact sciences. One of the interested tellings reported to the public from the physical sciences during the past 15 years is that in contrast to the traditional scientific interests in the microscopically minute world of elementary particles and the cosmological very large aspects of the universe, which are both felt very remote and open to rather idealized but exact mathematical treatments, the physical sciences have taken new interest in medium sized everyday world of complex, living, irregular (but not totally random) phenomena that we encounter in our everyday lives. Complexity, not simplicity, is purported to have become the focus of research, and we are all apparently supposed to know, at least intuitively, what it means.

As science for all its history has studied the complex phenomenal world to reveal the secrets of its appearances, it should not surprise us that 'complexity' itself could be its subject matter. Nevertheless it is a bit bizarre to imagine a truly *general* scientific concept of complexity. In specific fields such as evolutionary biology, molecular genetics, or the computational study of 'life-like' automata within Artificial Life, one finds precise and even operational concepts of complexity for specific scientific purposes, but the point of departure for these concepts is often rooted in everyday notions of complexity, and the concluding insights drawn from such studies may also interfere with pre-scientific everyday ideas about the subject. From a scientific point of view, doubts can be raised about the use of any *general* notion of complexity. Natural science is partitioned in a set of very specialized methods and approaches — why

then, should any particular concept of complexity not have a very restricted scope, relevance and validity? Scepticism about any new general all-encompassing theory of complexity is certainly warranted, as one is reminded about previous unsuccessful attempts to construct grand syntheses about everything, such as general systems theory (compare Lilienfeld 1978). Nevertheless, as science contributes to a common world picture (or a loose mosaic of such pictures), it is tempting to draw general lessons from a large set of particular investigations from various areas of inquiry. Complexity studies should thus be seen not as aiming at a new "synthetic theory" of complexity of any kind, but as a cross-disciplinary field of research and meeting place for dialogue between specialized groups of people such as biologists, physicists, philosophers, mathematicians, computer scientists, and, last but not least, science writers (with a background in science or journalism or both) who have contributed to popularise the field for a wider public and perhaps facilitated the meeting of experts from the specialised areas.¹ Let us briefly and preliminary characterize a few general meanings of the term complexity when used in connection with science (Ravn *et al.* 1995).

First, we have *descriptive complexity*. This applies to a situation when several different methods are needed to describe a phenomenon in a reasonably complete way. An organism, a photon, an individual consciousness are all in their own way descriptively complex: An organism may be described on different levels, each with a specific descriptive apparatus (biochemical, cell biologic, anatomic, ecological) if one endeavours a comprehensive picture. In quantum mechanics, even simple entities like a photon (a light quantum) require the use of two complementary descriptions which are both necessary and mutually exclusive (the wave particle duality). The consciousness of a person can, on the one hand, be described qualitatively from within as the content of what is subjectively experienced, i.e., from the "first person point of view", and, on the other hand, by the neurophysiological processes we can observe (and to some extent observe as correlated with a given person's reported conscious experiences), that is, from without, from the "third person point of view".

Second, we have what may be called *ontological complexity*. Something is complex in the ontological sense (disregarding whether we can know it completely or not), when it is organized as a system of many non-identical components who themselves have systems-like properties

(such as being further decomposable), and whose mutual interactions bring forth a kind of collective behaviour which is different from the behaviour of the parts. A phenomenon is complex if it has a specific sort of order which is 'interesting', i.e., which objectively is located equally far from the totally ordered and predictable on the one hand, and the completely random and disordered on the other hand. A living cell, the brain, the growing body as a morphogenetic system, a society, clusters of galaxies, are examples. To say that X is complex doesn't in itself say much about X . (As with all ontologic properties, we often need to specify how and from what perspective we know about this property, so to consider something as complex in the ontological sense often invokes the need to identify its descriptive complexity — or an alternative epistemic concept of complexity).

Third, we have the name of the above mentioned field, *complex dynamic systems* (sometimes called complex adaptive systems, Gell-Man 1994) where a lot of research from the perspective of natural science (but also with a growing interest from economics and social science) endeavours to investigate self-organizing systems, co-operative behaviour of agents, and non-linear dynamical systems creating emergent properties during their time evolution. Here we find efforts to define quantitative measures of a system's degree of complexity, for instance based on such notions as logical depth (Bennett 1988), hierarchical structure (Simon 1962, Huberman and Hogg 1986); algorithmic complexity (Chaitin 1974); or measures related to Shannon's information entropy concept (see review by Grassberger 1986). Some work in this field is related to interesting puzzles in chaos theory, artificial life and neural networks. We will return to this research below.

Fourth, the appearance of this field has stimulated some work in philosophy of science, for instance about the role of causality, interlevel relations and prediction in science (Newman 1996; Andersen et al., in prep.); about the implication of complexity for the 'disunity of science' and instrumentalism in biology (the debate between Dupré 1993 and Rosenberg 1994); and there have been attempts to describe the wider implications of what is seen by some philosophers to be a major transition from a classic, simplifying paradigm to a new 'complexity paradigm' of science (e.g., Morin 1977-91). Speculations have been made that complexity and the new focus on self-synthesising wholes is becoming a central part of a new scientific mode of thinking, substituting the former

mode which is purported to be entirely reductionist and analytic. Some of these thoughts may derive more from story telling mediated by science writers than from concrete studies of science at the working bench. It hardly plausible that one can talk in general about a shift in methodology on the high-level of science. The specific kinds of methodologies (with a small *m*) close to science, that continuously develop and change, are really important, but, as Ronald N. Giere once remarked, “appeals to grand things like simplicity, fruitfulness, and all this stuff, that is part of the rhetoric of science”.² Complexity, or at least ‘the complexity paradigm’ may well be part of all this stuff too. In any event, one needs closer analyses of the whole paradigmatic structure (in Kuhn’s original sense) of these areas before one can evaluate claims of a truly shift in scientific paradigm, whatever that exactly means.

Fifth, there is a quite separate set of notions of complexity in the social sciences, dealing with complicated social systems, their differentiation and segmentation, and with the various decision making processes in these systems that constantly rely on incomplete information. In the theory of Niklas Luhmann, *complexity reduction* is the phenomenon that social systems are exposed to a much greater ‘information pressure’ than what they can handle in real time by rational methods. This is why they must reduce this complexity, and this is in part done arbitrarily: A chosen action is simply just one out of a large set of probably just as reasonable actions, but the very decision to chose a particular one reduces the complexity. The particular possibility, *qua* being realized as an action, is subsequently ascribed a higher value. Reduction of complexity is also a property of the system’s own self-observation, because no system can possess total self-insight. Luhmann’s approach to social systems may also be applied to science. Accordingly, complexity reduction in scientific research is not necessarily so much a question of abstracting the right properties out of a physical system, or of choosing a crucial experiment, or of making an inference to the best explanation, or of choosing between alternative theories all underdetermined by data — as the epistemological concerns of traditional philosophy of science might suggest. Looking at ‘science in action’ in a Luhmannian optics, complexity reduction is more like a social system’s attempt to handle the ever increasing production of attention-demanding communication that goes on in every social system, including the scientific one, and including the micro-social level, that is, during usual practical work in the science labs, where interaction and

communication between scientists and students, post-docs, laboratory assistants, science policy makers, fund raisers etc., are just as important as the interaction between an isolated inquirer and an isolated piece of nature. We should not forget these micro-social aspects of science, even when dealing with its most abstract and 'theoretical' ideas, such as the idea of studying complexity. I leave it to others to speculate on the possibility that the emergence of the "sciences of complexity" is a reflection of the changing social situation for the scientific subsystem in a postmodern and hyper-differentiated world.

2. From the great chain of being to the great story of becoming

Seen from a perspective of the cultural history of ideas, the so-called sciences of complexity may be located right in between modern and postmodern science. Modern science can be viewed as a normative notion of inquiry involving a historically specific set of ideas, such as that of contributing to an increasing mastery over Nature, a ceaseless development of new and better technology, the idea of a steady progress of knowledge, and the grand narrative of a continuing complexification of the world and of ourselves (this is 'the great chain of being', not pouring down as emanations from a Supreme Existence, but steadily becoming, growing bottom-up by material and industrial power). The postmodern sciences may then be construed as a set of science-related ideas that relativize this modern picture; that is, they question the very possibility of control, prediction and indeterminate dominance over Nature; they are more sensitive towards a wish to differentiate critically within the notion of technological progress with respect to environmental concerns about sustainability; they find the belief in a linear accumulative progress of knowledge problematic; they question the unity of knowledge and science; and they abstain from integrating their findings in a great narrative. Disregarding the fact that I do not really know whether such a monster as a postmodern science exists or not,³ I think that in complexity studies one may find elements of both kinds of 'ethos'; both unification and plurality, both a striving to find a general theoretical frame to understand any complex system, and a more modest stance that emphasises sensitivity to the concrete cases of entangledness, diversity and heterogeneity.

In biology, a dominating paradigm is the neodarwinian theory of evolution by natural selection, also called “the modern synthesis” (Mayr 1982). This paradigm is highly compatible with the modern scientific world view, in which biological evolution, including human beings’ own natural history, is embedded within a whole pattern of cosmic evolution. The stages in this grand evolutionary scenario proceed from ‘the big bang’, which is said to have created the germ of the present physical universe about 15000 million years ago (Mya.), to the creation of our solar system and the Earth around 4600 Mya., and further on to the origin of life about 3800 Mya.⁴ The first eukaryotes (i.e., cells with a more complex internal structure with organelles) appeared for about 2100 Mya.; the first complex multicellular organisms known as the Ediacaran fauna are dated back to about 640 Mya.; the first chordates (animals with a spinal column) arrived at about 570 Mya.; the first primates originated for 65 Mya.; the first hominids for close to 30 Mya.; the *Australopithecus* for about 5 Mya.; *Homo* for circa 1,8 Mya.; and the first members of our species, *Homo sapiens*, for roughly 0,6 Mya.. Thus according to this picture, during the general evolution of the physical universe, biologic things appeared which perhaps could not be explained completely by the methods of physics, astronomy and chemistry. Biologic things are — in some intuitive sense to which I shall come back (and which has a lot to do with our notion of life and the concept of an organism) — *more complex* than physical things. Even within the realm of biology there seems to be various scales of complexity, roughly correlated with their later emergence during evolution: Eukaryote cells are more complex than prokaryote ones; multicellular organisms appear to be more complex in life cycle and ontogenetic development than single free living cells; and with some qualifications animals seem to be more complex than plants because animals can move in more active, compound and effective ways because they have a nervous system that is processing sensor and motor information; and animals with social behaviour are more complex than solitary animals. Of course, the required specification of what exactly is meant by “more complex” is a subject of considerable debate, but for a moment let us take for granted the intuitive appeal of this scheme and its general veracity.⁵

Given this scheme, it is important to realize that the contributions of natural science to describe cosmic evolution is far from being sufficient to complete the picture of emerging complexity during the world’s his-

tory, because it is hardly conceivable that human socio-cultural evolution — including the emergence of complex forms of social organization, institutions, technology, natural languages, and various forms of consciousness — can be reduced to, or fully described as a set of biologic or darwinian phenomena. Though we may conceive of a deep continuity between biologic and socio-cultural evolution, it is necessary to include human and social sciences of psychology, anthropology, history, sociology, linguistics, etc., to comprehend the full scale complexity growth during cosmic evolution. Such a broad perspective can be considered as a descriptive frame for understanding the complexification of the world — fallible, incomplete and preliminary as it is.⁶

This modern world view is based on science as well as metaphysical ideas — for instance, that a rational world picture is possible at all; that you are allowed to draw more than a modest instrumentalist interpretation of the findings of the branches of science; etc. — but such a view does not specify the precise meaning of the notion of complexity. It is used loosely to denote, trivially, that a system is hard to describe or composed of many different parts with various internal relations and a certain organization of matter, energy and information. Less trivially, it connotes science's own renewed interest in complex historical phenomena (such as self-organization, chaotic phenomena, fractals, non-equilibrium systems, etc.) and its attempt to cross the "complexity barrier" in a situation where the Newtonian world seems more distant to us than ever before. This is perhaps, as Depew and Weber (1995, p.430) remarked, part of what is meant by the "postmodern condition". However, when ideas about complexity, its emergence, quantity and quality, dependence on the frame of description, and relation to the notion of a living system is discussed, I presume that even though the image of science that derives from these discussions has acquired some attributes of a postmodern 'state of the art' (where scientists have tools to be self-reflective and locate their theories in a broader frame of socio-cultural development), the possibility of getting closer to a truer story — a more adequate understanding of the real world's manifold networks of phenomena — is not lost. Interestingly, such a story must emphasize the contingent character of the world's becoming as well as its generic principles, and in this sense, complexity *as history* and the narrative character of understanding in biology goes hand in hand.⁷

3. *Life as a threshold of complexity?*

In a sense, 'the sciences of complexity' have not first emerged by the end of the twentieth century; biology has for all its modern history been the science of living complexity. It is an old idea that life, or living systems are characterised as being *organised*, i.e., more complex, than inorganic systems in Nature. It was probably Jean Baptiste Lamarck who was the first scientist to thoroughly temporalize the static view of a 'chain of being', as he offered the revolutionary vision that the more complex could have originated from the less complex. In 1802 he coined the term biology, by which he wanted to denote the study of all which is pertaining to "living bodies, their organization, their developmental processes and their structural complexity" (G. Treviranus and K.F. Burdach independently invented the same term in 1800). Both Treviranus and Lamarck implied that they have identified a new field of research rather than give a new name to an old. Lamarck and, before him, other natural historians in the late sixteenth and early seventeenth century had the idea that *organization* was such an important distinct feature that it separated the living from the inorganic nature, and that this difference was far more fundamental than the difference between the animal and plant kingdoms. In the following century, the 'degree of organization' became an important key to the study of a natural (as opposed to arbitrary) classification of the order of living Nature.

In the middle of the twentieth century, two very important lines of research were founded, which stand as milestones for our coming to grasp living complexity. One was molecular biology, leading to the discovery in 1953 of the chemical structure of DNA,⁸ a structure adequate to store and transmit 'genetic information' (a term tightly connected to the older biochemical notion of 'biological specificity'). The other line of research, nearly fully independent of the first, was the computational or mathematical study of artificial automata, and especially the theory of self-reproducing automata, initiated by John von Neumann in the 1940's.

From the first line of research emerged the insight that every known living system is not only highly organized; this organization is coupled to a complex molecular apparatus that functions as a 'genetic memory', that is, as a store of information about the specific kinds of macromolecules (proteins) that make up the components of the system. Even though

self-assembly of molecules play an important role within the cell (and thus here we have a process of non-guided self-organization of simple components to complex wholes such as membranes and three-dimensional enzymes); the whole process of protein synthesis, crucial for the cell's metabolism, is highly 'directed' by the stored information code in the DNA and by the components of the cell's pre-organized 'machinery' of protein synthesis, a machinery (in the form of the complex architecture of the cell such as the oriented nucleus membranes, the endoplasmatic reticulum with ribosomes, etc.) that the cell has inherited from the mother cell by division along with the genetic information in the DNA. This insight may be summarized as a principle of complementary modes of existence — or description — of a complex living system; one mode is the physical-chemical workings of the cell's components, the other mode is more like a linguistic or informational mode where information is selected, stored, and interpreted by the cell's physical actions (see Pattee 1977, 1979). Only simple systems can exist by just one mode, complex systems need complementary modes to keep alive in the evolutionary game.

From the second line of research (with some delay though) followed various formal investigations into the nature of complexity in general, starting from basic computer science and situated today in the cross-disciplinary area of 'complex adaptive systems' research, Cellular Automata, Genetic algorithms, Artificial Life, etc. It is interesting that John von Neumann recognized the dual functioning of information in any self-reproducing system — as a passive set of data and as active instructions (potential and actual signs) — already in late 1940's, before the discovery of the DNA structure. He also speculated, as Lamarck did before him, about the difference between living complexity and non-complex systems, that is, the difference between, on the one hand, a system that can self-reproduce and continue to evolve, eventually to even higher levels of complexity and, on the other hand, a system that tends to behave as an isolated thermodynamical system that deteriorates or decreases in physical order, according to the Second law of Thermodynamics. As von Neumann suggested: "There is a minimum number of parts below which complication is degenerative (...) but above which it is possible for an automaton to construct other automata of equal or higher complexity" (von Neumann 1966, p. 80). This so-called *von Neumann threshold of complexity* (that he could not characterize in detail) is generally conceived

to be the same threshold attained by the simplest known living systems;⁹ a threshold we do not yet understand but which must be explained in any account of the origin of living cells that are able to undergo further open-ended evolution. This passage from simple proto-cells containing polymerising macromolecules such as polypeptides and polynucleotides to real organized cells with a phenotype-genotype duality corresponds to the transition from a simple system to Pattee's dual of a dynamic and a linguistic mode.

The first line of research is very pragmatic and experimentally oriented towards mapping out the structure and function of living systems without speculating in abstract terms about the origin and nature of complexity. This approach has revolutionised biology and biochemistry and has taught us more about complex living things than Lamarck, Darwin or Mendel ever would have imagined. The second line of research — more inspired by the universal, abstract, mathematical and physical approaches to dynamical systems — has contributed to deepen our understanding of the logic and 'universal' aspects of complexity. None of these research traditions, though, have explained to us what complexity in living systems exactly is. Yet in both cases we are justified to deduce that 'semiotic competence' as sign interpretation capacity (Hoffmeyer 1996) is a prerequisite for complex living systems (or, as it has come to be called, information processing capacity, a less fortunate term because it implies a problematic computer metaphor for life, compare Carello et al., 1984).

An ontological interpretation of both lines of research is that the von Neumann threshold of complexity reflects a separation between the first two primary ontological levels of reality (Emmeche *et al.* 1997), the physical and the biological, where the biological level is the set of entities with special emergent properties that are the characteristics of life. Though different paradigms of biology may give different and partly implicit general definitions of life — life as autocatalytic self-reproducing autonomous systems; life as autopoietic systems; life as evolution by natural selection of replicators, or life as biosemiotic systems — all these particular notions imply that life is an emergent phenomenon (Emmeche 1997). Complexity, life and emergence of more and more elaborate semiotic processes seem to be deeply related, and it is an important possibility that a more precise notion of complexity can be derived from its aspect of being an emergent phenomenon (see below).

The intuitive sense of complexity as something characteristic of living organization as opposed to dead or mechanical being has, as mentioned, a long history in science, and though we shall not pursue the debate between mechanism and vitalism, a closer analysis of the history of biological thought may well reveal that the 'resolution of the debate' was not a dominating mechanist stance, but rather a historical compromise in some form of organicism (exemplified by biologists such as J. Needham, P. Weiss, C.H. Waddington, J. Woodger, E. Mayr, R. Lewontin, R. Levins) which takes the complexity and physical uniqueness of the organism as a sign of the autonomy of biology as a natural science. This middle road was in part anticipated by Kant's notion of living complexity, that is, his idea that we cannot dispense with a heuristic principle of purposefulness when we consider an organism, that is to say, "*An organized product of nature is one in which every part is reciprocally purpose [end] and means.* In it nothing is vain, without purpose, or to be ascribed to a blind mechanism of nature." (...) "it may be that in an animal body many parts can be conceived as concretions according to mere mechanical laws (as the hide, the bones, the hair). And yet the cause which brings together the required matter, modifies it, forms it, and puts it in its appropriate place, must always be judged of teleologically, so that here everything must be considered as organized, and everything again in a certain relation to the thing itself is an organ." (Kant 1790 [1951 p. 222]).

4. *Is complexity in fact increasing?*

The evolutionary cosmology in science and the popular picture of an ever-rising complexification of nature are often taken for granted, but we should not forget their character of metaphysical assumptions, and it is not so clear what evidence we have for the idea of the increasing complexity during evolution. A sceptical voice is Daniel W. McShea (1991 and this volume) who asks whether complexity *in fact* increases as the conventional wisdom says. He argues that very little evidence exists; empirical inquires have been few, and most students of complexity have been preoccupied with theorising in ways that lack rigor. I will sum up and add a little to McShea's observations concerning the literature on biological complexity. First, within a biological context, words such as

order, organization and complexity have often been used interchangeably. Second, when dealing with organisms, we have to focus on morphological or ecological complexity, whereas the theoretical studies are (paradoxically) often reducing the question of complexity to formal systems that can be reduced to bit or number sequences. Third, there are difficulties with the mechanisms suggested to account for the increasing complexity.

For instance, internalist theories conclude that complexity increase is driven by inherent properties of either complex systems generally (Herbert Spencer's Law of Evolution from 1890, and his principle of the "instability of the homogeneous" is an early example) or of organisms in particular. An inherent property of organisms that drive complexity increase could be the tendency suggested by Saunders and Ho (1976, 1981) of easier acceptance of component addition (in mutants, during development) than component deletions, because of the firm integration of already existing components in the developmental pathways. A lot of work in non-equilibrium thermodynamics from the 1950's to the present has led to a modern version of Spencer's vision of a self-organizing universe (e.g., Prigogine and Stengers 1984; Wicken 1979, 1984) but the physical concepts of self-organization and increasing order are very hard to relate to the morphological complexity of organisms. With respect to Ho and Saunders' suggestions it is by no means clear that the suggested mechanism should hold true for all environments, and furthermore, as Castrodeza (1978) argues, it is extremely difficult to compare the complexities of various organisms, e.g., a bacteria and a multicellular organism — a bacteria may turn out to be more complex (at least with respect to its behavioural repertoire) than any individual cell in a higher organism, no matter how complex this organism may be at the supra-cellular level. Complexity is not something to be perceived directly, it is "a conceptualisation of certain structures into particular patterns or components in order to carry out appropriate comparisons. In principle this conceptualisation can be made in innumerable ways" (Castrodeza 1978, p.470).

Externalist theories typically invoke natural selection, and a few theories invoke no mechanism at all. But there exists no well founded empirical evidence for the suggestion that natural selection has a tendency to favour more complex organisms for less complex ones. McShea's survey criticizes attempts to make an operational definition of morphological complexity of organisms and subsequently to show empirically a

tendency to its increase during evolution. Given such a poor evidence, one may ask why is there such a pervasive consensus within evolutionary biology about increasing complexity during the evolution of multicellular organisms? McShea argues that we all share a gestalt, a deep impression of this increase, due to some anthropomorphic biases: For instance, if we compare a cat with a clam, we have a vague impression that there is “something more” going on in the cat — it may have greater intelligence, greater mobility, and greater similarity to us. But if complexity (in a purely morphological sense) has to do with number of different parts and the irregularity of their arrangements, comparison of parts and arrangements in cats and clams is not at all straightforward, as they are anatomically *very* different. We may assume evolutionary ‘modern’ organisms (like us) to be more complex, and we may mistake organisms which are less familiar to us for being less complex than us. Furthermore, we have a tendency to read progress into evolution and to connect progress with complexity. And maybe a few spectacular cases of complexity increase (such as the transition to multicellularity) so dominate our perceptions of evolution as to create the impression of a long term continuing tendency.

The lesson is to be very careful when a general notion of complexity is used in a comparison of different systems and to satisfy the need to specify the concept further in empirical research. However, McShea seems to overlook the capricious fact that a too strong requirement for a single well-defined measure of complexity forces us to focus on just one single of its aspects (as he does, namely on morphological complexity), and this tends to reduce a complicated notion to a simple one-dimensional concept and thereby loose what was originally intended by the idea of complexity.¹⁰ This dilemma is evident in most of the attempts to define a quantitative measure of complexity. By definition, a quantitative measure is reductive in abstracting from the concrete (and complex) richness of properties in the object under study to arrive at a single value on a particular scale.

5. Describing complexity - from Simon to Santa Fe

A possible escape route out of this dilemma — between exact measures of poor aspects of complexity and vague unspecific ideas of the richness

of Nature's intricacies — is pragmatically to admit that complexity, even though understood as a real aspect of the world, when perceived and comprehended by a local observer will always be relative to his or her descriptive vocabulary. The cybernetics pioneer W. Ross Ashby held a more radical view, when he remarked that “a system's complexity is purely relative to a given observer; I reject the attempt to measure an absolute, or intrinsic, complexity; but this acceptance of complexity as something in the eye of the beholder is, in my opinion, the only workable way of measuring complexity” (Ashby 1973; cf. Casti 1986, p. 169).

Wimsatt (1976) emphasized that a system, for instance a fruit fly, allows several possible descriptive decompositions — such as energy flow, cybernetic physiological or metabolic interactions, biochemical constitution, anatomical organs, developmental fields, or physical descriptions such as thermal conductivity, density or chemical composition. When the boundaries between the various decompositions are non-coincident (as with the fly) such a system is *descriptively complex*, whereas a piece of granite for instance — that allow for decompositions (chemical composition, thermal and electrical conductivity, density, tensile strength) that are spatially coincident — are descriptively simple.¹¹ A similar definition of interactionally complexity, proposed by Wimsatt, involves causal interactions of the subsystems. A system is interactionally simple if the interactions within a subsystem are stronger than those between different subsystems. Several theorists have emphasized the observer-dependence of such concepts as complexity and emergence (Rosen 1977; Casti 1986; Cariani 1991; Baas 1994; Brandts 1997). Salthe (1993) deepened the original notion of complexity as susceptibility to alternative descriptions by his concept of *intensional complexity*, i.e., the particular sort of descriptive complexity where the different descriptions relate to particular integrative levels, or levels of generality (see his ‘specification hierarchy’ versus the ‘scalar hierarchy’).

When we distinguished in the introduction between descriptive and ontological complexity, we can only know if an object is ontological complex relative to a descriptive apparatus or frame that allow us (1) to compare its degree of complexity with other objects in one given frame of description (either in a qualitative and rather vague sense, or through a quantitative scale we have defined); or (2) to compare a set of particular descriptions of the object to access how many different descriptive frames we need to apply to achieve a satisfying level of comprehension of the

phenomenon, such level being a matter of pragmatic decision. As we always recognize complexity through descriptive frames, we cannot *a priori* decide whether descriptive complexity entails ontological complexity. We are allowed to take either a realist interpretation, in which case it does, or an instrumentalist one, in which case 'ontological complexity' is simply a metaphysical limit concept that cannot be justified within science. However, whether we choose one interpretation or the other, there are special methodological problems with different notions of complexity. Let us finally comment upon some further attempts to define or explain what complexity really is.

Herbert A. Simon sketched in his seminal 1962 paper four central aspects of complexity, some of which were first explored in detail decades later, namely: hierarchy, evolvability, near-decomposability and descriptive simplicity: The idea is that a complex system is made up of a large number of parts that interact in a nonsimple way, so that it is not a trivial matter to infer the properties of the whole.¹² Complex systems often take the form of a *hierarchy* (composed of subsystems, again composed of their own subsystems, etc.), where the intensity of interactions between parts may be correlated with either spatial propinquity or communicative connectedness. Such hierarchic systems can *evolve* more quickly than non-hierarchic systems of comparable size (Simon gives a fable of two watchmakers, one produces watches simply by assembling them all the time from the basic elements, the other and more effective one assembles subassemblies into larger subassemblies, and so forth). That is, the existence of stable intermediate forms exercises a powerful effect on the evolution of complex forms.¹³ Simon compares natural selection to a problem solving strategy that relies on selectivity of the feedback of information from the environment and of the previous experience (Riedl 1978 has elaborated on this point). Whereas in a decomposable system, such as a gas, the intermolecular forces will be negligible compared to those binding the molecules, complex hierarchic systems are often *near-decomposable*, the interactions among the subsystems are weak but not negligible, that is, the short-run behavior of component subsystems is approximately independent of short-run behavior of other components, but in the long run, the behavior of any one of the components depend (eventually only in aggregate way) on the behavior of other components. The fact that many systems have a nearly decomposable, hierarchic structure enables us better to understand, describe, or "see"

such systems and their parts (Simon muses on the possibility that we might not even detect complex systems that are not hierarchic to some extent). Thus, Simon emphasizes that the common supposition that the description of a complex system would itself be a complex structure of symbols might be true, but it might as well be wrong. We can often abbreviate a very detailed description by 'chunking' up its parts. He remarks (*ibid.*, p.478) that "if a complex structure is completely unredundant — if no aspect of its structure can be inferred from any other — then it is its own simplest description. We can exhibit it, but we cannot describe it by a simpler structure". (This is what later was called an algorithmic complex structure; complex in the sense of incompressibility of its description, cf. Chaitin 1987). Hierarchic structures have a high degree of redundancy, and hence can be described in economical terms (compare Dennett 1991). Simon saw that we can have rather simple descriptions of complex systems. Such descriptions can be either state descriptions of the observed complete structure, or process descriptions, a kind of recipe for generating the structure (such as differential equations of continuous systems, or state transition rules for finite automata or other discrete systems).

This anticipates the meaning of complexity as studied by the Santa Fe Institute-inspired research programme of complex systems research in the 1980s and 90s, with its repeated emphasis on the emergence of complex patterns or collective behavior through the repeated low-level interactions between 'agents' governed by simple and local rules. Thus, from Herbert Simon in the early 1960s (with its boom in cybernetics, information theory, general systems theory, and artificial intelligence) to people such as Stuart Kauffman, John Holland, Chris Langton, Heinz Pagels and Murray Gell-Man in the 1990s (with chaos theory, complex adaptive systems theory, artificial life etc.) one can locate a set of cognate ideas about complexity that are deeply related, but not identical. A list of these ideas may look like this (references are not meant to signify priority in the particular case):

- Complex systems are often hierarchic (Pattee 1973, Allen and Starbuck 1982).
- Simple laws or simple rules of behavior may generate complex behavior (Gleick 1987; Wolfram 1984a,b). Thus, a complex system does not necessarily require a complex, long description (it does not

have to be ‘complex’ in the algorithmic sense¹⁴).

- In physics such phenomena are exemplified by phase-transitions, broken symmetries, dynamical instabilities and self-organization (Anderson 1972, 1991). Time-asymmetric self-organization — from small and meso-scale phenomena to the cosmic scale, from the time of the big bang (with its simplicity and featurelessness) to the present — is a real phenomenon of the physical universe.
- Hence, with the study of complex phenomena, time-asymmetry, chance, irreversibility, and as a consequence, *history* has entered hard science (Prigogine and Stengers 1984).
- Complex phenomena exhibit collective behavior on the macro level, and involves often “spontaneous pattern formation”. These patterns can be seen as *emergent* properties that are new (not pre-existing), not trivially predictable, and characteristic of the whole, not its parts (Goodwin 1994; Baas 1994).
- It is conceivable (though controversial) that the emergent large-scale patterns can re-influence the small-scale interactions that generated them, by a sort of ‘downward causation’ (Campbell 1974; Andersen et al, in prep.).
- Complex emergent phenomena can be simulated (if not realized, cf. Pattee 1989) by a computer, often by emulating an architecture of massive parallel information processing. The computer is a prime instrument for studying complexity (e.g., Wolfram 1984a, Knudsen et al., 1991).
- For living beings, complexity reflects the genotype-phenotype duality and the crucial dependence on an informational mode of working of the system (von Neumann 1966; Pattee 1977; Hoffmeyer 1996).
- Complexity is a genuine historical phenomenon (Mayr 1982; Gould 1989), it takes long evolutionary time to generate complex patterns, in nature as well as in formal systems (cf. Bennett 1986; Lloyd and Pagels 1988).¹⁵
- For complex living systems there are special and not fully understood relations between (a) natural selection (which is non-directively ‘tracking’ the environment as it changes randomly), (b) developmental and other ‘constraints’ on natural selection (Maynard Smith et al. 1985), and (c) generation of organization ‘for free’ due to general principles of self-organization (Kauffman 1993).
- Complexity is located between high physical order and high physical

randomness (Hogg & Huberman 1985), in the 'chaotic' zone (in the sense of chaotic attractors in dynamical systems) where the system is sufficiently flexible and able to store, transmit and transform ('compute') information (Bak et al. 1988; Langton 1992; though see Mitchell et al. 1994).

- Complexity may need explanations of another type than simple reductionist ones; complex multi-level systems with biologic functions or with consciousness may need both effective, functional, form-like and intentional explanatory modes (Kant 1790; Rosen 1985; Popper 1982; Emmeche *et al.* 1997).

These claims may all except perhaps for the last one be mutually reconcilable, but we can add two further claims, namely

- Complexity denotes a common, general phenomenon that can in principle be discovered by science and defined as a universal physical quantity (e.g., Lloyd and Pagels 1988).
- Complexity does not denote any essentially common or generic phenomenon, as a term it may be viewed as denoting a diverse set of concepts with certain family similarities (e.g., Brandts 1997).

The latter stance is best in accord with the view explained above that descriptive complexity is, per definition, an observer-dependent notion. It requires specification of a frame of reference for any given complex system to be described. There can always be chosen among several possible frames that cannot be reduced to one another. Let us finally mention some problems where philosophy hopefully can contribute with conceptual clarity, or at least contribute to locate where to look for solutions.

6. *Dynamics and computation*

The computer has become an seductively attractive metaphor for a complexity-generating natural system. An unresolved issue is how we conceive of the relation between 'information', 'computation', and a natural complex system (Emmeche 1994). Among the new notions of complexity a prominent one is the idea of simulating Nature's complex causal net-

works on a computer (by, e.g., generating beautiful ‘organic’ patterns by constantly iterating simple rules such as the branch- and leaf-formation rules in ‘algorithmic plants’ (Prusinkiewicz and Lindenmayer 1990)). This has been very fruitful for modelling purposes, but it also seems to imply that even a natural system somehow ‘computes’ its next state in an algorithmic fashion, where the laws of nature correspond to the algorithms of a computer programme. To give an example, if Stephen Wolfram is right, then *computational irreducibility* may not be just a special property of some formal systems, related to the famous Halting Problem in computer science, and implying that there is no faster way (no ‘master algorithm’, no general decision procedure) to determine the output of a computer programme than to run the program. Rather, it may be equivalent to some deep fact about natural complexity, namely that simple physical laws are not enough to enable us with an adequate description of complex phenomena, because what is important is the very process that generates (‘computes’ as it were) this complexity.

Nothing is wrong with good metaphors so long as we don’t take them as reality. But here enters the unresolved issue of what computation (and information) really is. We can distinguish two basic views, (a) that computation is an intrinsic, natural property of a system’s time-evolution; and (b) that computation is an observer-relative, ascribed property, dependent on intentional human observers. As an example of (a) I will give a quote from Dufort and Lumsden (1997, p.70): “There is no question that naturally occurring analog systems with continually varying state variables like the brain and the cytoplasm do in fact process information, or “compute”, at some level (...). This, in general terms, is exactly what computers do”. (And, by extension, what most ‘natural systems’ do if they can be described as dynamical and continuous!). The contrasting viewpoint, (b), is represented by J. R. Searle (1992, p.223): “an outside agent encodes some information in a form that can be processed by the circuitry of the computer. (...) The computer then goes through a series of electrical stages that the outside agent can interpret both syntactically and semantically even though, of course, the hardware has no intrinsic syntax or semantics: It is all in the eye of the beholder”. So if we ask Searle whether the brain is intrinsically computational, “the answer is trivially no, because nothing is intrinsically computational, except of course conscious agents intentionally going through computations” (p. 225, *ibid.*). Probably Searle would not object to Dufort and Lumsden’s

suggestion that if a computer can be considered as a dynamical system, then perhaps a dynamical system can also be thought of as a computer — because anything could be considered as anything else from a particular point of view; the fruitfulness of such a perspective must be tested in practice — but Searle (or viewpoint (b) in general) would be sceptical about the suggestion that computation and dynamics may be “dual representations of the same underlying phenomenon” (Dufort and Lumsden, p.69), because it should be recognized that, even though dynamics and computation may be viewed as equivalent, an algorithmic emulation of a system behaviour does not necessarily correspond to what the system actually does (cf. Brandts 1997, p. 63); here a distinction must be made between ‘simulation’ and ‘realization’ (as also emphasized in the writings of Rosen, Pattee and Cariani).

An inherent shortcoming of the dynamical systems approach as well as the computational approach to understand self-generating complexity is that the primitives of such systems, as well as their state spaces, even though very large, are pre-defined and fixed from the outset for a given model, which makes it a dubious means to represent what we intuit as genuine creative natural phenomena, the irreducible emergence of new properties seen in the biologic evolution of complex systems, such as the appearance of new functional relations between enzymes and genes in metabolism (for a long argument, see Kampis 1991).

A related problem is that most quantitative measures of complexity are based on information theory (eventually in the version of algorithmic information theory) where the properties only apply to formal (computational) systems, and fail to take into account the difference between syntax and semantics (Brandts 1997). And biologic systems surely seem to contain a kind of biologic meaningfulness, some kind of intrinsic information (*pace* Searle) that acts as a partial specification of the construction process of development. Rolf Landauer (1988) observed the danger that the concern with the formulation of a definition of complexity comes at the expense of clearer questions, for example, does a system that can give rise to open-ended evolution need a minimal degree of spatial heterogeneity and other kinds of complexity? (confer the ideas of von Neumann above). Neither simple nor complex quantitative measures of complexity will in themselves bring us an understanding of complex living systems — to my opinion the most basic kind of systems that we deem complex. Perhaps what should be sought for is another idea of what

‘understanding’ a complex system really could be like, other than the reductive top-down decomposition and the corresponding bottom-up re-synthesizing. Perhaps we need a more fundamental change of modelling framework to bring not only biology, physics and mathematics, but also the human sciences in closer contact with an emerging understanding of complexity. And perhaps such an understanding will make the very notion of complexity as an essential generic phenomenon look naive.

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NOTES

1. See the popular and semi-popular writings about “the sciences of complexity” of Coveney and Highfield 1995; Brockman 1995; Kauffman 1995; Ravn *et al.* 1995; Goodwin 1994; Gell-Man 1994; Lewin 1992; Waldrop 1992; Pagels 1988; Gleick 1987; Rucker 1987; Poundstone 1985.
2. p. 232 in Callebaut 1993.
3. though I have tried to characterize Artificial Life as close to being one, see Emmeche 1994.
4. The numbers given here collected from various sources are, of course, rough estimates that may vary according to the source, this is, however of minor importance to the general point I want to make: That generation of living complexity can be seen in cosmic perspective, as an outcome of evolutionary processes, and that the sciences try to map out this sequence.
5. One familiar reason for the high level of scepticism among biologists (cf. the discussion of McShea’s critique below) is the unlucky historical coupling of the modern western idea of progress and perfection in evolution (which is highly ideological, of course) with the notion of a tendency to see increasing complexity in evolution. Present day biologists reject talking about ‘higher’ or ‘lower’ organisms in any absolute sense and refuse teleological and finalistic notions of evolution. A critique of the ideological structure of progressionist evolutionism in biology is Gould (1989), see also the discussion in chapter 7 in Lewin (1992).
6. Karl Popper emphasized both non-reductionism, the incompleteness of any particular scientific description, and the openness and indeterminate character of the evolution of the universe. See Popper 1974, 1978, 1982.
7. Compare again Depew and Weber (1995, p. 390): “Narrativism in biology is one way of acknowledging ineliminable complexity.”
8. or we might say that a very satisfying model of DNA’s structure was

- constructed.
9. such a system as for instance *Mycoplasma genitalium* is not known to be “the simplest organism” but is probable close to be this; see Wells 1997.
 10. A critique of McShea is also formulated by Hoffmeyer (1996, p.60 f), who remarks that over and above morphological complexity, “one ought obviously to allow, at the very least, for behavioural and social complexity”. Hoffmeyer proposes increase in “semiotic freedom”, i.e., in the richness or ‘depth’ of meaning that can be communicated among organisms as a better measure for complexity, but at the same time he warns against attempts to quantify such a notion. From the perspective of Complex Systems research, a related view is stated by Norman Packard (in Lewin 1992, p. 137 ff.).
 11. Even though Wimsatt’s idea is quite productive, it is not obvious how to decide (e.g., in his example, see his figure 1) whether there is coincidence “spatially” or not, because some of the descriptive decompositions are not tied to space at all, such as with the cybernetic flow diagram for the fruit fly, which is more like a functional scheme.
 12. The organicist, emergentist, and co-founder of the modern synthetic theory of evolution, Ernst Mayr accepts this notion of complexity (Mayr 1982, p. 52), which can be related to emergence of new properties of the whole, defined clearly as either deductive emergence or observational emergence (Baas 1994).
 13. This is recognized today in molecular evolution, where the origin of new proteins is often explained as recombinations of older sequences coding for earlier proteins or sub-domains of proteins. The genome of a multicellular organism is the product of a long process of ‘shuffling’ of ancestral precursors to its component genes.
 14. Following the theory of algorithmic complexity by the American mathematician G. Chaitin, many bit-strings can, due to their redundant content, be reduced or compressed with no loss of information (known from image compressing algorithms of practical importance for image transmission and -processing). Such strings are non-random. Random strings, however, cannot per definition be compressed further, they are in this sense their own shortest description. The length of any string measured in bits express the amount of ‘differences’ (yes/no-answers to questions) needed to describe a structure unambiguously. As a measure of complexity it has the problem that very disordered, ‘noisy’, ‘high-entropic’ systems comes out with a high measure of algorithmic complexity, and thus it fails to capture the intuitive property of a complexity measure to vanish both for the very ordered and the very disordered.
 15. The computer scientist C. H. Bennett has suggested a measure for a struc-

ture's degree of *complexity*, namely its logical depth. Logical depth is defined as the time needed (measured as number of computational steps) for the shortest possible program to generate the structure; i.e., the time consumption from the input (the minimal algorithm) to the resulting output (Bennett 1986). A true deep structure is thus characterized by the mathematical property that it cannot be generated faster (by fewer computational steps) via a simulation on any other computer.

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