Complexity Definitions (Evolutionary Biology)

1. Dietrich Fliedner's "6 levels of Complexity"[1] –

From the point of view of Biotic & social processes, there could be a 6-point scale that can be identified, which create a multi-level description of complexity-based processes:

Level 1 - the process takes place mainly between 2 concrete participants (simple movement). Control is exercised by the environment and it could not as yet be regarded as a system (solidum).

Level 2 - the process orders the movements; it is horizontally (temporally) oriented and passes in each case through several (4) stages (movement project). The system is the sum of the elements and orders itself through its elements (equilibrium system).

Level 3 - the process distributes energy (demanded products), it is vertically (between superior and inferior environment, market) oriented and passes in each case through several (4) bonding levels (flow process). The system is more than the sum of its elements and it regulates itself as a whole (flow-equilibrium system).

Level 4 - the process converts energy into products; it is horizontally (temporally) oriented and passes in each case through a number (8) of stages (7 by overlapping - process sequence); it is based on division of labour. Each system organises itself structurally as a whole (non-equilibrium system).

Level 5 - the process is vertically (hierarchically) oriented and in each case passes through the hierarchical levels (with overlapping). Each system generates itself structurally by organising its elements and subsystems (hierarchic system).

Level 6 - process is horizontally (spatially) oriented and probably passes much larger number of spheres (13 with overlapping) in each case (universal process, universal system). Each system within the spheres generates itself materially: autopoiesis.

2. Basic Premises (Claus Emmeche)[2] –

"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"

> *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, etc.) 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).

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[1] Journal of Artificial Societies and Social Simulation vol. 4, no. 1

[2] *Philosophica* vol. 59, 1997 (1), pp. 41-68

Ontological complexity. Something is complex in the ontological sense (disregarding whether we can know it completely or not), when it is organised 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 degenerate version of complexity in this sense is a system whose components are simple but have complicated relations that give rise to a special higher-order behaviour). 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.

Complex dynamic systems (sometimes called complex adaptive systems3), which refers to self-organising systems, co-operative behaviour of agents and non-linear dynamic systems that create emergent properties during their time evolution. Here there can be quantitative measures of the complexity degree of systems, based on such notions as logical depth,4 hierarchical structure, 5 algorithmic complexity, 6 or measures related to Shannon's information entropy concept.7 Work here is also related to interesting puzzles in chaos theory, artificial life and neural networks.

Some other related issues dealt with by philosophy of science at large need also be mentioned here. Amongst these, it is possible to refer to the role of causality, inter-level relations or scientific prediction,[8] the implication of complexity for the ‘disunity of science' and instrumentalism in biology.[9] There are also wider implications of the transition from a classic, simplifying paradigm to a new ‘complexity paradigm' of science.[10] Possibly, complexity as focused on “self-synthesising” wholes is becoming a central part of a new scientific mode of thinking, substituting the supposed “analytical” reductionist mode.

3. Note about complexity and social sciences -

In social sciences, the notion of complexity is mostly associated with such issues as complicated social systems, differentiation and segmentation of such systems, or various processes of decision making in these systems that rely on incomplete information. Many times, this is associated with the exposure of social systems to a much greater ‘information

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[3] Gell-Mann, M. (1994), *The Quark and the Jaguar*. New York: W.H. Freeman

[4] Bennett, C.H. (1988), `Logical depth and physical complexity', p. 227-257 in: R. Herken (ed.): *The Universal Turing Machine, A Half-Century Survey.* Oxford: Oxford University Press

[5] Simon, H.A. (1962), `The Architecture of complexity', *Proceedings of the American Philosophical Society* 106 (6): 467-482; Huberman, B.A. & Hogg, T. (1986), `Complexity and adaptation', *Physica* 22D(1-3): 376-84

[6] Chaitin, G.J. (1987), Information, Randomness & Incompleteness, Papers on Algorithmic Information Theory, World Scientific, Singapore (2nd ed.: 1992)

[7] Grassberger, P. (1986), `Toward a quantitative theory of self-generated complexity', *International Journal of Theoretical Physics* 25(9):907-938

[8] Newman, D.V., 1996: `Emergence and strange attractors', *Philosophy of Science* 63: 245-261; Andersen, P.B., Finnemann, N.O., Christiansen, P.V. and Emmeche, C. (eds.) (in prep.): *Downward Causation - Minds, Bodies and Matte*

[9] See, for example, the debate between Dupré and Rosenberg - Dupré, J. (1993), *The Disorder of Things: Metaphysical foundations of the disunity of science.* Cambridge: Harvard University Press; Rosenberg, A. (1994), *Instrumental Biology or the Disunity of Science*. Chicago & London: University of Chicago Press

[10] E.g., Morin, E. (1977-1991), *La Méthode*. 4 vols. Paris: Seuil

pressure' than what they can handle in real time by rational methods. It is often referred to as "complexity reduction" since such a situation might require to reduce this complexity, partly, arbitrarily. The result is that a selected action might simply be taken out of a large set of just as reasonable possible actions, but the very decision to select one particular action reduces the complexity. The particular selected possibility, manifested through an action, is subsequently ascribed a higher value.[11]

Reduction of complexity is also reflected in any system's own self-observation, because no system can possess total self-insight. In the same fashion, it can be said that complexity reduction in scientific research is not necessarily abstracting right properties out of a physical system, or choosing a crucial experiment, making an inference to the best explanation, or choosing between alternative theories underdetermined by data. Rather, it might be the epistemological concerns suggested by traditional philosophy of science.

4. Evolutionary biology paradigm -

A commonly accepted paradigm in the realm of evolutionary biology is referred to as "the modern synthesis" but it may well be related to as some sort of neodarwinian approach. In a nutshell, it asserts that the more modern a system is the more complex it gets.

This also means that biology should be considered as "the science of living complexity." It draws from the old idea that life, or living systems are characterised as being *organised,* i.e., more complex, than inorganic systems in Nature. This can be linked to the 1802 first use of the term "biology" by Jean Baptiste Lamarck which, for him, was a denotation of the study of all which is pertaining to "living bodies, their organization, their developmental processes and their structural complexity".[12] Two other lines of research must be mentioned here: One is molecular biology – which led to the discovery of the chemical structure of DNA in 1953. The other is the computational (or mathematical) study of artificial autonoma – mainly, as treated by Johm von Neumann. Here, the von Neumann threshold of complexity should be mentioned:

> "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."[13]

The basic idea is that complexity works in somewhat dual manner as a principle of complementary modes of existence - or description - of a complex living system.

On the one hand, there is a mode which can be regarded as 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.[14] Only simple

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[11] This approach is represented in Luhman, N. (1987), *Soziale Systeme. Grundriß einer allgemeinen Theorie*. Frankfuhrt/Main: Suhrkamp Tachenbuch Verlag. It can be applied to natural sciences.

[12] G. Treviranus and K.F. Burdach independently invented the same term in 1800.

[13] von Neumann, J. (1966), *Theory of Self-Reproducing Automata*, edited and completed by A. W. Burks. Urbana: University of Illinois Press, p. 80

[14] See the model offered by Pattee, H.H. (1977), `Dynamic and Linguistic Modes of Complex Systems.' *Int. J. General Systems* 3: 259-266; Pattee, H.H. (1979), `The complementarity principle and the origin of macromolecular information', *BioSystems* 11: 217-226

systems can exist by just one mode, complex systems need complementary modes to keep alive in the evolutionary game. In this manner, the passage from simple proto-cells containing polymerising macromolecules such as polypeptides and polynucleotides to real organised 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. With this biology and biochemistry had advanced far beyond the models drawn by Lamarck, Darwin or Mendel, enabling much better understanding of complex living things.

The other attitude was inspired by universal, abstract, mathematical and physical approaches to dynamical systems. It enabled a better understanding of the logic and 'universal' nature of complexity. Neither, however, has been able to explain what exactly complexity in living systems is. But still, it is possible to deduce that 'semiotic competence' as sign of interpretation capacity[15] is a prerequisite for complex living systems – otherwise also known as "information processing capacity." [16]

Ontologically, it can be construed that the von Neumann threshold of complexity reflects a separation between the first two primary ontological levels of reality - the physical and the biological, [17] where the biological one consists of a set of properties that represent the characteristics of life. Various biological paradigms suggest different definitions of life: autocatalytic self-reproducing autonomous systems; autopoietic systems; evolution by natural selection of replicators, biosemiotic systems, etc. However, they all look at life as an emergent phenomenon.[18] They also link complexity, life and elaborate semiotic processes to one another thus enabling more precise notion of complexity as an emergent phenomenon.

5. The Emmeche list of "notions of complexity" -

It is possible to associate ideas about complexity that are deeply related, but not identical. A list so constructed might take the following format:

> Simple laws or simple rules of behaviour may generate complex behaviour.19 A complex pattern may be generated by simple mechanisms, hiding an order that can be expressed in a compressed form.
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> In physics such phenomena are exemplified by phase-transitions, broken symmetries, dynamical instabilities and self-organisation.20 The study of complex phenomena enable

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[15] Hoffmeyer, J. (1996), *Signs of Meaning in the Universe*. Bloomington: Indiana University Press

[16] In this regard, see also Carello, C., Turvey, M.T., Kugler, P.N., and Shaw, R.E. (1984), `Inadequacies of the Computer Metaphor.' p. 229-248 in: M.S. Gazzaniga (ed.): *Handbook of Cognitive Neuroscience*. New York: Plenum Press

[17] Emmeche, C., Køppe, S. and Stjernfelt, S. (1997), `Explaining emergence: Towards an ontology of levels', *Journal for General Philosophy of Science* 28: 83-119

[18] Emmeche, C. (1997), `Autopoietic systems, replicators, and the search for a meaningful biologic definition of life', *Ultimate Reality and Meaning* 20 (4): 244-264

[19] Gleick, J. (1987), *Chaos. Making a new science.* New York: Viking Penguin; Wolfram, S. (1984a), `Cellular automata as models of complexity', *Nature* 311: 419-424; Wolfram, S. (1984b), `Universality and complexity in cellular automata', *Physica D* 10: 1-35

[20] Anderson, P.W. (1972), `More is different', *Science* 177: 393-396; Anderson, P.W. (1991), `Is complexity physics? What is it?', *Physics Today*, July `91, p.9-11

to look at time-asymmetry, chance, irreversibility - and thus also history in terms of hard science.[21]

For living beings, complexity reflects the genotype-phenotype duality and the crucial dependence on an informational mode of working of the system.[22]
Complexity is a genuine historical phenomenon;[23] it takes long evolutionary time to generate complex patterns, in nature as well as in formal systems.[24]
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,[25] and (c) generation of organization ‘for free’ due to general principles of self-organization.[26]
Complexity is located between high physical order and high physical randomness,[27] ‘on the edge of chaos’, i.e., near 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.[28]

6. Self Organisation (Umur Ozkul) -

Evolutionary system cannot merely be a simulation of life. Rather, we can look at it as more like a selection of proper building blocks. During the symbiosis of the mitochondria and the host cell, the DNA had already developed elaborate machinery. Similarly, if some of the tools are missed, the system could still get elaborate enough so as to gain expertise for the next developmental (or evolutionary) era. Nevertheless, we do not know yet if such a system can give results in a feasible duration.

It therefore might be preferred to base an evolutionary system on a pure functional language. Functional languages are so elegant that:

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[21] Prigogine, I. & Stengers, I. (1984), Order out of Chaos. Man's New Dialogue with Nature. Toronto: Bantam Books (La Nouvelle Alliance: Metamorphose de la Science. Paris: Gallimard 1979)

[22] von Neumann 1966; Pattee 1977; Hoffmeyer 1996, op cit.

[23] Mayr, E. (1982), The Growth of Biological Thought. Diversity, Evolution, and Inheritance. Cambridge: The Belknap Press, Harvard University; Gould, S.J. (1989), Wonderful Life: The Burgess Shale and the Nature of History, New York: W.W.Norton & Company

[24] *Cf.* Bennett, C.H. (1986), `On the nature and origin of complexity in discrete, homogeneous, locally interacting systems', *Foundations of Physics* 16 (6), 585-592; Lloyd, S. and Pagels, H. (1988), `Complexity as thermodynamic depth', *Annals of Physics* 188: 186-213

[25] Maynard Smith, J., R. Burian, S. Kauffman, P. Alberch, J. Campbell, B. Goodwin, R. Lande, D. Raup & L. Wolpert (1985), `Developmental constraints and evolution', *Quarterly Review of Biology* 60(3): 265-287

[26] Kauffman, S. (1993), The Origins of Order. Self-organization and selection in evolution. Oxford: Oxford University Press

[27] Hogg, T. & Huberman, B.A. (1985), `Order, complexity, and disorder', Xerox Palo Alto Research Centre

[28] Bak, P., Tang, C., Wiesenfeld, K. (1982), `Self-organized criticality', *Physical Review A* 38 (1): 364-374; Langton, C. G. (1992), `Life at the edge of chaos', pp. 41-91 in: C. G. Langton *et al.*, eds.: *Artificial Life II* (= Santa Fe Studies in the Sciences of Complexity, vol. X). Redwood City, Calif.: Addison-Wesley; Mitchell, M., Crutchfield, J.P., Hraber, P.T. (1994): `Dynamics, computation, and the `Edge of Chaos': a re-examination', p. 497-513 in: G. Cowan, D. Pinesand D. Meltzer (eds.): *Complexity: Metaphors, Models, and Reality.* (= Santa Fe Institute Studies in the Sciences of Complexity, Proceedings volume XIX), Redwood City, Calif.: Addison-Wesley

They are mathematically reducible. Straightforward optimizations are possible. Equivalence of programs can be shown.

Semantics of a functional language can be written in itself. The best way to have an interpreter written by the language itself.

They easily allow object oriented extensions.

They can be compiled for massive concurrency.

They can be very intuitive and pedagogic.

They can pave programs striving for artificial intelligence.

Data is constant functions or functions are data, vice versa. Thus the evolutionary system is promising to evolve programs processing other programs (or itself)! These properties of functional languages might lead to interesting developments.

Currently, genetic programming, genetic algorithms, artificial life is massively making use of random number generators. Unfortunately, to generate every single random number, some 5 million transistors are used in a computer for a considerable fraction of a second. However sometimes nature seems to use, instead of random numbers, chaotic series that emerge as a naive property of dimensions at which you are faced with quantum effects.

7. Constructing synthetic approach (Francis Heylighen[29]) -

The study of complexity – particularly when taken to the province of evolutionary biology - demands a transcendence of the holism-reductionism polarity. Perhaps the simplest way to visualise a model which would satisfy these two seemingly contradictory requirements is to consider the (mathematical) concept of a network. A network consists of nodes, usually represented as points, and connections between nodes, usually represented as arcs or arrows leading from one point to another. The nodes can be viewed as the distinct parts of the complex network (= plexus), the connections as the relations which braid these elements together. Inversely, the nodes can be viewed as connections, tying together the arrows, whereas the arrows can be viewed as distinct elements.

The reductionistic approach may be formulated simply as a method which tries to eliminate as much as possible the connections, whereas the holistic approach eliminates as much as possible the distinctions between the nodes. In this sense both methods "reduce" a complex phenomenon to a basically simple entity (either a set of nodes or an undifferentiated whole) by neglecting an essential part of its features. If influence is exerted on one of the parts (e.g. a node) of the complex, this influence will propagate to the other nodes through the connections.

However, since the nodes have distinct positions or functions in the network, each of them will react in a different way. Moreover, without analysing the network in detail and hence destroying it, we cannot have a complete knowledge of how each will react. This means that in general we cannot predict how a complex system will react to any influence, originated by the observer, by the environment or by its own dynamics.

Equivalently, we cannot retrodict or reverse its evolution either, i.e. we cannot reconstruct its past by collecting information about its present behaviour.

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[29] See: Heylighen, F., “Building a science Of complexity”, Proceedings of the 1988 Annual Conference of the Cybernetics Society

8. Complexity in evolutionary biology: account of the American Academy of Science[30] -

A definition drawn from the realm of information identifies genomic complexity with the amount of information a sequence stores about its environment. Investigation into the evolution of genomic complexity in populations of digital organisms and detail monitoring of evolutionary transitions that increase complexity show that because natural selection forces genomes to behave as a natural "Maxwell Demon", within a fixed environment genomic complexity is forced to increase.

Investigations into trends in the evolution of certain types of structural and functional complexity reveal some evidence of a trend that might indicate growth in complexity, but nothing is really conclusive. "Something may be increasing. But is it complexity?"[31]

Of course, complexity can be defined as "that which increases when self-organising systems organize themselves"[32]. But to address this issue, complexity needs to be also measurable.

Structural and functional complexity may well be examined by looking at genomic complexity. Genomic complexity may well be mirrored in functional complexity and vice versa. There is, however, a notable difficulty in matching genes with function.

Several developments could shed new perspectives to this old problem. On the one hand, genomic complexity can be defined in a consistent information-theoretic manner (the "physical" complexity[33]), which appears to encompass intuitive notions of complexity used in the analysis of genomic structure and organization.[34]

On the other hand, it has been shown that evolution can be observed in an artificial medium,[35] providing a unique glimpse at universal aspects of the evolutionary process in a computational world. In this system, the symbolic sequences subject to evolution are computer programmes capable of self-replicating through the execution of their own code. In this respect, they are computational analogues of catalytically active RNA sequences that serve as the templates of their own reproduction.

In populations of such sequences that adapt to their world (inside of a computer's memory), noisy self-replication coupled with finite resources and an information-rich environment leads to a growth in sequence length as the digital organisms incorporate more and more information about their environment into their genome.[36] These populations allow us to observe the growth of physical complexity explicitly and also to distinguish distinct evolutionary pressures acting on the genome and analyse them in a mathematical framework.

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[30] Adami, C., Ofria, C. and Collier, T. C., "Evolution of Biological Complexity", *Proceedings of the National Academy of Sciences*, USA 97 (2000) 4463-4468

[31] Mc Shea, D. W., *Evolution 50* (1996), 477-492

[32] Bennett, C.H. (1995) Physica D 86, 268-273

[33] Adami, C. & Cerf, N.J. (2000). *Physica* D 137, 62-69

[34] Britten, R. J. & Davidson, E.H. *Quarterly Review of Biology*, (1971), 46, 111-138

[35] Adami, C. (1998) *Introduction to Artificial Life* (Springer, New York); Lenski, R. E., Ofria, C., Collier, T. C., & Adami, C. *Nature* (1999) 400, pp. 661-664

[36] Evolution in an information-poor landscape leads to selection for replication only and shrinking genome size, as in the experiments of Spiegelman; see Mills, D.R., Peterson, R. L., and Spiegelman, S. (1967) *Proceedings of the National Academy of Sciences* USA 58, 217

9. Information Theory & Complexity -

Key aspect of information theory is that information cannot exist in a vacuum, that is, information is physical.[37]

In biological systems the instantiation of information is DNA. To some extent, it is the blueprint of an organism and thus information about its own structure. More specifically, it is a blueprint of how to build an organism that can best survive in its native environment, and passes on that information to its progeny. This view corresponds essentially to Dawkins' view of selfish genes that "use" their environment (including the organism itself), for their own replication.[38]

Thus, those parts of the genome that do correspond to something (the non-neutral fraction) correspond in fact to the environment the genome lives in. This view is referred to as "Genes embody knowledge about their niches".[39] This environment is extremely complex itself, and consists of the ribosomes the messages are translated in, other chemicals and the abundance of nutrients inside and outside the cell, the environment of the organism proper (the oxygen abundance in the air as well as ambient temperatures), among many others. An organism's DNA thus is not only a "book" about the organism, but is also a book about the environment it lives in including the species it co-evolves with. It is well-known that not all the symbols in an organism's DNA correspond to something. These sections, sometimes referred to as "junk-DNA", usually consist of portions of the code that are unexpressed or un-translated (i.e., excised from the mRNA).

More modern views concede that unexpressed and un-translated regions in the genome can have a multitude of uses, such as for example satellite DNA near the centromere, or the poly-C polymerase intron excised from Tetrahymena rRNA. In the absence of a complete map of the function of each and every base pair in the genome, it is difficult to decide which stretch of code is "about something" (and thus contributes to the complexity of the code) or else is entropy (i.e., random code without function).

Populations of digital organisms often evolved the ability to perform complex logic functions requiring the coordinated execution of many genomic instructions. Complex functions evolved by building on simpler functions that had evolved earlier, provided that these were also selectively favoured. However, no particular intermediate stage was essential for evolving complex functions. The first genotypes able to perform complex functions differed from their non-performing parents by only one or two mutations, but differed from the ancestor by many mutations that were also crucial to the new functions. In some cases, mutations that were deleterious when they appeared served as stepping-stones in the evolution of complex features. These findings show how complex functions can originate by random mutation and natural selection.[40]

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[37] Landauer, R. (1991) *Physics Today* 44(5), 23-29

[38] Dawkins, R. (1976) The Selfish Gene (Oxford University Press)

[39] Deutsch, D. (1997) *The Fabric of Reality* (The Penguin Press, New York), p. 179

[40] Lenski, R. E., Ofria, C., Pennock, R. T. & Adami, C., "The evolutionary Origin of Complex Features", Nature, Vol. 423 (May 2003), pp. 139-144

According to Daniel Dennett, "…evolution will occur whenever and wherever three conditions are met: replication, variation (mutation) and differential fitness (competition)".[41] A tractable system is required in order to shed light on principles relevant to any evolving system. Digital organisms are also of interest as computer scientists and engineers explore ways to apply evolutionary principles to program design, engineering and robotics.[42]

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10. Functional complexity[43] -

Functional complexity, or the number of functions of organisms, has figured prominently in certain theoretical and empirical work in evolutionary biology. Large-scale trends in functional complexity and correlations between functional complexity and other variables, such as size, have been proposed. However, the notion of number of functions has also been operationally intractable, in that no method has been developed for counting functions in an organism in a systematic and reliable way.

Thus, studies have had to rely on the largely unsupported assumption that number of functions can be measured indirectly, by using number of morphological, physiological, and behavioural "parts" as a proxy. Here, a model has been developed that supports this assumption. Specifically, the model was able to predict that few parts will have many functions overlapping in them, and therefore the variance in number of functions per part will be low. If so, then number of parts is expected to be well correlated with number of functions, and we can use part counts as proxies for function counts in comparative studies of organisms, even when part counts are low.

McSheah mentions a number of works that support the notion that use of parts can be a good indicator functional complexity. For example, the argument that selection for greater efficiency should favour increased division of labour within organisms, and therefore lead to an increase over the history of life in the number of different internal functions an organism is able to perform.[44] A umber of cell types can be used as a proxy for some internal functions, where the upper limit on number of cell types for metazoans has tended to increase.[45]

In fact, functional complexity should tend to increase on different grounds, namely that organisms with more functions are better able to accommodate more dimensions of environmental adversity, or take advantage of opportunities in more dimensions. In other words, increased functional complexity is advantageous in all or most lineages, and therefore

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[41] Dennett, D. in *Encyclopaedia of Evolution* (ed. Pagel, M.), Oxford Univ. Press, New York, 2002

[42] Holland, J. H., *Adaptation in Natural and Artificial Systems*, MIT Press, Cambridge, Massachusetts, 1992; Koza, J. R., *Genetic Programming*, MIT Press, Cambridge, Massachusetts, 1992; Lipson, H. & Pollack, J. B., "Automatic design and manufacture of robotic life forms", *Nature* 406, 974–978 (2000); Foster, J. A., "Evolutionary computation", *Nature Rev of Genetics* 2, 428–436 (2001)

[43] Daniel W. McShea, "Functional Complexity in Organisms: Parts as Proxies", *Biology and Philosophy* 15: 2000, pp.641–668

[44] Bonner, J.T., *The Evolution of Complexity*, Princeton, Princeton University Press, 1988

[45] Valentine, J.W., Collins, A.G. and Meyer, C.P., 'Morphological Complexity Increase in Metazoans', *Paleobiology* **20**, 1993, pp.131–142

will tend to increase, on average.[46] Correlation has been discovered - when using number of cell types as a proxy - between organismal size and number of internal functions.[47]

Increasing taxonomic diversity should produce an increase in the complexity of ecological roles and organisms with a greater number of different morphological “tools” should then evolve to fill those more complex roles. This means that increasing diversity demands increasing functional complexity, which in turn will be reflected in greater numbers of parts.[48]

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[46] Heylighen, F.,‘The Growth of Structural and Functional Complexity during Evolution’, in F. Heylighen and D. Aerts (eds), *Evolution of Complexity*, Kluwer Academic Publishers, Dordrecht

[47] Bell, G. and Mooers, A.O., ‘Size and Complexity Among Multicellular Organisms’, *Biological Journal of the Linnean Society* 60, 1997, pp. 345–363

[48] Cisne, J.L., ‘Evolution of the World Fauna of Aquatic Free-Living Arthropods’, *Evolution* 28, 1974, pp. 337–366