Functional Fractals in Biology

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We begin by quickly reviewing how reductionism as an ideology copes—or does not cope—with the complexity and indeterminacy of the living world. We then discuss the relationship between teleonomy, meaningful information, and cybernetics, with reference to its application to the study of informational processes in biology. Our goal is to outline the properties of what we call functional fractals (Núñez and De Marco 2007). We suggest that a functional fractal is an appropriate abstraction for theorizing about the organization of biological complexity.

Complexity and Indeterminacy

We subscribe to the view that the methodology appropriate for the physical sciences is not suitable for biology. As a branch of the natural sciences, biology has followed the path of physics. It has been based on observation followed by the collection and sorting of data using various classifications (like that of Linnaeus). The Darwin–Wallace ideas on common descent and natural selection nurtured biology with the theory required to tackle the complexity and diversity of the living world. In the 20th century, physics and chemistry advanced the study of nature using theory-consistent empirical analyses. Biology did not. In spite of increasing progress in evolutionary theory, 20th-century biology moved progressively into the analysis of elementary physical objects (von Holst 1956), being somehow invariant to the fact that any given analysis cannot be continued ad infinitum. In biology, many questions are not yet theory-consistent (for an example, see Rose 2009).

Greek philosophers advanced the view that matter is made of indivisible elements, thought as the minimum geometric limits of the physical world. It was the view that different substances and materials were made of variants of such "atoma" that led to useful classifications of matter (Mendeleev 1901). Founded on the idea that progress in science depends upon dissecting the physical world into its elementary objects, biology became the subject matter of physics and chemistry. As pointed out by Rose (1997: 296), however, "each level of organization of the universe has its own meanings, which disappear at lower levels." Living systems are undoubtedly complex. Unlike inanimate objects, they exhibit structural and functional organization, chemical uniqueness, variability, genetic programs, life paths, and historical nature. These properties are semantically crystallized through the concepts of pleiotropy and polygeny (Mayr 1982). In modern biology, the significance of these two concepts is frequently overlooked.

Biologists seem to pay little attention to the fact that wholes have irreducible properties, as postulated by Wiener (1948), von Bertalanffy (1968), Weiss (1969), and others. Either consciously or unconsciously, some subscribe to the idea that methodological reductionism can account fully for the structural and functional complexity of the living world, as proposed by Russell (1927) and other reviewers of the concept of emergence (Blitz 1992). Such reductionist philosophy has shaped the advancement of 20th-century biology. For example, think of the concept of a gene: The physical nature of Mendel's heredity elements remained elusive until 1944. When Johannsen (1909) coined the term "gene," he linked it to the "visible" traits (features) of an organism, without providing further speculations on the possible interactions and mutual dependence of those traits. In a few decades, the work by Morgan, Delbrück, Schrödinger, and others moved the subject matter of interest from visible traits to physiochemical entities (e.g., Morgan 1926; Timoféeff-Ressovsky et al. 1935; Schrödinger 1944). Avery et al. (1944) then reported that DNA was in fact the material of heredity. And shortly after the

February 17, 2009; accepted April 7, 2009
Biological Theory 3(4) 2008, 293–296.

elucidation of the structure of DNA, the enzymes responsible for DNA replication and the genetic code were discovered. Eventually, molecular biology arose as a branch of biology dealing with the properties of the genetic material, but not with the traits that had first led to the concept of genes.

Away from breeding experiments and heritability estimates, the study of the complex features of an organism turned into the study of molecular objects that cannot give rise to such features by themselves (exceptions to this rule arose from the analysis of mutant structural features; see, e.g., Kühn 1941, 1953). The concepts of traits and genes were no longer connected to each other as before. Traits now appear elusive outside population and evolutionary biology, and genes are regarded as fragments of DNA carrying information for the formation of proteins; what began as a theoretical conflation ended as an empirical one. Nowadays, the functional limits of genes are rarely discussed. The description of gene function is routinely limited to the characterization of feature variations in intracellular pathways or more general cellular processes like cell division or growth—or, more recently, also as variations in the average performance of experimental subjects as they move along tasks of elusive adaptive value. Yet, we agree in that what makes an organism is not the presence of a series of specific genes, but the unique assortment of genes of its entire genome. And we also recognize that genes are meaningless outside their interactions (Dover 2000), and that "genes and environments are dialectically interdependent throughout any individual's lifeline" (Rose 1997: 133). In short, we agree in that there are no one-to-one relationships between "modern" genes and traits.

On the background of modern evolutionary thought (Mayr 1982), biology's most recent sources of theory were cybernetics (Wiener 1948) and information theory (Shannon 1948). Less than a century ago, the advent of these two fields led to a complete reformulation of key concepts in vast areas of biology. And it was in such a scenario that reductionist methodology helped to explain the complex manifestations of the living world that the vitalists had assigned to an "élan vital," like goal-seeking behavior and communication. The notions of communication and control, for example, which were well developed in the context of engineering, led biologists to advance key concepts in physiology. Hormones were seen as messengers in a chemical communication channel; frequency modulation along axons was thought of as based on linear and nonlinear cable properties; muscle spindles were revealed as servomechanisms allowing the regulation of muscle contraction and voluntary movements; and so on. As Peter Corning (2001) points out, "cybernetic control processes are now routinely described and analyzed at virtually every level of living systems, inclusive of social, political and technological systems."

Eventually, the long-lasting controversy between vitalists and mechanicists was replaced by a more subtle debate between reductionists and students of complexity. Some maintained that all biology could be explained in terms of physics and chemistry (Crick 1966), while others subscribed to the view that the behavioral flexibility of an organism cannot be fully inferred by analyses of isolated constituents (Sinnott 1963). Today, as Rose (1997: 296) has noted, reductionism as an ideology "insists on trying to account for higher-level phenomena in terms of lower-level properties." And it does so by means of "a faulty cascade of reification, arbitrary agglomeration, improper quantification, belief in normative statistics, spurious localization, misplaced causation and the confounding of metaphors with homologues" (Rose 1997: 296). Technology gives a very simple solution to such a debate.

In technology, the task of optimizing the outcome of a system comprising a single-digit number of elements can successfully rely on mathematics. And the same is true if the number of components increases to some extent, but one still possesses substantial knowledge about the functional organization of the system as a whole. This is, however, virtually impossible if one deals with biological systems, for they comprise a number of elements and interactions which can never be determined (Rechenberg 1994). Further, the constellation of elements and interactions of any such system is essentially unique, and it changes with time and space. Most aspects of the living world cannot be mathematically described. In biology, predictions are only probabilistic (Scriven 1959). This indeterminacy fits neatly with the adequacy of natural selection for optimizing the functioning of naturally evolving systems.

Teleonomy, Meaningful Information, and Cybernetics

The complexity and indeterminacy of the living world do not preclude the advancement of biology. But the organization of biological systems has properties that are not reducible to physical order (Weiss 1971). This happens because the cybernetic processes embedded in any living system are fundamentally relational (Wiener 1948). They depend upon each other in such a way that it is only their joint action that allows the system to acquire and use energy efficiently. Thus, although following the rules of strong causality (Rechenberg 1994), cybernetic processes cannot even be described by the laws of physics (Corning and Kline 1998).

In cybernetic systems, purposeful work depends upon the usage of "meaningful" information (see Rapoport 1956; von Foerster 1980)—information based on semantics (Wicken 1987) rather than statistical order (Shannon 1948). From a functional perspective, meaningful information is not equivalent to thermodynamic entropy, but a derivative of the relationships of a system that reduces entropy (Rapoport 1956). Corning and Kline (1998) refer to meaningful information as "control information," which is defined and specified by the relationship between a particular cybernetic system and its environment. The existence and functional effects produced by control information are always context-dependent and user-specific (Corning and Kline 1998).

Systems theorists affirm that living systems are ordered by teleonomic processes using control information and feedbacks in specific system–environment relationships. It follows, therefore, that any suitable paradigm for theorizing about the functional properties of the living world will depend upon the study of highly integrated entities with purposeful behavior (Rosenblueth et al. 1943) and capacities for handling context-dependent and user-specific information. “Highly integrated” means that, irrespective of the variety of ways in which the physical processes of the media may be utilized for informational purposes, these entities will be invariant to their physical environments as long as these environments do not convey control information. If these functional entities are embedded in a higher-level system, then their very existence and purposeful behavior would only make sense in light of the behavior of the system as a whole, simply because their active behaviors will be part and parcel of the system they serve. Because they are functionally specified, they will be intangible in the absence of the whole. Yet, they may be methodologically accessible without risk of ontological damage (Lorenz 1973). At first sight, any such entity may be reminiscent of a black box (Ashby 1956). However, black boxes are specified by geometrical arrangements, and their possible functions are therefore constrained a priori. This is why their otherwise unknown contents can only be inferred via specific input–output relationships. By contrast, our functional entities are invariant to their geometry and physical media. They are fundamentally defined by the content of the information they handle, their capacity to gather and control energy in teleonomic processes, and the way in which they serve the work of a higher system. Because these properties can be measured and generalized, we shall refer to such entities as “functional fractals” (Núñez and De Marco 2007).

Mandelbrot (1975) coined the term “fractal” while referring to structures that show self-similarity and scale invariance. His landmark work led to full-fledged theories of the geometry of complex structures, which helped to describe irregular and fragmented geometrical patterns found in nature. In principle, fractals account for shapes, without reference to functions. Still, their self-similarity and scale invariance can be found in functional units for informational processing. (One might still argue about how to designate such units, but their very existence and features become evident even in highly complex human endeavors; e.g., Warnecke 1992.) In cybernetic terms, any such unit would be a functional fractal. A functional fractal is a naturally evolving cybernetic system. It is scale-free and has a measurable degree of independence from its physical media. It has its own dynamics and regulatory mechanisms, and it enhances a system’s capacity for purposeful behavior.

Take the following example: A single neuron cannot process complex sets of information arising from multiple sources of various physical properties, process them simultaneously so as to set a threshold level of response, and then control the activity of a target according to such level all by itself. But an array of neurons may be organized in such a way that the various sets of information are first filtered and processed by some neurons, integrated by additional ones, and finally used by a reduced number of neurons controlling the activity of the target (all done in milliseconds). From a functional point of view, the latter cybernetic system has a much greater capacity for handling information in purposeful work. Both the probability that information from the various sources is available at the same time and the adaptive value of the system’s response will shape the informational processing capacity and functional organization of the array of neurons. From the point of view of functional organization, the capacity to regulate a well-defined set of adjustable movements (e.g., Küpfmüller and Poklekowski 1956) can be thought of as a functional fractal. It follows that the structure of a functional fractal is shaped by its phenotypic efficiency in a context-dependent manner. (The question of whether such an abstraction may also be linked to a parallel, albeit second-order, functional unit of selection remains open.) The ultimate result of a multidimensional array of interrelated functional fractals is to enhance—and to stabilize—an organism’s capacity for handling meaningful information and for controlling the usage of energy. In this scheme, it will be the joint work of such units that accounts for the technical abilities of any living system at its highest level of organization.

Cybernetic processes are transformations that can be described consistently throughout various series of measures. Purposeful behavior depends upon cybernetic processes, although physical processes do not always appear to be purposeful. While physical processes relate to matter, technology relates to function. It works “with” matter in search of a goal. Technology thus focuses on strategies. We propose that strategies give rise to functional fractals, and that these entities are the smallest entities that can be meaningful to biologists. A functional fractal may be composed of one or more strategies, meaning that strategies may be shared between functional fractals. In this paradigm, any such entity cannot be entirely isolated because that would interfere with the work of other functional fractals. But this does not mean that they are not empirically accessible. In order to access them methodologically, the first step involves estimating their capacity for handling control information and for controlling the usage of energy. The second step involves characterizing their communication capacities as they work interactively with other functional fractals. The analyses should be technical (functional), and conducted under conditions closely mimicking natural events (contextual).

Current biology finds itself in a curious position. It has increasing analytical power, but it does not rejoice in complexity. More than two decades ago, Ernst Mayr stated that a new philosophy of biology was needed: "This will include and combine the cybernetic-functional-organizational ideas of functional biology with the population-historical program-uniqueness-adaptedness concepts of evolutionary biology" (Mayr 1982: 73). We believe that this requires renewed emphasis on the study of the technical organization of the living world, and suggest that the concept of functional fractals is an appropriate tool for theorizing about the organization of biological complexity.

References

Ashby WR (1956) An Introduction to Cybernetics. London: Chapman and Hall.

Avery OT, McLeod CM, McCarty M (1944) Studies on the chemical nature of the substance inducing transformation of pneumococcal types. Journal of Experimental Medicine 79: 137–158.

Blitz D (1992) Emergent Evolution: Qualitative Novelty and the Levels of Reality. Dordrecht, the Netherlands: Kluwer.

Corning PA (2001) The missing element in Norbert Wiener's cybernetic paradigm? Kybernetes 30: 1272–1288.

Corning PA, Kline SJ (1998) Thermodynamics, information and life revisited, Part I: 'To be or entropy.' Systems Research and Behavioral Science 15: 273–295.

Crick F (1966) Molecules and Men. Seattle, WA: University of Washington Press.

Dover G (2000) Anti-Dawkins. In: Alas, Poor Darwin (Rose H, Rose S, eds), 55–77. New York: Harmony Books.

Johannsen W (1909) Elemente der exakten Erblichkeitslehre. Jena, Germany: Gustav Fischer.

Kühn A (1941) Über eine Gen-Wirkkette der pigmentbildung bei insekten. Akademie der Wissenschaften [Nachrichten] 6: 231–261.

Kühn A (1953) Entwicklung und Problematik der Genetik. Nagturwissenschaften 40: 65–69.

Küpfmüller K, Poklekowski G (1956) Der regelmechanismus willkürlicher Bewegungen. Zeitschrift für Naturforschung 11B: 1–7.

Lorenz K (1973) The fashionable fallacy of dispensing with description. Naturwissenschaften 60: 1–9.

Mandelbrot BB (1975) Les objets fractals. Forme, hasard et dimension. Paris: Flammarion.

Mayr E (1982) The Growth of Biological Thought. Cambridge, MA: Harvard University Press.

Mendeleev DI (1901) Principles of Chemistry. New York: Collier.

Morgan LV (1926) Correlation between shape and behavior of a chromosome. Proceedings of the Natural Academy of Sciences USA 12: 180–181.

Núñez JA, De Marco RJ (2007) Technology and the foundations of biology. Biological Theory 2: 194–199.

Rapoport A (1956) The promise and pitfalls of information theory. Behavioral Science 1: 303–309.

Rechenberg I (1994) Evolutionsstrategie '94. Stuttgart, Germany: Frommann-Holzboog.

Rose S (1997) Lifelines: Biology, Freedom, Determinism. Harmondsworth, UK: Penguin.

Rose S (2009) Should scientists study race and IQ? No: Science and society do not benefit. Nature 457: 786–788.

Rosenblueth A, Wiener N, Bigelow J (1943) Behavior, purpose and teleology. Philosophy of Science 10: 18–24.

Russell B (1927) The Analysis of Matter. London: Allen and Unwin.

Schrödinger E (1944) What Is Life? London: Cambridge University Press.

Scriven M (1959) Explanation and prediction in evolutionary theory. Science 130: 477–482.

Shannon CE (1948) A mathematical theory of communication. Bell System Technical Journal 27: 379–423, 623–656.

Sinnott E (1963) The Problem of Organic Form. New Haven, CT: Yale University Press.

Timoféeff-Ressovsky N, Zimmer KG, Delbrück M (1935) Über die natur der genmutation und der genstruktur: Nachrichten der gesellschaft der wissenschaften zu Göttingen. Mathematische-Physikalische Klasse, Fachgruppe 6(13): 189–245.

von Bertalanffy L (1968) General System Theory: Foundations, Development, Applications. New York: Braziller.

von Foerster H (1980) Epistemology of communication. In: The Myths of Information: Technology and Postindustrial Culture (Woodward K, ed), 18–28. Madison, WI: Coda Press.

von Holst (1956) Zur Einführung. In: Regelungsvorgänge in der Biologie (Mittelstät H, ed), 7–8. Munich, Germany: R Oldenburg.

Warnecke HJ (1992) Die fraktale Fabrik: Revolution der Unternehmenskultur. Berlin: Springer.

Weiss P (1969) The living system: Determinism stratified. In: Beyond Reductionism: New Perspectives in the Life Sciences (Koestler A, Smythies JR, eds), 3–55. New York: Macmillan.

Weiss PA (1971) Hierarchically Organized Systems in Theory and Practice. New York: Hafner.

Wicken JS (1987) Evolution, Thermodynamics, and Information: Extending the Darwinian Program. New York: Oxford University Press.

Wiener N (1948) Cybernetics, or Communication and Control in the Animal and the Machine. Cambridge, MA: MIT Press.