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SEMIOSIS AND PHASE TRANSITIONS IN BIOLOGY: the Future of Biosemiotics within a Genuinely Evolutionary Conception of the World

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ABSTRACT

Since the days of Darwin and Wallace evolution has been a leading unifying factor in new biological theorizing, along with other key conceptual strands from thermodynamics, genetics and molecular biology. Physics, whose explanatory resources underpin those of the special sciences, has until quite recently stood impervious to evolutionary thought however. The thoroughly ahistorical conception of nature promoted by traditional physics, bundled with other philosophical preconceptions, conspired against any conceptual unification of physics with biology other than strict reductionism.

This article aims to show that new developments in both physics and biology promise prospects for reversing this situation by means of a non-reductive unification of physical and biological theories within a truly evolutionary natural philosophy—including cosmology. For several reasons, such an upcoming synthesis could become auspicious for the incorporation of biosemiotic ideas as central explanatory resources (in contrast to the present situation).

To develop the reasons behind this expectation, I offer first a summary of some remarkable developments in cosmology, particle physics, condensed matter physics, and biology, all of which relate to the notions of symmetry breaking, phase transitions and scale invariance. Next, I indicate how these trends merge with the rise of novel forms of causation (e.g., circular, downward, reciprocal) in systems biology and self-organization theories. Finally, I speculate on how the characteristic form of causation in biosemiotic transactions (i.e., semiosis) interlocks with those other types of causal relations found in living systems.

SEMIOSIS AND PHASE TRANSITIONS IN BIOLOGY

> *Thus the temperature of water is, in the first place, a point of no consequence in respect of its liquidity: still with the increase or diminution of the temperature of the liquid water, there comes a point*

> *where this state of cohesion suffers a qualitative change, and the water is converted into steam or ice.* Georg Wilhelm Friedrich Hegel, ***Logic***.

> *We then gave one of the best known examples, that of the transformation of the form of water which at 0 C. changes from a liquid to solid and at 100 C. from liquid to gaseous, where thus at both these points of departure a mere quantitative change in temperature produces a qualitative change in the water.* Frederick Engels, **Dialectics of Nature**.

1. INTRODUCTION

In recent decades, there has been an increasing urge in the fields of both physics and biology to reassess explanatory schemes and procedures under the challenge of unexpected and hard-to-assimilate revelations, whether experimental or theoretical. Here I will try to outline some changes in philosophical attitudes that have been fostered by the need to accommodate those new discoveries within the conceptual fabric of multiple disciplines.

This emerging outlook promises to create new cooperative links between the sciences, to their mutual benefit. If these links sufficiently mature, we can anticipate the rise of a highly unified conception of nature, in which the panoply of phenomena studied by the various sciences is perceived as localized cross-sections within a hierarchy of levels, forming a single evolutionary continuum. As a result, it is to be hoped that the sciences themselves would succeed in overcoming long-standing barriers that have conspired protractedly against their conceptual and explanatory integration.

Such changes in philosophical attitude stem from developments in several branches of physics in the second half of the twentieth century. These developments were brought about through the introduction of a common explanatory mechanism: the **breaking of symmetries during phase transitions**. Concepts and methods developed during the study of critical and scale-independent behavior in phase transitions have since been applied as a powerful tool for explaining a wide range of facts, as well as for the successful prediction of various novel phenomena. The unparalleled success of applying similar techniques (e.g., the normalization group and associated methodologies) across formerly unrelated disciplines and processes has promoted a new vision for the unification of the sciences —**one that does not depend exclusively on the reduction of theories to the single and most basic one**.

Philosophical reflection on the nature of these new conceptual tools and methods among physicists and philosophers has sparked a changed philosophical outlook concerning issues such as the emergence of novelty in nature, the limits of reductionist explanations and the relationship of physics to the so-called special sciences. In order to reach some understanding of this philosophical stance and **its import for the integration of semiotic ideas into biology**, it is expedient to review briefly the following topics:

1) A few basic notions concerning symmetry breaking in physics and the possibility of their extension to living systems

2) Some of the epistemological implications of these ideas for attaining a truly evolutionary conception of nature

3) The prospects that thereby unfold for a conceptual integration of physics and biology and, *a fortiori*, biosemiotics

2. PHASE TRANSITIONS

With hindsight, the ideas expressed in the epigraphs from Hegel and Engels appear as prescient adumbrations of the pervasive role of explanations involving phase transitions in contemporary science. What these thinkers foreshadowed under such vague expressions as "the transition of quantity to quality" is now perspicuously understood through the concept of symmetry breaking and through the role of this phenomenon in the emergence of ascending levels of complexity. This whole approach to the generation of novelty in nature has become encapsulated in the motto "*more is different*," echoing the title of Phillip Anderson's landmark paper (Anderson 1972).

Literature on the subject of emergence is vast and complex, dating back to ancient times and encompassing a multitude of separate, albeit interrelated, strands. All the same, for our purposes there are reasons to focus on the particular line of thought originating in Anderson's paper (or, with hindsight, in Hegel and Engels). This orientation is, as I hope to show, quite promising in regards to two central concerns of biosemiotics: 1) the place of semiotic transactions within the explanatory apparatus of the life sciences;

and 2) the functions of semiotic causation in the evolutionary emergence of life's characteristic features, such as autonomy, replication and purposeful behavior.

The viewpoint evoked by the maxim "more is different" arose as a reaction to an explanatory ideal of science that has been widely held, at least until recently. This ideal aspires to explain everything that transpires, at all scales and levels of reality, in terms of some fundamental entities and laws operating at a rock bottom, microscopic level (a *theory of everything*). Anderson's opposing standpoint came to light through a reflection on the role of symmetry breaking in the explanation of phenomena, such as phase transitions, in which different levels or scales of nature are simultaneously involved.[1]

3. CRITICALITY

To see how this unfolds, consider the example of the Hegelian qualitative transformations of the states of water, caused by quantitative changes of temperature. The term "phase" refers to a state of matter within which macroscopic properties are uniform. In the cited example these are liquid, ice and vapor. The transition from one phase to another is determined by the interplay of a few control parameters, in this case temperature and pressure. A phase transition is a drastic discontinuity in a property, such as density, at a particular (*critical*) point at which a function relating the control

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[1] The views originally articulated in *More is Different* have been expanded by Anderson himself and various other authors, most notably by Robert Laughlin and David Pines (see e.g., Anderson and Stein 1985, Laughlin and Pines 1999, 2000, Laughlin 2006). Among emergent phenomena Laughlin and Pines have called attention to what they call "protectorates." They appear in systems that display similar, generic behavior (universality) notwithstanding the fact that the details of their microphysical structure are quite different. The emergent properties of these states are said to be "protected" against changes at the low underlying scales. Anderson has given simple examples of functionality that is independent of the details of the underlying components: "One may make a digital computer using electrical relays, vacuum tubes, transistors, or neurons; the latter are capable of behaviors more complex than simple computation but are certainly capable of that; we do not know whether the other examples are capable of "mental" phenomena or not. But the rules governing computation do not vary depending on the physical substrate in which they are expressed; hence, they are logically independent of the physical laws governing that substrate." (Anderson 1995)

parameters undergoes a sudden discontinuity or divergence. The boiling and freezing points of water at normal barometric pressure are clear examples. Another typical example is the transition from paramagnetic to ferromagnetic behavior in an iron bar, when the temperature falls below the critical Curie point.

A critical phase transition marks the point at which one of the symmetries of nature (i.e. an invariance with respect to a group of transformations) is broken. In our example the molecules in liquid water move randomly in all possible directions and no special frame of coordinate axes is singled out. When the liquid's temperature falls below a critical threshold the water suddenly freezes. At that point a crystal structure is formed along one randomly selected set of axes. This means that the rotational symmetry (indifference with respect to all possible orientations) has been broken in favor of one particular direction.

Phase transitions are characterized by an *order parameter p*, which is a function $f(t)$ of a control parameter t, such as temperature. The function $f(t)$ varies continuously and takes the value 0 when it reaches the critical point. In first-order transitions (as in our water example) $f(t)$ becomes discontinuous at 0; in second-order transitions (as in our magnet example) the function is continuous, but its first derivative undergoes a discontinuity at 0. The order parameter is a **measure of the order** (deviation from the initial symmetry) realized in the system.

4. UNIVERSALITY AND SCALE INVARIANCE

At a critical point a system often exhibits a remarkable type of behavior properly known as *criticality*, which can best be understood in contrast to non-critical systems, which are typically addressed by traditional science. For non-critical systems the general procedure is to concentrate on a particular length or time scale of phenomena and disregard all others, by treating the values at larger scales as constants and by taking statistical averages for the values involved at the lower scales. Criticality is a characteristic of those dynamical systems for which this approach fails. The diverse scales cannot be separated in this manner because they are simultaneously involved in the generation of the critical behavior under consideration.

Criticality is often associated with *universality*. It was experimentally discovered that critical systems that are structurally different at the microscopic level could show remarkably similar behavior at and around their various critical points. Furthermore, it was shown that it is possible to characterize this "universal" conduct through the use of a power law with a critical exponent *e* that is the same for all those different systems. [2] Systems with the same critical exponent are said to belong to the same universality class.

Universality in phase transitions is intimately connected to the phenomenon of *scale invariance*. This refers to situations where processes or the laws that govern them do not change when scales (e.g., of length, energy, etc.) are multiplied by a constant coefficient. It is experimentally observed that near phase transitions fluctuations appear at all length scales. This suggests that a theory capable of explaining these phenomena must be explicitly scale-invariant.

Of great interest for this discussion is the fact that in phase transitions, analogous to what happens in living systems, the **global structure of the phenomena** causes changes in the behavior of the system at the local level, an instance of downward causation.

5. HISTORICITY OF THE ELEMENTARY PARTICLES AND THE COSMOS

Phase transitions and symmetry breakings are involved at the most basic level in the explanation of an exceedingly wide range of processes occurring at all levels and scales in nature—from elementary particles to the entire universe. An important fact for our purpose is that these explanations account not only for why these processes take place, but also for *why they emerge into existence at a point in time*. As Pierre Curie remarked in his famous 1894 paper, *the asymmetry creates the phenomenon.*

[2] Power laws and power law distributions appear everywhere in nature and the social sciences. They take the general form $y = y_0 x^e$ and when the data are plotted into a log-log graph they fall approximately on a straight line ($\log y = e \log x + \log y_0$). The scaling exponent *e* is often a fraction of one, for instance 0.75. Allometric scaling laws, such as those relating the metabolic rates of animals to their body mass, are of much interest in biology, but their causal underpinnings are controversial (see e.g., West and Brown 2005, Stumpf and Porter 2012).

Explanations of this nature bring a dimension of novelty into physics in that they invoke the *history of the processes*. This historical dimension, so frequently found in biology and other "special" sciences, remains typically absent in ordinary physical explanations, which have been conceived *sub species aeternitatis* since Descartes' time.[3] Symmetry breakings connect the historicity of the elementary particles with that of the universe. This bridge extends from the lowest length scale currently open to experimental exploration to its opposite, maximum extreme.

According to contemporary cosmology, the "cooling" brought about by cosmic expansion progressively reduced the energy concentration (temperature) in the early universe. Consequently, its original unified symmetry underwent consecutive breakings into the less general symmetries that currently govern the operating universal forces (except for gravity), which successively separated. In similar evolutionary terms, and invoking the same mechanism, the Standard Model of particle physics has detailed the epochal origin and properties of subatomic particles and has predicted with remarkable accuracy the existence and characteristics of some new ones, such as the Y and Z bosons and the celebrated Higgs particle.

Some contemporary physicists (see e.g. Smolin 2009. 2012 a, 2012b, Thirring 1995) have rediscovered Peirce's conception that the laws of nature themselves are the result of a protracted evolution out of former, less restrictive laws. This seems to indicate the rise of a unifying evolutionary perspective within the physical sciences that may portend their future integration with the life sciences. In what follows I speculate on the possibility of generalizing the explanations of critical phenomena through symmetry considerations to the realm of living systems, and contemplate the opportunities this may afford for integrating biosemiotic ideas into such a unified view of nature.

6. EXTENDED CRITICALITY AND HETERODOX CAUSATION

Organisms and their collective associations are complex, self-organizing systems whose relatively autonomous components interact cooperatively in such a way as to display a peculiar kind of **functional coherence**, distinctive of the living state. One attractive approach to characterize this coherent

[3] Stuart Kauffman and other authors have remarked the importance of historicity in biological explanations (see e.g., Kauffman 2000).

dynamics and explain its emergence in living systems has been advanced by Mossio, Saborido and Moreno under the rubric of *organizational closure* (see Mossio, Saborido and Moreno 2009).

Among the main characteristics of organisms, the capacities for metabolism, reproduction and self-maintenance seem crucial. The proposed idea of organizational closure is a generalization of the notion of self-maintenance, a phenomenon that also occurs in non-living dissipative systems (such as a flame). Self-maintenance is characterized by a kind of global causation in which the boundary constraints of the system react upon its environment in such a way as to perpetuate those very constraints. In systems with organizational closure, a network of organized structures exists, producing reciprocal constraining effects on their boundary conditions, insuring their continuance, and bringing about a collectively orchestrated self-maintenance.

Organizational closure is one example among others of processes in living systems that seem to call for unorthodox forms of causation that are absent from traditional physics, such as downward and circular causation.[4] One common characteristic of these types of causal action is that they reach across different levels of organization and length scales. As we saw in the preceding sections, this is a feature that also characterizes critical phenomena with their associated features of symmetry breaking and scale invariance.

In view of this similarity, several authors (e.g., Bailly, Longo, Montévil, Kauffman – see References) have proposed generalizing the concept of phase transition in a way that promises to account for the advent of these novel forms of causation and of their interplay in the integrative regulation of the life functions. This conception is termed **extended criticality**. It envisions organisms as far-from equilibrium systems undergoing protracted and continuous symmetry breakings that in turn lead to new symmetries, in a regime of permanent transition. In contrast to phase transitions in physical systems, which undergo critical changes at one isolated point, extended

[4] For current views on top-down and other kinds of non-standard causation see Juarrero 2009, Ellis 2012 and Noble 2012. Ellis distinguishes five types of top-down causation. Noble observes “Causation is, therefore, two-way, although this is not best represented by making each arrow two-way. A downward form of causation is not a simple reverse form of upward causation. It is better seen as completing a feedback circuit …”

transitions are conceived as processes going through dense, extended intervals of criticality (see, e.g., Longo and Montévil 2011).

7. SEMIOSIS AND PHASE TRANSITIONS

The concepts of symmetry and symmetry breaking are the highest unifying and explanatory notions in contemporary physics and subsidiary sciences. Explanations of the essential characteristics of living beings in terms of these concepts are very welcome, in view of a possible conceptual integration of biology and physics. Biological causation may turn out to be a generalization of classical physical causation, in the sense that ordinary causation may then appear as a special, limit case of the forms of causation manifest at the level of living systems.

The new, liberalized philosophical stance behind the ideas I have briefly reviewed, together with others presently emerging in self-organization and complexity studies, cannot fail but to awaken the sympathy of many biosemioticians. Nevertheless, those researchers will also find with dismay a deficiency in most of these portrayals of causal actions that lead to organizational coherence and maintenance. These treatments frequently fail to take into account semiotic action—the very heart of their discipline. It is hard to explain this oversight, given the ubiquitous role of semiotic transactions (e. g., intracellular and extracellular signaling) in most regulatory processes.

One possible but partial explanation of this circumstance may hinge on a failure to grasp the original, singular character of semiosis vis-à-vis other forms of causal action. Many biosemioticians subscribe, as I do, to a Peircean conception of semiosis, based on the triadicity of the sign relation and, *a fortiori*, on the whole philosophical framework of Peirce's categories. This explication of semiosis helps to render intelligible the differences between this kind of causation and those ordinarily invoked in the physical sciences. But among many scientists ignorance of this philosophical view, or lack of adherence to it, may hinder an appreciation of those differences.

In former contributions (see e.g., Fernández 2011) I have proposed a view of semiosis that, albeit compatible with the Peircean account, can be explicated in terms fully independent of any particular philosophical underpinnings. I will succinctly state here this conception in the interest of promoting the inclusion of semiosis within the circle of ideas I have this far surveyed.

My account is based on the observation that in ordinary physical causation we deal with transfers of energy in which the magnitude of the effect is quantitatively related to the energetic level of the operating causes. The results of an explosion, for instance, are so related to the quantity of the explosive; the loudness of a radio is similarly a monotonic function of the amount of electric energy delivered to the speaker.

Energy transfers also mediate semiotic causation. But once a minimum energy threshold is reached, the magnitude and nature of the effect is quite independent of those of the cause. Instead, the nature of the effect will depend on the character of a relational pattern that the causing agent has managed to embody into an energetic vehicle. Upon reaching a suitably constituted receptor, this vehicle triggers a specific type of behavior, which constitutes the effect.

Semiosis is here understood as a type of second-order causation ("metacausation"): it causes changes, amplifications or inhibitions upon ordinary processes of physical (first-order) causation. It does not act directly by a discharge of energy, as in physical causation. Instead it changes the course of events by modifying the constraints that in all physical phenomena modulate the flow of energy towards its final dissipation. This abstract characterization can best be apprehended through some illustrative examples.

At the cellular level, during extracellular signaling, cells receive from an external agent specially targeted chemical ligands (e.g., hormones, neurotransmitters, etc.). These messengers transmit an energetic pattern that is embodied in the molecule's particular chemical structure, shape, and folding order. They act by binding to specific receptors, which are suitably structured proteins located on the cell membrane. The specific pattern of the ligand triggers a similarly specific reaction in the receptor, with the release of a second messenger that enters the cytoplasm to trigger specific responses, such as gene activation.

At the level of anthroposemiotics, the reading of this page is a good example. By means of a word processing program I am at this moment embodying patterns of thought onto standardized blotches of ink. When light bounces off the page and enters the pupils of my reader's eyes, it becomes the energetic medium that re-embodies those patterns onto the receptors that line my reader's retina. If the reader has so far remained awake, the transmitted patterns will reach in turn the cerebral cortex.

Those of us who prefer a Peircean reading of this characterization of semiosis as second-order causation need only to rephrase it in terms of the object of the sign (the pattern embodied by the external agent), the sign vehicle (the energetic vehicle) and the interpretant (the change produced on the actual or possible behavior of the receptor).

8. CODA

Much is left unsaid or underdeveloped in this short paper. Readers may wonder how different parts of it fit together beyond their communality under the overarching concepts of symmetry and symmetry breaking. The truth is that deeper interconnections are apparent but as yet not clearly defined, at least for this author. Their clarification and substantiation remains an open, ongoing project directing present and future efforts. Nevertheless, the following remarks may address some of these issues.

In this article, as in previous ones, I consider that the marginal status of biosemiotics at present is due in part to some deficiencies in the integration of biology's concepts and explanations with each other, as well as with those of other basic sciences. It seems to me that the overall exclusion of semiotic transactions is both cause and effect of this lack of integration in biology. The history of science teaches us that unification is often achieved through generalization (see, e.g. Fernández 2012). Incorporation of semiotic ideas may bestow upon biological theories a greater level of generality and, reciprocally, insufficient generality may currently conspire against the assimilation of semiotic ideas within biology.

As mentioned before, the most basic unifying conception proper to biology is that of evolution. For most of the twentieth century this idea arrogated a narrow form dictated by the absolute primacy of natural selection as an explanatory mechanism. As previously noted, there are emerging signs of new and general evolutionary conceptions taking hold in the physical sciences. I see in these developments the promise of a unified science corresponding to an integrated view of nature as a cohesive and continuously evolving continuum. Within it, biosemiotics would find its rightful place as a link between the life of bacteria and the life of human culture and creations. This is a vision that would harmonize the converging aspirations of fully disparate thinkers: Darwin and Lamarck, Hegel and Marx, Whitehead and Peirce.

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