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THE ROLE OF SEMIOSIS IN EVOLUTION – FROM BIOSEMIOTICS TO TECHNOSEMIOTICS

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ABSTRACT

In biosemiotics we attempt to make intelligible the origin, organization and evolution of living systems by throwing into relief the fundamental roles that semiotic causation and semiotic scaffolding play within those systems. We attempt to discern the semiotic interactions involved in guiding and controlling their internal and external dynamics (e.g., metabolism, reproduction, interactions with the environment, etc.) and in establishing the communicational links that relate parts of the organism to each other and connect the whole organism to its environment. To achieve this end we have to successfully integrate explanations based on semiotic causation into well-established accounts given by traditional biology, the latter typically grounded on chains of efficient causation (e.g., bioenergetic flows, oxidation-reduction mechanisms, etc.). How this integration is to be achieved in different situations is somewhat elusive at present. This contribution aims at clarifying some of this elusiveness and offers some possible ways to dispel it.

To that end I review and extend previous results on the various functions of semiosis in both communication and control, and briefly sketch the evolutionary trajectories of those functions from protocells to humans. I aim to show the progressive generalization of the roles of semiotic interactions in and between organisms and between living systems and their environment. This generalizing drive is seen to unfold in an ascending sequence of evolutionary transitions. As in other forms of generalization, there subsist behind the changes certain features that remain invariant throughout that progression. These features are partially retained and expanded at each new evolutionary stage. An outline is presented of the manner in which these common characteristics become manifest at the emergence of new traits, structures and functions, through the agencies of exaptation, replication, divergence, convergence and compositional (combinatory) novelty. These developments are illustrated with examples from different stages of biological evolution. Parallels and analogies are then examined between those biological examples and similar features of the rise of semiotic novelties in the evolution of human material culture, focusing on the evolution of technosemiotic artifacts (e.g., books, microphones, sound recorders, radio receivers, etc.).

1. INTRODUCTION

One fundamental task of biosemiotics is to organize and reconceptualize our knowledge of living systems, their functions, origins and evolution, in terms of the crucial role played by semiotic causation and semiotic scaffolding in practically every aspect of their internal dynamics (i.e., energy and nutrients acquisition, metabolism, reproduction, etc.) as well as in their complex energetic and semiotic interchanges with their surroundings. Within each living being there is an unceasing deployment of signaling interactions between and among its constitutive parts. These internal exchanges are regulated and coordinated with the assistance of another, equally complex semiotic interplay. This second interactional traffic takes place between the whole organism and the entities and events occurring within its habitat. Specialized organs or organelles, working as receptors of sensorial information or as effectors of responsive actions, mediate this additional semiotic interchange between the organism and the living and abiotic components of its external environment.

In biosemiotics we need to bring about the integration of this all-pervasive semiotic regulation with traditional descriptive and explanatory accounts of biology, which are typically grounded in chains of efficient causation (e.g., bioenergetic flows, oxidation-reduction mechanisms, etc.). To achieve this end we must articulate the way in which semiotic causation interlocks with the physical mechanisms that drive the flow of matter and energy through cells and through all other living systems. The elucidation of this interconnection is a difficult endeavor – and one biosemiotics has just started to pursue, and on whose success the future of the discipline crucially depends. This paper offers some considerations and hypotheses that may contribute to this task of integrating semiotic causation and ordinary forms of physicochemical (energetic) causation.

Among the multiple ways in which one can approach the relationships between semiosis and physical causation, I propose to explore two particular issues that appear promising in light of conceptual and historical considerations, and which turn out to be intimately related. The first issue concerns the relation of semiosis to physical regulation, as this latter occurs both in organisms and in cybernetic devices, from thermostats to digital computers. The second one pertains to the relation of semiosis to the generation of evolutionary novelty, as indicated by the emergence of semiotic novelties as basic determinants of major transitions in the evolution of living beings. These two perspectives will be examined in the next four consecutive sections, followed by a concluding section aimed at disclosing their mutual relatedness.

2. SEMIOSIS AND PHYSICAL REGULATION

In the idealized causal framework of classical physics, which is saddled with strict determinism and time reversibility, **whatever is not forbidden is compulsory**[1]. For various reasons this scheme proves far too narrow for the explanatory aims of both quantum physics and biology. Through different routes these two disciplines succeed in widening their causal schemes, although both require recourse to classical causation within some well-defined contexts.

Here we are not concerned with quantum physics, so let us consider, for instance, the energetic dynamics of living cells (e.g., metabolic or maintenance processes). These transformations are made fully intelligible as consequences of physical and chemical operations conceived and described in terms of classical causation. Yet, the peculiar features that distinguish living systems from ordinary inanimate objects seem to rise

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[1] Physicists use this expression with a different meaning to invoke a heuristic principle, not about causality but about the possible existence of unknown subatomic particles or other postulated exotic entities.

from processes not fully explainable or even describable in terms of classical causation. These are precisely the processes involved in enacting the organism's powers as an autonomous (self-regulating) agent. Autonomous agents display forms of spontaneity and purposeful intervention in their environment that indicate that these peculiar powers enable the agent to perform actions of a novel causal nature: they are **neither forbidden nor compulsory** with respect to the laws of nature.

I would like to advance the hypothesis that the point of intersection of ordinary physical causation and semiotic causation resides in the physical process of **regulation**. We think of autonomous agents as self-regulated or self-governed (from Greek: *autos* + *nomos*).[2] To regulate is to cause something to behave in accordance with a law or rule (from Latin: *regula*). Self-regulation or meta-regulation seems only possible on the basis of ordinary regulation. Only a system able to regulate its environment can aspire to regulating itself. We must assume then that ordinary regulation constitutes the basic phenomenon.[3]

Regulation is possible because the world agents inhabit is, in a sense, pre-regulated. The existence of science and that of organismal life is predicated on the fact that the behavior of things and process around us is constrained by universal rules, traditionally called "laws of nature," and is thus to a great extent predictable. Through purposeful actions we (and all other organisms) are capable of altering the initial or boundary conditions upon which universal laws act, and in this way bring about intended new circumstances. This seems to be the most elemental form of regulation. We say, for instance, that a beaver regulates a river's flow when it alters its boundary conditions by building a dam. Analogously, we regulate the illumination of a room by lifting or lowering the window blinds. This type of regulation is the most elementary, being produced by individual and discrete actions.

To advance our discussion we need to consider a more general form of regulation, in which **one process exerts continuous regulation upon another process**. For instance, the way in which changing the concentration of insulin determines glucose levels in the blood of animals; or the manner in which a car accelerator's changing position determines the amount of fuel delivered to the engine at different times, which in turn regulates the vehicle's speed. An autonomous agent uses this form of regulation —which from here on we will call **modulation**— for two different kinds of purposive action, **energetic action** and **semiotic action**. Energetic action aims at physically changing the environment, usually by performing work upon it, as in the case of a marmot digging her borrow. Semiotic action aims at altering the behavior of other organisms through the emission of signals directed to their sensory organs or receptors, as in the case of a marmot's warning calls to alert her congeners to a predator's approach.

3. MODULATION IN ORGANISMS AND IN HUMAN ARTIFACTS

[2] It goes without saying that there is much more to autonomy than self-regulation. See e.g., Etxeberria & Moreno 2007, Ruiz-Mirazo & Moreno 2012.

[3] Regulation or control is of course the subject matter of cybernetics, which includes the study of communication, automatic regulation and goal seeking behavior by means of feedback systems. There is no space here for discussing its multiple and complex connections with the ideas developed in this paper. For interesting philosophical issues in the relations between biosemiotics and cybernetics see Cobley 2010.

Human artifacts are peculiar entities, with an amphibian existence between living and inanimate worlds. On the one hand they are biological products, the outcome of biological evolution, which accounts for the purposiveness of their design. An explorer who finds a clarinet on some alien planet has ample grounds for inferring that organisms have visited that planet at some time. On the other hand, when artifacts are spatially detached from external human organs their behavior usually can be accounted for without departing from the causal scheme of classical physics. For this very reason human artifacts —and particularly signaling devices— may offer a desirable entry point into the hard-to-extricate relations between semiosis and ordinary physical causation.

To motivate this abstract extrication let us briefly examine the role of **modulation** in natural and artificial instruments. In human phonation the vocal folds modulate the flow of air ascending from the lungs into the glottis, oscillating back and forth laterally. An analogous process in a singing bird's vocal apparatus, called the syrinx, performs the singing by modulation of the airflow. Wind instruments produce musical sound in the same manner, modulating the length of a column of air inside a resonating tube. Let us see how modulation relates physical and semiotic causation.

Semiotic causation brings about the embodiment of a given general form (a **type**) onto a new, concrete supporting medium, producing a **token** or replica of that type. It is important to realize that in the most general case the token is a dynamic process rather than a static thing. The static replicas considered in most semiotic discussions are actually records. They are remarkably lasting tokens that allow the reiterated reproduction of the embodying process. For instance, the characters (letters, punctuation marks, etc.) on this page are permanent records of a writing process, consisting in the movements of a pen, or keys striking a keyboard. By visually scanning the page a person or a technosemiotic device can read and reread the page an indefinite number of times.

The human voice is a good example of the general semiotic action by which a form embodied into a process becomes re-embodied into a different process. A form initially embodied as a pattern of movements of the vocal folds becomes re-embodied into a sequence of acoustic vibrations of the air through the process of modulation. Unless these vibrations in turn become immediately modulated into mechanical oscillations in a tympanic membrane or a microphone, they are lost forever through the energy dissipation of their dynamical supporting medium. In the evolution of human material culture the ephemeral nature of the phonation process was remedied by some of the most momentous of all technosemiotic inventions: writing, printing, sound recording, etc. The invention of the triode valve in the first decade of the twentieth century made it possible to modulate weak audio frequency signals into powerful high frequency electromagnetic waves. Starting with the development of radiotelephony this invention (along with its successor, the transistor) launched the field of electronics, unleashing the unremitting chain of technosemiotic novelties that holds such compelling sway on our existence today (see e.g. Fernández 2013a).

General types (shapes, signs, etc.) gain existence only by becoming embodied into individual processes and things (replicas); conversely, individual processes and things exist only as supporting media of general types. A formless thing is as ghostly a fantasy as a disembodied form. The closest approximation to a formless thing we can imagine is that of a totally undifferentiated whole, an ideal approached by a blank page or an unexposed photographic film. When we write on a blank page the traces of ink break the page's characteristic symmetry (i.e., undifferentiation of locations) and thereby become carriers and also permanent records of information. Analogously, our voice acts by breaking the silence of an undifferentiated flow of air.

The preceding considerations lead to the hypothesis that modulation is the most general case of the conveyance by which a form is taken from one supporting vehicle and incorporated into another. This conveyance is a peculiar kind of transfer; in contrast to physical transportation the form does not need to depart from the first medium in order to be incorporated into the other. Such an act of conveyance is — I propose, following Peirce — an instance of semiotic causation. Modulation, a meta-process in which one physical process conveys a form by regulating another, extends a bridge between two chains of ordinary physical processes. **It is a mediatory link that partakes of the nature of both physical and semiotic causation and serves to connect them.**

If this hypothesis proves fruitful, it may serve to discern the interrelations of semiosis and ordinary causation in living systems, by explicitly revealing the links of semiotic and energetic processes in the innumerable examples of modulation already known in biology, and by looking for new examples. Enzymes and fluctuations in substrata, such as nutrient concentrations or pH variations, regulate all major metabolic pathways. Gene expression is modulated through many processes in sequences of complex stages, from transcription to translation and beyond. It is hard to find biological processes in which modulation plays no role, i.e., where ordinary causation acts without the guidance of semiotic causation.

To further develop our argumentation we need to take a considerable detour through a subject that at first blush may appear remote: the role of semiosis in evolution. Its relevance to the preceding ideas will be brought out in the concluding section.

4. SEMIOSIS AND EVOLUTION

An oft-quoted dictum in biology textbooks is that, in Dobzhansky's words, "nothing in biology makes sense except in the light of evolution." Biosemioticians could add their own slogan, "Nothing in biology makes sense except in the light of semiotics." My purpose here is to show that these two dicta are, in a sense, equivalent: semiosis and biological evolution are two sides of the same coin. My argumentation is based on a cluster of philosophical ideas brought forward by Charles Peirce in the mature stages of his thought. These may be encapsulated in the statement "**evolution is concrete generalization**." Here I will use these ideas informally, with no attempt at developing the philosophical argumentations that serve to support them. I endeavor to do this separately, in a forthcoming article (Fernandez forthcoming) to be presented at the Peirce Centennial Congress.

Many of the attributes inherent in our intuitive conception of "living being" also apply to ordinary semiotic beings, i.e., signs (see Nöth 2014). Among these features we count reproduction, propagation, temporal directionality, evolvability and an inner drive to generalization. Organisms are individual instantiations of biological types (e.g., species, taxa, etc.) and signs exist exclusively as individual replicas of physical forms. The forms transmitted by signs jump easily from one embodiment into a totally different one. The word "rabbit," for instance, can be incorporated into a string of vocal sounds as readily as it appears recorded here, in the guise of a series of printed characters. Sign supporting media are quite indifferent to the nature of the form; the transfer is a relatively simple physical process, often made mechanically by technosemiotic devices.

Organismal types, in contrast, can be transmitted from one replica into another only through the agency of **biological reproduction**, a sequence of transformations of great complexity involving the entire supporting medium. In each cell this medium is made of a vast array of molecules undergoing a dynamical orchestration of energetic and semiotic actions. In reproduction, through an extremely complex process that includes the replication of molecular genetic records (RNA, DNA, etc.), the medium divides itself into two separate tokens, embodiments of the same original type.[4] Thus, in contrast to organisms, signs are simple, elemental components of living processes. The similarities between signs and organisms referenced earlier result from the essential contribution of semiotic actions to the chemical and energetic operations that serve as a dynamic medium for the embodiment of a biological type.

If we envisage individual organisms as generalizations of sign replicas, various defining properties of life will appear also as generalized versions of features present in signs. A generalized feature must display novelty, but at the same time must retain essential aspects of the original trait, as a special, limit case. Generalization often includes increased complexity. A simple example in the realm of conceptual generalization is that of the real numbers as generalized natural numbers: the reals form a more complex system in which the natural numbers appear as restricted special cases.

Going from conceptual generalization to concrete generalization we will consider biological reproduction as generalized sign replication, and biological evolution as generalized sign evolution. There is a succession of increasingly complex semiotic generalizations in biological evolution, best illustrated by the semiotic aspects of the so-called major transitions in the history of life. In a series of seminal books and papers Maynard Smith and Eörs Szathmáry brought to the fore the significance of these major transitions in evolution. Their original list included the following transitions:

> (1) From replicating molecules to populations of molecules in compartments (protocells); (2) from unlinked replicators (independent genes) to

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[4] In a paper that deplores the peripheral role of evolutionary thought in twentieth century biology as resulting from the philosophical narrowness of the neo-Darwinian view and of the reductionist stance of molecular biology (Woese and Goldenfeld 2009) the authors say (p.18):

> Nobody saw that the solution to the real problem of the gene did not lie in the here and now. **Instead, it lay in the emergence of an incredible and complex mechanism that can extract information (pattern) from the sequence of one type of macromolecule and "express," i.e., store, most of it as the structure (sequence pattern) of another macromolecule** [emphasis added].

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> chromosomes; (3) from RNA, as both information carrier and enzyme, to DNA as the carrier of information and proteins doing the work of enzymes; (4) from prokaryotes to eukaryotes; (5) from asexual cloning to sexual reproduction; (6) from single-cell eukaryotes to multicellular organisms with differentiated cells (plants, animals and fungi); (7) from solitary individuals to colonies with non-reproducing castes; and (8) from primate societies to human societies with language.

This list was later expanded through the observations of critics and collaborators to include other major evolutionary events, such as the origin of the nervous system (Jablonka and Lamb 2006). A reassessment and criticism of this ongoing research program appeared recently as a collection of essays in a book (Calcott and Sterelny 2011). Other prominent evolutionists have proposed alternative sequences of similarly pivotal events, e.g., Lane's "ten great inventions of evolution" (Lane 2009). Lane's list emphasizes energetic developments while Maynard Smith and Szathmáry give the greatest weight to semiotic novelties (new ways to store, transmit, process and interpret information).[5] I don't think these two sides of novelty creation can be divorced, since they are complementary. An expansion of the semiotic powers of organisms usually results in a parallel increase in their capacity for causal intervention on their environment, and vice versa (see e.g., Fernández 2013b). Organisms exert purposive actions to regulate or control their environment and acquire free energy. They usually accomplish these goals by tapping or redirecting surrounding energy flows through actions that display a synergetic combination of semiotic and physical causation.

5. FROM BIOSEMIOTICS TO TECHNOSEMIOTICS

The view of the evolutionary process advocated by neo-Darwinism for many decades was shaped by an ideological stance as old as the Enlightenment, a view that tends to deny spontaneity to the natural world. According to this passive perspective novel types appear in most cases through a blind, directionless mechanism altogether external to the organisms themselves. Natural selection, conceived in this manner, constantly filters out the less successful outcomes of reproduction from a pool of randomly generated variants. Many new discoveries are presently challenging the limitations of this entrenched perspective, and new conceptions attempt to expand or greatly modify the received views (see e.g., Aerts et al. 2012, Bejan & Lorente 2010, Lane et al. 2013, Noble 2011, Pigliucci 2009, Shapiro 2011, Woese & Goldenfeld 2009).

The outlook advocated here is antithetical to the neo-Darwinian stance: it assumes that nature and human culture partake of a spontaneous drive toward growth, variety and the generation of novelty. Following Peirce, this drive is conceived as a

5 Maynard Smith and Szathmáry also note other commonalities: individuals able to replicate independently before a transition can only replicate as parts of a larger whole afterwards, e. g., free-living bacteria can no longer replicate once they have evolved into intracellular organelles. A recent proposal considers the origin of major transitions in the inversion of causal structures from bottom-up to top-down causation, with a concomitant switch of the flow of information, redirected to go from higher to lower levels of organization (see e.g., Walker *et al*. 2012).

generalizing, self-reinforcing tendency in many ways analogous to the intellectual impetus behind the growth and expansion of concepts and theories. All forms of generalization partake of some essential characteristics. These include the emergence of novel properties, structures or functions that retain and amplify some general features of their ancestors, while simultaneously eliminating some previous limitations or constraints. Usually those ancestral features appear as restricted or limit cases of the new generalized version.

Biological evolution conceived as concrete generalization unfolds as a gradual progression of novelty generation. This is occasionally interrupted by sudden bursts of divergence into numerous new types that depart more radically from their ancestors (see e.g., Koonin 2007). Some of the major transitions are associated with these bursts of evolutionary differentiation. When we envision the history of life as a series of minor and major generalizations, general patterns of novelty creation emerge and are remarkably analogous to those found in similar progressions, such as the various branches of the evolution of human symbolic and material culture (language, science, arts, technology, etc). Here our focus is on the parallels between the evolution of life forms and that of human artifacts. A detailed comparison of similarities and differences between biological and technological evolution yields the following essential commonalities (for a full treatment with many examples from biology and technology see Fernández 2014):

> **Novelty**: emergence of traits, functions or structures without precedents; **exaptation**: novelty created by co-option of former novelties into new functional applications; **divergence**: evolutionary trajectories bifurcate at the creation of new types; **convergence**: at some points in widely divergent evolutionary trajectories convergent innovations show closely similar features not attributable to common ancestry; **compositional novelty**: radically new artifacts or organisms often result from a novel combination of well entrenched ancestral parts or processes; **replication**: novelties emerge at a point in time and later propagate through space by the assembly of multiple working copies.

As remarked before, organisms purposively intervene in their environment in two principal ways, usually combined. In one case they act on the environment through physical causation, by channeling energy flows. In the other case they act through semiotic causation, by emitting signals for inter-organismal communication. Artifacts created to extend the powers of human energetic and semiotic actions are powerful drivers of human evolution. I will call them **technoenergetic** and **technosemiotic** artifacts. Examples of the first are windmills, watermills, steam engines, bulldozers, nuclear bombs, etc. Examples of the latter are writing utensils, books, printing presses, telegraphs, telephones, tape recorders, microscopes, telescopes, etc.

A major transition in the evolution of technoenergetic artifacts, commonly known as the "industrial revolution" of the eighteenth and nineteenth centuries, resulted from the invention of the steam engine and other devices capable of converting the energy stored in fossil fuels into mechanical work, for manufacture, construction and transportation. A major transition in the evolution of technosemiotic artifacts, parallel and roughly contemporary to the aforementioned one, resulted from inventions for the transmission and storage of information by means of electricity (electric telegraph, telephony, radio, sound recording, etc.).

It is seldom noticed that energetic and informational devices cannot function without mutual cooperation. This is likely due to the fact that in the past an organism (usually a human) often substituted for one of them. For instance, steam engines could not work without the regulation exerted by human beings; telegraphs could not function without the muscular exertions of their operators.[6]

6. CONCLUDING REMARKS

In the preceding sections I have endeavored to bring to light the interplay of semiotic and physical causation and, in a separate vein, the role of semiosis in biological and technological evolution. These two issues are intimately related because the evolution of living systems and that of artifacts go through fairly similar stages. Both cases involve the development of novel carriers of causal efficiency, in the form of energy flows coordinated and regulated by means of channeling processes.

For instance, an enormous energetic revolution launched with the rise of photosynthesis. In this process solar energy is harnessed by the transfer of electrons from donor substances (water splitting in ordinary plant photosynthesis) through a chain of complex chemical events. The energy is finally stored in the covalent bonds of carbohydrates. Regulation, carried out by enzyme actions, pH modulation, etc., is absolutely essential at every stage of this chain, which includes the entire Calvin cycle. Similar channelings of energy fluxes are ubiquitous in technoenergetic artifacts, which incorporate many types of regulators (of voltage, pressure, etc.) to control rates of change or production. The introduction of Watt's centrifugal governor in rotating steam engines was a crucial step in their evolution.

This reciprocity between the evolution of life as a semiotic process and the evolution of regulatory mechanisms in technology has deep roots in the nature of generalization. Semiosis proceeds through an indefinitely growing chain of interpretants, in which each becomes the immediate object determining the next interpretant. Each new interpretant is a potential generalization of the preceding sign and becomes an actual generalization of it when it joins other signs in the composition of new, more developed signs.

In human symbolic culture some elemental signs are symbols acting as vehicles of concepts. In scientific thought concepts combine to make propositions, propositions combine into arguments, and arguments become theories. Signs grow by composition and propagate by replication into a growing number of stable replicas (e.g., oral traditions, writing, etc.). Analogously, organisms evolve through replication and composition (bacterial conjugation, horizontal gene transfer, sexual reproduction, multicellularity, symbiogenesis, etc.). The evolution of human artifacts follows patterns quite similar to these (see e.g., Fernández 2014).

In synopsis, the ideas advanced here include the following hypotheses and arguments:

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[6] Karl Marx perspicaciously remarked this fact in a letter to Engels on January 28, 1863. See Marx and Engels 1975, p. 448.

Abstract generalization (as evinced in the symbolic constructions of mathematics and science) is merely a special case of the generalization that occurs concretely in nature in processes that generate novelty, growth and variety. When a process, entity or form is generalized, the outcome of the generalization incorporates the instance that underwent generalization as a special case of that outcome, and retains some of its general features.

Biosemiotics is especially concerned with the interrelation of physical (energetic) causation and semiotic causation. These different forms of causation interlock in the regulation process. The most general form of regulation is modulation, in which two dynamical, temporally extended processes are so related that one continuously regulates the other. Instances of modulation are ubiquitous in organisms and in technosemiotic artifacts, and constitute the main point of intersection of physical and semiotic causation. Modulation is also the most general process for the embodiment of a general form (type) into singular concrete replicas (tokens).

Simple signs compound into successively more complex signs. In written language letters are compounded into words, words into sentences, sentences into arguments, etc. Simple signs exist as embodied in individual replicas and are easily replicated because of their indifferent relation to their embodying media. Organisms, on the contrary, are embodiments of biological types into a medium composed of self-regulated orchestrations of energetic and semiotic actions. They replicate through biological reproduction, which demands an extremely complex separation of the medium. This separation is regulated by the replication of a network of genetic records (including transcription and translation) to yield functioning replicas of the same type.

The interaction of physical and semiotic causation in organisms can be better understood by looking at its analogues in other branches of evolution, such as cultural and technological evolution. Parallels between the evolution of organisms and that of artifacts indicate the existence of deep commonalities in the creation of novelty by means of composition, replication, exaptation, divergence and convergence.

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