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What is innovation? New lessons from biology

(¿Qué es la innovación? Nuevas lecciones desde la biología?)

Sergio F. Martínez*
Instituto de Investigaciones Filosóficas, UNAM, México

ABSTRACT: During the 19th century, evolutionary models of innovation followed a famous thesis of continuity, according to which methods and explanatory patterns of biology should have an important say in the social sciences. In the 20th century, this thesis was considered unacceptable as part of the sharp separation of biology from the social sciences. Recent advances in the biological sciences suggest a way in which a version of the thesis of continuity can be reinstated, to suggest new ways of explaining innovation in the social sciences. Key kinds of innovation can be explained in terms of the evolution of robust complex systems, interpreted as processes of path creation.

KEYWORDS: innovation, innovability, evolutionary models of innovation, robustness, path dependence and creation, protocols.

RESUMEN: *En el siglo XIX la innovación tendía a modelarse utilizando la tesis de la continuidad según la cual los métodos y patrones explicativos de la biología deberían de tener algo importante que decir en las ciencias sociales. En el siglo XX esta tesis fue rechazada como parte de la separación disciplinar entre la biología y las ciencias sociales. Avances en las maneras de entender la innovación en la biología contemporánea sugieren una manera en la que una versión de la tesis de la continuidad puede ser restablecida como parte de nuevas maneras de explicar la innovación en las ciencias sociales. Tipos importantes de innovación pueden ser interpretados en el contexto de la evolución de sistemas complejos como creación de trayectorias.*

PALABRAS CLAVE: innovación, innovabililidad, modelos evolucionistas de la innovación, robustez, dependencia y creación de trayectoria, protocolos.

* ***Correspondence to:*** Sergio F. Martínez. Instituto de Investigaciones Filosóficas, UNAM, Circuito Mario de la Cueva, s/n (Ciudad Universitaria, Distrito Federal, Mexico) – sfmar@filosoficas.unam.mx – http://orcid.org/0000-0001-8108-8400

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Introduction

The question of what innovation is started being discussed as a scientific question in the 19th century, hand in hand with the development of the concept of evolution. Novelties or innovations allow us to establish biological distinctiveness or relatedness and more generally, to extrapolate from the existence of specific traits in a few organisms to more inclusive wholes. Darwin's theory of natural selection, to the extent it explains how existing traits diversify, was a major contribution in this direction. It seems natural, as Darwin and most of his contemporaries believed, that this theory should extend its explanatory power to elucidate critical features of social life. Darwin, however, proposed a different version of the traditional account of this continuity. For most contemporaries of Darwin, this continuity was the consequence of the existence of universal laws (or mechanisms) that would support such continuity, and thus evolution was sufficient cause of all innovations. For Darwin, continuity was not a mere consequence of a law, it was rather the result of a contingent mode of operations of different causes.[1] That is, Darwin promoted the idea that the continuity which his theory of organic evolution by natural selection establishes (among living forms), supported a controversial "thesis of continuity", according to which, the methods and explanatory patterns of biology should have an important say in explanations of change in the social sciences, but not as a consequence of the existence of a law that would cover the continuity in question. Darwin's thesis was brought into disreput during the 20th century, as part of the discrediting of the relevance of biology to the social sciences.[2] Recent advances in the biological sciences, and in particular in our understanding of the sources of innovation, suggest a way in which a version of the thesis of continuity can be reinstated as a methodological guide relating biological and social sciences. After showing the limitations in the usual accounts of innovation in the social sciences and biology, I will briefly discuss recent views on innovation in biology that associate evolutionary innovation with the evolution of robust complex systems. This leads to a promising way of modeling innovation as path-creation processes.

In the first section, I provide a brief summary of many accounts of innovation in the social sciences and identify a common underlying assumption. In the second section, I provide an overview of how innovation has been characterized in biology and point to the kinds of accounts which lead to my proposal. The third section shows how recent accounts of innovation in biology can be extended to accounts of cultural innovation. The fourth section offers three related reasons which support a revised version of the thesis of continuity.

1. The Many Faces of Innovation

What constitutes innovation has been a topic of increasing importance in the social sciences, education, and the biological and cognitive sciences since the 1960s. A growing

[1] As Wright formulated the idea: "strictly speaking, natural selection is not a cause at all, but it is the mode of operation of a certain quite limited class of causes" (1870, 293).

[2] For a detailed account of how such separation took place from the perspective of the social sciences, see Degler (1991).

literature on innovation aims to establish *innovation studies* as an autonomous interdisciplinary endeavor, with one of the first models in this tradition proposed in 1962 by Everett Rogers, in his book *Diffusion of Innovations*. The key idea is that innovations have to overcome the inertia caused by old ways of doing things, which leads specific people or communities to reject an innovation, that from a "rational" or "purely economic" perspective should be accepted at once. In other words, innovation, in the form of concepts or technologies or ways of organization, happens or is generated somehow in society; and studies of innovation principally aim to explain the factors that impede their acceptance. As he tells it, Rogers became interested in the diffusion of agricultural innovations by observing how farmers in his native Iowa delayed the adoption of new ideas "that could be profitable for them" for several years (see Rogers 1995, xv-xvii). This basic idea has been extended in literally thousands of studies of diffusion of innovations, in practically all spheres of human activity involving the adoption of new technologies: communication technology and marketing; the organization of hospitals, public health and the spread of antibiotics; agriculture; kindergarten, university and driving instruction; and practically any social activity involved in social changes. *It is not then surprising that Rogers claims that the regularities brought to light by the diffusion model should ultimately explain different processes of social change* (see Rogers 1995, xviii).

The diffusion model has been very influential. The underlying idea, that innovation can, and should be, explained by modeling the relation of a user with a technology, and the way the user reacts to and adopts (or not) the technology, is the point of departure for explanations of technological innovations well beyond the diffusion model. This user-centered assumption is widespread in the whole field of "innovation studies", although it disposes us to ignore questions about the sources of innovation. Ignoring such questions allows the model to be applied to many different kinds of processes, under well-controlled empirical conditions; nevertheless, considering that these sources are vital in understanding innovation, a serious limitation is built into this sort of approach.

Many models recognize the need to incorporate the sources of innovation into the discussion. Eric von Hippel, for example, in his well-known book *The Sources of Innovation* (1988), characterizes innovation as a process that is distributed across users, manufacturers and suppliers, as well as other participants in the process. This model allows for an interesting analysis of many innovations; nonetheless, innovation is still seen as a process taking place between specific agents and a particular technology, in such a way that the perception by an agent that a technology can be, or is, an innovation, is essential for the analysis. More to the point we want to make in this paper, the sources of innovation are classified according to function. An individual (or a firm, or a technology) will have different functional roles depending on the particular innovation being examined. With respect to innovations in aircraft, Boeing is a manufacturer; but with respect to a metal-forming machine, it is a user.

There is no doubt that a functional account of the sources of innovation can lead to important insights. However, not all innovation is amenable to such an account. As we shall see, in biology and the social realm, important innovations are not related to their present functions, for example, structural features supporting capacities for change; such kinds of (what we will identify as) path-creation processes can be seen as supporting a revised version of continuity.

In the preface to the *Oxford Handbook of Innovation* (2005), the editors (Fagerberg, Mowery and Nelson) introduce the book using the famous metaphor of the blind men

and the elephant. The literature on innovation—they say—is like the elephant perceived by each of the different blind men. Each author seems to be addressing a different issue. Their diagnosis is that such a variety of accounts over innovation arises because it is a multifaceted phenomenon that "cannot easily be squeezed into a particular branch of the social sciences or the humanities" (Fagerberg et al. 2005, v). But then, as they perceive it, the increasing literature on innovation runs the risk of turning into isolated discussions, unable to communicate among themselves, and thus preventing the development of a more complete understanding of the phenomenon. The book in question aims to give a picture of the whole.

I do not think the book is particularly successful in this regard. It is indeed a very good collection of separate articles, and some of them attempt to relate different questions and methods. But by assuming that a complete understanding of innovation can be expected by aggregating knowledge of different functional perspectives into an increasingly complete picture, we disregard the systemic and path-dependent structuring of innovation that is closely related to its having resulted from an evolutionary process. This path–dependent structure of innovation is not fully captured by functional accounts of innovation, and as we shall see, such a structure might be crucial in understanding the way in which different innovations can be related to each other.

Yes, innovation is multifaceted, but in a sense that does not fit the metaphor of the elephant. It is not an aggregative phenomenon, as suggested by the metaphor. Many processes of innovation are better modeled as systemic capacities enabling the scaffolding of innovation through the facilitation of variations (as outlined in section 4).

Darwin suggested in later writings that the same explanatory pattern used in the *Origin of Species* to explain the branching biological diversity modeled in the tree of life could be used to explain human cultural evolution (Darwin 1871; Martínez 2000). This idea presupposes the "thesis of continuity" according to which, an understanding of the continuity between human and animal experience and cognition was required in order to explain social (cultural) innovations. The rejection of this thesis goes hand in hand with an overhaul of the social sciences and their sharp separation from biology, which is the mark of the social sciences in the 20th century (see, for example: Richards 1987; Degler 1991). However, as we see below, the culprit is not the thesis of continuity as such, but the accompanying implicit assumption that innovations have to be explained in terms of (adaptive) function. This kind of explanation leaves us room to consider the important role history and temporality should play in an account of innovation.

One way in which history and temporality have been taken on board in accounts of innovation in the social sciences involves the introduction of the concept of path dependence. A path-dependent process is a self-reinforcing process unfolding into one of several potential states. The state emerging from the process depends on the particular sequence (and ordering) of the events that unfold. The concept of path dependence has been used in economics and other disciplines to explain the emergence of novelty as serendipitous (Dosi 1982). However, the assumption that historical accidents result in phenomena locking into suboptimal choices with full information seems to be hard to demonstrate (Liebowitz and Margolis 1990). This has led several authors to introduce a version of path dependence which they call "path creation". In economics the idea is that to escape the selection pressure of markets, one can design technology which, even if inefficient by today's standards, can lead us into an innovative path. Path creation brings into play "not only the social and

institutional processes inherent in path dependence, but more importantly, the sociocognitive processes of enactment that are involved in the creation of new states" (Garud and Karnoe 2001, 7).

This way of understanding path dependence and path creation can be very useful in social sciences in which the concept of agency can be taken as uncontroversial; cases in which, for example, the processes of enactment playing a crucial role in the designing of new paths are clear. We will show how a generalization of this idea of path creation can lead us to a reformulation of the thesis of continuity. Ultimately, the thesis of continuity is about the explanation of the sense in which history matters for characterizing innovation. To make this connection clear, we have to introduce recent advances in our understanding of innovation in biology.

2. The Problem of Innovation in Biology

The way in which innovation was treated until recently in biology was closely related to the adaptive function of a trait considered novel. The diverse wing patterns of butterflies or the feather structure of birds are innovations, in the sense that such traits acquire new functions. As has often been pointed out, this way of understanding innovation as the fixation of a trait in a population ignores the origin of the trait (the cause of the emergence of the variation). It is easy to understand the role of selection in optimizing a function, but it is harder to explain how selection plays a role in the origin of novel traits (Müller and Newman 2005). Furthermore, particularly relevant for our purposes, such a characterization of innovation excludes from the outset the possibility of innovations that are not related to new functions.

Many alternative definitions have been proposed. One proposal is based on an idea already suggested by Darwin—that innovations could be the result of "secondary causes" not related to natural selection. The most famous explanation of innovation along these lines relies on the concept of "exaptation", according to which, novelties may have originated for reasons unrelated to their present function. This explanation can account for many innovations, but there are limitations (see for example Newman et al. 2006; Moczek 2008). Overcoming these limitations prompts us to characterize innovations in a more systemic way, as path-creation processes being generated by specific capacities for change.

The basic idea is the recognition that specific structural features of a complex system afford specific capacities for change and stability, and that such affordances apply equally for biological or cultural systems. These capacities grounded on systemic structures are discussed nowadays under different names in biology, but are mainly associated with *facilitated variation* (Kirschner and Gerhart 2005), or *evolvability* (Wagner 2011; Calcott 2014). In these and other authors promoting related views, the basic idea is that the evolution of developmental resources explains innovation, thus opening the possibility that innovation in other complex systems, in which the evolution of developmental resources is the key for understanding change through time, can be explained likewise. As we shall see, such an account of innovation provides a way of reformulating Darwin's thesis of continuity. But before this, we have to provide the framework for the thesis of continuity.

3. *From Biological to Cultural Evolution*

As Maynard Smith famously characterizes Darwinian evolution by natural selection (1986), in order for Darwinian evolution to occur, it is sufficient that we have a population of entities satisfying the following properties: 1) the entities must be able to multiply; 2) there must be variation within the population; and 3) some of the variations must be hereditary. Maynard Smith shows that if these conditions are met, natural selection is an inevitable outcome. But in order for this account of evolution to be more than an (abstract) outline of Darwin's theory, we have to say what the population in question is, what the units of hereditary variations are, in specific cases, and what the specific processes bringing about variation are. This requires an interpretation of the abstract framework that usually leads to what is called a "neo-Darwinian" account of evolution.

During the first decades of the 20th century, a paradigmatic "neo-Darwinian" interpretation of the theory of natural selection developed, that aimed to establish evolutionary theory in mechanistic principles. Neo-Darwinism starts with the incorporation of Mendel's law and transmission genetics as the basis for a characterization of the theory of heredity that Darwin lacked. Neo-Darwinism claims that genetics can give a precise answer to evolutionary questions, under the assumption that the fundamental unit of heredity is the gene, and that genetics provides the details of the processes leading to its inheritance. This gene-centered view of evolution has profound implications for the modeling of cultural evolution and for an account of cultural innovations. Since in the neo-Darwinian model of evolution, the phenotype reproduces but is not inherited, and the genotype is inherited but is not (directly) reproduced, it is possible to avoid the question of the origin of hereditary variation.[3]

Following neo-Darwinism, the first well-known models of cultural evolution assumed that innovations were particulate and that an analogous blackboxing of the question about the origin of hereditary variation not only was possible but indeed desirable. It would allow for the idealized transmission mechanism to pass information from head to head and implicitly, at least, reduced innovation to nothing more than a random mutation of a gene-like entity with a high fitness. Memetics is a well-known label under which such accounts have been developed (see Blackmore 1999; Aunger 2002). Two key assumptions of memetics are relevant to the present discussion. Memetics assumes that cultural innovations are particulate (or discrete) and that transmission of information takes place from head to head. However, as several critiques have pointed out, cultural innovations can very seldom be modeled as particulate (or discrete) (Henrich et al. 2002; Wimsatt and Griesemer 2007). Also, as Sperber (1996) already argued, even if one accepts the basic framework, ideas cannot be modeled as directly transmitted from one brain to another, since their transmission is mediated by observation. Someone observes a certain behavior and then infers the underlying representation or idea that leads to this behavior. Thus, processes of (psychological) inference play a crucial role in biasing the ideas that are transmitted. The nature of cognitive processes producing social learning and supporting (via inference and joint action) the transmission of innovations help us to explain how innovations are pro-

[3] Contrary to what Darwin thought, namely that hereditary variations are acquired through development, neo-Darwinism assumes that the origin of variation is random.

duced and transmitted through generations of agents. But that means acknowledging that the inheritance mechanisms of cultural innovations cannot blackbox the specific mechanisms supporting the stable transmission of innovations through generations of agents. It can be argued that, as far as such mechanisms promoting innovation can (and should) be characterized through generations of agents, these mechanisms are developmental resources (effective as part and parcel of specific systemic or organizational environments). Thus *biology should not be seen as merely a source of analogies for the construction of explanatory models of cultural change, but as allowing us to identify capacities for systemic innovation.* In the next section, I will briefly summarize three reasons supporting this view, and elaborate on the sense that this points to a version of the thesis of continuity.

4. From Biological Innovation to Cultural Innovation

There are three important interrelated reasons why we should pay attention to systemic innovations in biology, in order to advance our understanding of the phenomena of innovation in the cultural (or social) realm.

a) The first is that, insofar as recent accounts of evolution recognize the importance of the causal interaction between development and evolution, the role of inheritance in evolution cannot be reduced to the question of what the "unit" of heredity is. What the right unit of heredity is, will depend on the mechanism of inheritance that is relevant in explaining the reproduction of the population in question. In other words, *what the right unit of heredity is depends on the lineage that the unit is supposed to explain, and thus on the processes of development on which we want to focus our attention*. The motivation for assuming that a task of any model of cultural evolution is the identification of the "right" unit of heredity is gone; different inheritance systems promote different units (Caporael et al. 2014).
b) The second related reason is that if "niche construction" is considered part of the evolutionary process, what is biological and what is cultural evolution cannot be separated into two sharply distinct causal processes (Laland and Brown 2002).
c) The third reason is that, as recent discussions about innovation in biology make clear, innovation should be understood as a (kind of) process that can (and should) be described as identifiable in different levels and kinds of organizations, in order to really characterize it (Parter et al. 2008; Wagner 2011; Brigandt and Love 2012). Next, I proceed to elaborate on these reasons and discuss their relevance, the third one in particular, for my purpose in this paper.

Neo-Darwinism assumed a sharp separation between heredity and development, arising from the modeling of heredity in terms of chromosomes carrying genes that pass from one generation to another undisturbed by the environment. As Eva Jablonka and others have emphasized, this is only one of the inheritance systems that matter in understanding evolution.[4] Jablonka distinguishes four inheritance systems: genetic, epigenetic, behavioral and

[4] Cavalli-Sforza and Feldman (1981); Boyd and Richerson (1985) have long discussed the importance of a second non-genetic inheritance system that is able to codirect genetic evolution.

symbolic (see Jablonka and Lamb 2005). Epigenetic inheritance systems underlie the transmission of the functional state of genes and cellular structures through cellular heredity systems that constitute cell lineages (associated with the formation of different organs in human beings, for example). Behavioral inheritance systems are involved in the transmission of behavioral information through social learning in mammals and other animals. And according to Jablonka, symbolic inheritance systems are what underlie our capacity for language and rationality, and make us special in the biological world.

We do not need to accept *in toto* the categories proposed by Jablonka in order to discuss nongenic inheritance systems. I suspect that at the very least, a sharp distinction between behavioral and symbolic inheritance is hard to maintain; but what matters for us here, is that there are good reasons for thinking of different inheritance systems that can be characterized as capacities for the generation and maintenance of different lineages of organizations (cell structures, behavioral habits, human languages, cultural traditions, practices). Innovations make sense in the context of these lineages. An innovation in a liver cell is (an heritable) change in the way a certain substance is processed, for example; a change that has implications for the functioning of the liver.

Similarly, a technological innovation is not just a change in the physical components of a tool (or device, or organization). It is a change that allows the tool to be a better tool for a particular task, even if that change makes the tool unsuitable for other tasks. A knife for butchering an animal is not very good for cutting vegetables. In each case, an innovation is a change that has implications for the reproducibility and diversification of a lineage of organisms or artifacts, which in turn are constitutive of lineages of structures or forms of organization that arise from the interaction of different inheritance systems.

The second reason is a direct consequence of giving due importance to the recent characterization of evolutionary theory as niche construction theory, or more broadly, a consequence of taking the relation between development and evolution seriously. During most of the 20th century, pointing to the way in which an author appealed to biology to argue for a thesis in social science was exposing a serious defect in the explanation. In the second half of the 20th century, several attempts to incorporate evolutionary theory in the explanation of social phenomena were put forward and strongly criticized, sociobiology (Wilson 1975) and evolutionary psychology (Barkow et al. 1992), among others. All of these accounts assume a one-way causal link between biology and culture. In cases in which feedback from human behavior to genetic evolution is considered, it is assumed that this influence takes place by generating mutations (neo-Lamarckism), or by changing the probabilities of survival. Since Lamarckism was considered a dead end, most approaches took the latter route—in which culture can have a say in biological evolution, but only by allowing the possibility that it also plays a role in human adaptations. It is in this sense that, for example, evolutionary psychology talks of prehistoric minds as tool boxes of task-specific adaptations that were acquired by the human mind in the Stone Age. Such approaches often assume that *Homo sapiens* is the only species with the ability to modify its own selective environment, and thus the assumption goes hand in hand with the idea that symbolic thinking is a prerequisite for such ability.

Niche construction theory takes a more radical view of the relation between biology and culture. It elaborates on the well-known observation that organisms modify their environments to focus on those modifications that have evolutionary or ecological consequences, inherited through nongenetic systems of inheritance. Such nongenetic in-

heritances generate a form of feedback in evolution. The selection and modification of habitats is an example of niche construction present in plants and animals (Odling-Smee 1988; McNally and Brown 2015). Artifacts like burrow systems or ants' nests have generated selection pressures leading to the evolution of thermoregulation systems, the forms of organization and distinct behaviors present in defense, or routines for maintenance or repair. Artifacts like the Acheulean axe have generated selection pressures that brought about the evolution of the kind of social cognition distinctive of homo sapiens.

In either case, the separation of the evolutionary processes in question in biological and cultural processes is not fundamental. Unless we want to maintain the dogma that there is only one culture, the sort distinctive of human beings, there is no reason to attempt to distribute, as a matter of fundamental importance, causal responsibilities to culture and biology (for an elaboration of these ideas, see for example Laland et al. 2000). The key point for us is that the claim that niche construction can have evolutionary consequences which are not explainable by natural selection alone, leads to the view that key human innovations require explanatory resources beyond those at the disposal of adaptationism.[5] In particular, it leads to the recognition that explanation of current function is not enough to explain current structure.

Now I focus on the third reason for taking biological innovation as scaffold for modeling social innovation (as a version of the thesis of continuity). The geneticist Hugo de Vries (1905) reinforced Wallace's idea that natural selection could not explain crucial innovations like the human mind, when he said that "natural selection may explain the survival of the fittest, but it cannot explain the arrival of the fittest." In his book *The Origins of Evolutionary Innovations* (2011), Andreas Wagner quotes De Vries, adding that this question about the origin of innovations is still present. He aims to provide evidence for the thesis that it requires more than a combination of natural selection and random change to account for evolutionary innovations. As he reminds us, many evolutionary innovations have been studied in great detail, but "case studies cannot provide the general perspective needed to answer this question" (Wagner 2011, 2). Hence why he thinks there is a need for a general explanatory framework that could account for innovability (the capacity to innovate) in biology and beyond. He does not pretend to provide such a framework, but only contribute to what he considers should be building blocks of such a theory.

In order to provide concrete steps towards a theory of innovability, Wagner pays attention to three classes of systems that, as he shows, are central to innovation: large metabolic networks, regulatory circuits, and macromolecules. The main message of the book is that these systems are components of genotype networks that are necessary in order to understand all biological innovations. Moreover, he shows that a suitable abstracted notion of network organization can be traced from macromolecules to (some) technological systems, and thus through all major evolutionary transitions. What is particularly important for the point I want to make, is that *the identification of such distinctive network organizations, as Wagner shows, requires the identification of a capacity through different levels of organization.* As will become clearer below, Wagner's point can be reformulated as saying that innovation should be understood in terms of capacity for change that is path dependent.

[5] I am, of course, focusing on explanatory adaptationism (as opposed to what is often called empirical adaptationism): see Godfrey Smith (2001).

Wagner's point has been made by several other authors in different terms and contexts. Csete and Doyle introduce the concept of protocol (see for example 2002). Protocols are the organizing principles underlying the modular structure of a complex system (like a macromolecule or a Boeing 777). Modularity means different things for different people, but the core idea is that modules are parts or subsystems of a larger system, which function as relatively stable units with respect to changes in the larger system. Modularity has been a key topic in biology for a long time; however, Csete and Doyle's claim is that protocols are more important than modules for modeling biological complexity. Protocols are prescriptions or constraints that describe the possible architectures, rules or codes of conduct. As Csete and Doyle put it, "protocols here are rules that prescribe allowed interfaces between modules, permitting system functions that could not be achieved by isolated modules" (2002, 1666). They give the example of Lego pieces as modules, the shapes that allow one type of piece to fit with another; the snap would be the basic Lego protocol. Protocols are more important than modules in understanding complexity, precisely in the sense that matters to us: protocols refer to the capacity of the system to innovate, namely, to generate new architectures and functions through the display of protocols that are robust. Robustness allows for innovations that in turn can function as scaffolds for other innovations. Protocols are not mere rules, and not just any rule is a protocol. A protocol facilitates the layering of additional protocols, that in turn "fit" with other protocols through feedback and other means of appropriate signaling. Thus the sense in which protocols are more important than modules (for characterizing innovation) can be formulated roughly as follows: *biological (and social) complexity cannot simply be explained in terms of functions and adaptations, but require us to consider protocols and feedback loops that provide robustness and evolvability.* Laws about (transfer of) energy or about the modular structure of materials, for example, require less control and are less relevant in understanding the complexity of a system, than robustness. Robustness, and not optimality or adaptiveness, should be the main focus for models of complexity.

In several writings, Kirschner and Gerhart propose a "theory of facilitated variation" (FV) (see for example Gerhart and Kirschner 2007), which aims to characterize different notions of innovation in biology (arising in genetics, developmental biology and evolution, among others), departing from the insight that organisms are designed so that random genetic changes are channeled in phenotypic directions that are potentially useful. Of course, the main objection to this sort of theory has been that it is hard to explain how FV spontaneously emerges during evolution. Kirschner and Gerhardt provide experimental and historical evidence for FV in several writings (see in particular 2005). Parter and co-authors (2008) develop computer simulations of logic circuits and RNA secondary structure which show that FV is enhanced in environments that are somehow constrained to change in a systematic way, such that the varying environments are made of the same set of subgoals, but in different combinations. Their finding is that systems which change under the guidance of (stable) protocols (that constrain the stability of the units of change) tend to remember their history and have the capacity to generalize to new environments. This is precisely the sense in which I have said above that innovation is path dependent. The original way of understanding path dependence in economy identifies such a dependency as a constraint on innovation. A series of contingent facts ends up "locking in" the QWERTY keyboard, for example. But path dependency can be seen not only as historical (contingent) constraints on future processes, but as the protocols that guide those future processes

through constraints by restricting them to combinations of a given set of subgoals (a given set of possible interfaces). This formulation of path dependency can be seen as a more general version of the concept of path creation proposed by Garud and Karnoe (see section 1). Calcott (2014) formulates a similar idea in terms of a shift "from adaptationism to evolvability". Adaptationism is understood by Calcott as implying that current structure can be explained in terms of current function; but this is questionable, because slight variants of a system facilitating innovation can play an important role in such an explanation, to the extent that protocols reduce the number of accessible variants, and thus projects path dependency into the future (into path creation). Calcott focuses on the proposal that there are underlying universal principles that explain the organization of biological and (complex) technological systems, and emphasizes the importance of distinguishing between two explanatory tasks: on the one hand, the task usually associated with adaptability, which explains the capacity for a system to achieve some particular task at a time; and on the other hand, the task of explaining the capacities of systems to change over time. *It is this second diachronic goal which is the explanandum of evolvability and that is involved in accounts of innovation in terms of protocols* (Calcott 2014). This is a kind of path dependency in which innovations result from protocols that take dependency on the past as an explanatory resource for the creation of alternatives constrained by such protocols.

5. Conclusions

To the extent that the path dependence in question supports the right abstractions (and generalizations) from biology to the social realm, we can take such path dependence as modeling the kind of continuity that Darwin was aiming to characterize between biology and the social sciences. It suggests that innovation (at least in complex systems satisfying some very general conditions) has to be modeled as a phenomenon taking place across different levels of organization; and thus, attempts to characterize innovation processes as aggregative are misleading. Innovation is robust path dependence with the capacity to facilitate new organizational achievements i.e. path creation. The continuity from biology to certain technological achievements has led to productive ways of modeling specific technological innovations, like electronic circuits (Wagner 2011) and software engineering (Calcott 2014). The key insight—that it is robustness and not function that we have to focus on, to model innovation as a kind of process across different levels of organization—is an idea with a promising future. It means paying attention to hierarchical ontologies of social processes, as opposed to the traditional tendency to construct models of technological change based on flat ontologies that lead to modeling innovation as an aggregative phenomenon.[6]

[6] For an interesting suggestion pointing to the need to pay attention to hierarchical ontologies in models of technological change, see the work of Geels (for example 2010).

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Sergio F. Martínez is research professor at the Instituto de Investigaciones Filosóficas, UNAM (Mexico). He is currently interested in the philosophical implications of taking seriously the material culture of science for developing a historicist philosophy of scientific practices, and in exploring the implications of contemporary biology and cognitive sciences for this project.

Address: Instituto de Investigaciones Filosóficas, UNAM, Circuito Mario de la Cueva s/n Ciudad Universitaria, Ciudad Universitaria, Distrito Federal, Mexico. Email: sfmar@filosoficas.unam.mx