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Complexity Perspectives in Innovation and Social Change

Springer

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Introduction

David Lane, Denise Pumain and Sander van der Leeuw

The project that resulted in this book originates in an encounter of three of the authors (David Lane, Sander van der Leeuw and Geoffrey West) in the summer of 2001 at the Santa Fe Institute around two main themes: (1) a different way of looking at the invention and innovation of artefacts, and (2) the possible impact of innovation on urban dynamics. One of us was a physicist (West), one a statistician (Lane) and one an archaeologist (van der Leeuw). Almost immediately, we asked Denise Pumain (an urban geographer) to join us in this adventure.

Fortunately for us, our meeting coincided with an initiative of the head of the newly formed unit for a project officer of the Future and Emerging Technologies Program of the European Union's Directorate for Information Science and Technology, Dr. Ralph Dum, to stimulate a wide spectrum of research into the potential uses of Complex Systems approaches. Hence, we brought four teams together, at three European universities: the University of Modena and Reggio Emilia (Lane), the University of Paris 1 (Panthéon-Sorbonne) (Pumain and van der Leeuw), and Imperial College, London (West).

Ralph encouraged us to apply, and after the usual vetting procedure our proposal for a project that considered the Information Society as a Complex System (ISCOM) was accepted and funded. We began work in July 2002, and the project lasted for four years, until the end of June 2006. Those years turned out to be a very exciting intellectual adventure for all of us, as well as the members of our teams and the colleagues whom we invited to our workshops in London, Santa Fe, Venice, Modena, and Paris. Some of the results lie in front of you. But we do not think that we are exaggerating if we say that the collaboration influenced the thinking of all of us to such a point that other results will follow in due time, whether under our name or under that of the many other members of the team (see the list that follows this introduction).

Two conclusions stand out from the project. Firstly that innovation and invention have, in a sense, been among the stepchildren of modern research, whether in the

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social sciences or in the humanities, and secondly that the role of innovation in urban dynamics is much more important than is generally acknowledged.

We live in a world that is driven by invention and innovation, but that has not always been so. In the XVIIth century, innovation was a ‘dirty word’. The world order was deemed to be immutable; people behaved as their ancestors had done (or at least they believed they did, and they often strived hard to meet that ideal) (Girard 1990).

Little by little, though, over the last three centuries, ‘history’ and ‘tradition’ ceded place to ‘nature’ as the concept invoked to explain the world order. We still speak in many instances of ‘it is natural’ when we wish to express the fact that we think that a kind of behavior is in harmony with the world order. In the process, in the first part of the XIXth century, History has become a discipline, rather than the omnipresent way to explain what happened or what happens.

Simultaneously, we observe a growing *emphasis on the new rather than the old* – particularly during, and as a result of, the Enlightenment and the Industrial Revolution (Girard, 1990). As science and technology gained in importance, the conceptual and instrumental toolkit of the (western) world grew exponentially, and in doing so enabled humanity to identify and tackle more and more challenges. As a result, the number of inventions and innovations around us is increasing dramatically. This is clearly visible if one looks at the number of inventions that are patented in the industrial countries.

After the industrial and nuclear revolutions, we are now witnessing the silicon, information technology and communications revolutions, and the nanotechnology, biotechnology, and cognitive revolutions are on the horizon, each of which is opening another whole new domain of knowledge, know-how and innovation. For the moment at least, there does not seem an end in sight to this acceleration of change in our world.

In that context it is in our opinion surprising that the scientific community has generated so little understanding of the process of invention and innovation itself. Generally, the world reacts *a posteriori* to innovations once they have been introduced. Could we not attempt to shift our stance from a re-active to a pro-active one, and come to understand and guide the process of invention and innovation itself? That would put us in control rather than dealing with things after they have gotten out of hand, and it would potentially allow us to accelerate the innovative process in those domains in which that is most needed, and maybe slow it in others

What has thus far held back our understanding of the process of invention and innovation? Our tentative working hypothesis is that this lack of understanding is directly related to the fact that the majority of the scientific community has looked at invention and innovation using a positivist, scientific perspective. In essence, invention and innovation have mainly been studied ‘a posteriori’. From such a perspective, creation cannot be described or understood. Hence, we have left ‘invention’ completely to one side in innovation studies, relegating it to the domain of ‘personal creativity’, and we have focused uniquely on innovation, i.e. on the ways in which an invention is adopted and spreads throughout a population.

The first towns in the world were founded about six or seven thousand years ago. After a slow start, urbanization is now everywhere around us. Currently, about 50% of the world population lives in towns, and this number is growing so rapidly, that the 80% threshold may be reached within twenty to forty years. In effect, urbanization seems to be an unstoppable ‘explosion’ that is only equalled by the explosion in inventions we have seen over the last century or so. Hence, the idea that there might be a relationship between the ‘innovation explosion’ we have just referred to and the ‘urban explosion’ seems worth looking into.

Our team has convincingly demonstrated that innovation (as represented by the number of people involved in research, the number of research organizations, the number of patents submitted, etc.) scales super-linearly with the size of urban agglomerations, while energy scales sub-linearly and services linearly (cf. Bettencourt, Lobo, & Strumsky, 2007; Strumsky, Lobo, & Fleming, 2005, Bettencourt et al., 2006; Pumain et al., 2006 and Chapters 7 and 8 in this book). This seems to point to the fact that, whereas economies of scale in energy use are an important phenomenon in urbanization, managing information–generating new things and patterns of Organization–is the actual driver behind urbanization.

Because people congregate in cities, the latter harness the densest and the most diverse information processing capacity. Not only does this relatively high information processing capacity ensure that they are able to maintain control over the channels through which goods and people flow on a daily basis, but their cultural (and, thus, information-processing) diversity also makes them into preferred loci of invention and innovation.

The super–linear scaling of innovation with city size enables cities to ensure the long-term maintenance of the information gradient that structures the whole system. It is due to a positive feedback loop between two of any city’s roles. One the one hand, most flows of goods and people go through towns and cities. That confronts them most intensely with information about what is happening elsewhere, and this – again – enhances their potential for invention and innovation. But the same connections enable them to export these innovations most effectively – exchanging some part of their information processing superiority for material wealth. Cities are demographic centers, administrative centers, foci of road systems, but above all they are the nodes in the system where the most information processing goes on. As such, they are the backbone of any large-scale social system. They operate in network-based “urban systems” which link all of them within a particular sphere of influence. Such systems have structural properties that derive from the relative position all the cities occupy on the information-processing gradient, and in the communications and exchange networks that link them to each other (White, Chapter 5 in this volume). Although the role of individual towns in such systems may change (relatively) rapidly (Guerin-Pace, 1993), the overall dynamic structures are rather stable over long periods of time. In the long run, the organisation of human habitat in networks of cities reduces the uncertainties of a closed environment by relying on more distant resources as well as by creating new ones. There is a shift from a human ecology toward another way of structuring the planet, entangling territories (geographical structures based on continuity) in societal networks (that are based on connectivity).

The books of the Methodos series explore some of the new ways that emerge from the complex systems paradigm. Without entering into the debate about the possible emergence of a unified science of complex systems, we want here to develop a new theory of human social change, within a perspective that is informed by the recent developments of the complex systems paradigm. In this book, we will explain why we think that this paradigm can help us to identify the specificity of innovation and change in social systems.

Part I of this book: *From biology to society*, specifies how a new kind of organisation has emerged with the historical apparition of human societies. Although *Homo sapiens* is a biological species, whose individual elements do not in themselves differ from any other animal species in their biological organisation, and although social systems do share some properties with animal social organisations, two main radically new and distinctive features were created through the process that led to human social organisation. The first one is a self- monitored, directed (intentional) modality of social change. We shall demonstrate that this new kind of evolutionary driver is the result of the integration of new functionalities in social structures due to cultural processes. The second distinctive feature that is essential to our approach of social systems is that it is comprehensive: to shift from a static description of social structures to a dynamic one, we need to consider a variety of social interactions that are usually separated in disciplinary explanations of social systems. The modifications in social organisation that are directed at monitoring social changes, and that produce emergent patterns instantiated in organisations do affect a social system in every aspect and at all its levels of organisation. We describe how function, structure and process are affecting each other, and we build a dynamic, interactionist interpretation of the evolution of social systems.

In this attempt, it is important to determine which ingredients are necessary for developing a theory of human social innovation that is both general, and precise enough to be relevant. We believe that complexity theories are the necessary framework for developing a modern interpretation of change in complex systems. However, we question two principles that are part of the application of this theoretical approach to physical and biological systems. These are, firstly, the search for invariance and universality in processes. We demonstrate that human social change cannot be described in Darwinian terms, because something new has appeared, *i.e.* the fact that human societies are inherently responsible for their own innovation. This then leads us to question the applicability of the Darwinian approach of biological evolution to human social evolution, which we discuss in the first five chapters of this book.

Part II, *Innovation and urban systems,* and Part III, *Innovation and market systems,* develop examples of the application of these ideas and work out more precisely a number of aspects of this perspective. Urban systems are at the core of many important issues in contemporary societies. While cities concentrate a majority of the world population and human activities, the urban way of life may encounter limits that are increasingly perceptible in terms of the potential shortage of environmental resources (mainly energy, soil and water), in terms of organising a livable social mix, and in terms of managing local systems that are threatened by the unpredictable effects of their increasing connectedness to a multiplicity of networks through globalisation.

Sustainable development, social cohesion and territorial cohesion have become challenging issues for the monitoring of urban systems, in modern information societies as well as in developing and poor countries. It is thus essential to develop a proper understanding of urban dynamics in its complex articulation of a typical hierarchical structure with monitored but highly decentralised innovation processes that periodically renew the functionalities of individual towns and cities in increasingly better connected and wider-spread systems of cities. This enlarged (comprehensive) view of urban spatio-temporal evolution and its connection to social innovation is developed in Chapter 6. In biology, scaling laws have been identified as useful methodological tools reflecting the effect of energetic and geometric constraints on the development and structural organisation of living systems. Two chapters are dedicated to the application of this methodology on urban systems, using different approaches to determine to what extent further urban growth may depend on similar effects or not.

Markets are perhaps less easy to coin as complex social systems whose evolution requires a specific social input in a general theory of complex systems. Indeed, they are very often analysed within a unique disciplinary framework, and sophisticated mathematical models derived from the principles of economic theory are sometimes thought of as very successful descriptions of even the most capricious fluctuations in stock exchange evolutions that would open the way to quasi physical theories of these very decentralised and complex systems. However, we claim that such interpretations can only operate in specific contexts, where the social ingredients of what constitute the markets are clearly defined. If we want to understand real market evolution, we have to develop a broader theory of markets as social organisation. A major point we insist on is to demonstrate how social interaction is linked to the invention of new artefacts and their functionalities in social systems. This is done in three chapters of section three, including a reflection on the implications of our perspective for social policies favouring innovation.

Our complexity perspective has several methodological implications that we develop in Part IV of this book, *Modeling innovation and social change*. Models are the indispensable steps that enable a fruitful dialog between theory and empirical studies. In dealing with social change, we need abstract narratives that can identify what is really changing and what remains invariant over time in the evolution of social systems. Within the continuous and more or less rapid flow of social innovation that manifests itself in the production of new artefacts, new institutions, technological inventions, scientific breakthroughs, but also new social practices, collective representations and beliefs as well as new modes of social interaction, what are the features that are significant for interpreting social change? What are the decisive configurations in structure, function and process that are necessary for driving that evolution? Among those, what are the possible levers for intelligent monitoring, or partial control over the anticipated evolution? Models are useful tools for answering these questions.

The abstract description of social evolution can be translated into models. Mathematical and computational models help us to understand how social systems can share some features of their structure and evolution with other complex systems, as reflected for instance in structural power laws or scaling laws, whereas the parameters that are involved in these models take specific values which may imply a quite different qualitative evolutionary behaviour from natural or living systems. Because of that, we chose to develop not only analytical models of social change, but more flexible models that are no longer analytical but computational, including multi-agent models. These models allow the handling of both invariant features, including entities and rules whose properties represent stylised facts from observed empirical evolution, and creative aspects of social organisation when the nature of agents or artefacts is transformed through dynamic interactive processes. Although this can be partially modelled, the exogenous intervention of the modeller is still necessary to match such a creative evolution.

Another way in which computational models are helpful is that they enable the exploration of unexpected events and unforeseeable futures. Social changes do not operate in a predefined space where everything that might happen has been predefined. Mathematical models are not able to handle systems where something new can change the meaning of variables and parameters or create new categories. Whether the methods of artificial intelligence will be able to do so is still a matter of debate. We use AI here in modelling as a tool for exploring the limits between what can be endogenously produced from interactions within the model, and what has to be imported as exogenous knowledge by the model designer. Models are tools of random search in a space of not-yet-definite potential futures. Whenever possible, we have privileged data-driven simulation as a way of constructing models. This is the case for a variety of applications presented in section four (especially Chapters 13 and 17 on the dynamics of urban systems). The theory is injected in the model as abstract knowledge defining endogenous processes, and the results of simulation allow us to identify which specific processes have to be inserted from the outside to match observed or projected structures and functionalities.

As editors of this volume, we would not want to conclude this introduction without expressing our thanks to many people. First of all to the authors of the papers, who were our partners in the discussions and debates that led to these pages. Secondly to all those who helped us, at various times, to organize the many workshops and dealt with the inevitably complex administrative procedures, among whom we would like to mention particularly Irene Poli, Federica Rossi, Antoine Weexsteen, Martine Laborde, and the staff of the Santa Fe Institute. And thirdly to Callie Babbitt, who did all the final editing and typesetting of the manuscripts.

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Part I
From Biology to Society

Chapter 1
From Population to Organization Thinking

David Lane, Robert Maxfield, Dwight Read and Sander van der Leeuw

1.1 Introduction

Our species is still very young by biological time scales, and it is too early to know if we represent the cutting edge of a biological success story, like cockroaches or dinosaurs, or a brilliant but ultimately failed and short-lived experiment in niche construction and destruction. In the mere 200,000 or so years of *Homo sapiens*' story, and in particular in the approximately 50,000 years since we began to accrue the accoutrements of culture like language, art and multi-component artifacts, members of our species have populated a vast extent of the earth's surface and exploited for our own purposes an ever-increasing share of the planet's biologically utilizable solar energy. In the last few centuries, we have ravaged the stock of bioprocessed solar energy accumulated over millions of years, transformed minerals extracted from below the earth's surface into a huge variety of forms and new materials that satisfy what we regard as our needs, and increasingly concentrated the human population in urban spaces to which nearly all the raw materials necessary for human survival have to be imported from elsewhere. At the individual level, our first *Homo sapiens* ancestors managed to keep themselves going on the 100–300 watts their bodies were able to generate, assisted in their quest for survival by the handful of artifacts they knew how to make and use; in contrast, current residents of New York City mobilize on average about 10,000 watts to propel them through their daily rounds of activity, and the shops in their city offer them a choice of something like 10^{10} different kinds of artifacts to help them accomplish whatever it is they might feel inclined to do.[1]

How have we managed to accomplish so much so fast? The main premise of this chapter is that we have done it through a new modality of innovation, through which human beings generate new *artifacts* that they embed in new *collective activities*,

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[1] See Chapter 12. The number of artifacts refers to the number of different SKU's – that is, product labels used for distinct bar codes – on offer in New York, as estimated and reported in Beinhocker (2006). This is of course a rather crude measure of "kinds of artifacts".

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which are in turn supported by new *organizations* and sustained by new *values*. Over time, this new innovation modality gave rise to a positive feedback dynamic, which explains how we have generated so many transformations in our selves, our societies, our culture and our environment.

What is this new innovation modality? We begin by describing something it is *not*. Much of modern biology is based upon Darwin's theory of biological novelty, which analyzes the processes through which species come into being and are transformed, by means of mechanisms of heritable variation and selection. Given the tremendous scientific success of this theory, it is not surprising that many authors have sought to adapt it to other contexts. In particular, it is becoming increasingly fashionable to construct theories of innovation in human society and culture on a Darwinian foundation. We shall argue that this move is mistaken.

To be clear about the claim we are making, we need to define precisely what counts for us as a Darwinian foundation. An evolutionary theory seeks to understand a phenomenon by describing the processes that brought that phenomenon into being and that generate the transformations it successively undergoes.[2] A *Darwinian account* is a special kind evolutionary theory that, like the theory Darwin set out in the *Origin of Species*, rests on two foundational bases:

- it is characterized by what Ernst Mayr (1959, 1991) called *population thinking*; and
- it analyzes the transformation processes with which it is concerned in terms of two *fundamental* and *distinct* classes of mechanisms: variation and selection.

We discuss these two concepts, in the context in which Darwin introduced them, in the second section of the chapter, and we explain why they were such a great success in this context. We then describe some issues that must be resolved before they can be successfully applied in other contexts.

In the third section, we examine some features of human sociocultural innovation that distinguish it from biological evolution. We argue that these features are not consistent with the foundations underlying a Darwinian account. In particular, the distinction between variation and selection processes is difficult to maintain – and even when they can be distinguished, they frequently fail to be fundamental, since another kind of process, negotiation, underlies both of them. In addition, it is often impossible to identify a relevant "population", which is the critical starting point for population thinking.

In the fourth section, we describe a shift in perspective, from population thinking to *organization thinking*. After analyzing some critical differences between

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[2] In contrast, essentialist theories seek to explain phenomena by isolating their (unchangeable) essences and classifying all other aspects of the phenomena either as deducible consequences of these essences or inessential epiphenomena. For example, a noted neoclassical economist once told one of us, that "if it isn't about optimization and rationality, it isn't economics". Essentialist theories tend to be associated with the "typological thinking" mentioned in the following section, just like Darwinian accounts are associated with "population thinking".

biological organization and sociocultural organization, we propose an innovation modality alternative to the Darwinian account. We call this modality *organizational self-transformation*, and we argue that it bears a relation to sociocultural evolution similar to the Darwinian account's relation to biological evolution. We conclude by describing some features of organizational self-transformation, in particular the positive feedback dynamic to which it gives rise. This dynamic, which we call *exaptive bootstrapping*, has generated the proliferation of artifacts and organizations that construct our current sociocultural world – and us.

1.2 Darwin's Theory of Biological Evolution: What It Is, Why It Works

For over a hundred years before Darwin published the *Origin of Species*, students of natural history had collected a huge body of evidence illustrating what they regarded as a nearly perfect match between the morphological characteristics and behaviors of biological individuals and the environmental opportunities that these individuals exploited to earn their living. For example, the woodpecker's beak seemed *designed* to drill into bark to extract the insects the woodpeckers ate, while the hummingbird's beak and capacity to hover could hardly be improved upon as a way to sip nectar from flowers. Such matches between structure and functionality were generally interpreted as evidence for the existence of a benevolent Designer, who had constructed a world able to sustain in harmonious equilibrium all the products of His creation, including the many species of plants and animals that the natural historians were busy describing and classifying.

For these natural historians, a species was an immutable, ideal organization, exquisitely tuned to the exigencies of the environment in which members of the species sustained and reproduced themselves. This organization was more or less perfectly instantiated in all the individuals that belong to the species. Ernst Mayr (1959, 1991) labeled this way of construing biological organization *typological thinking*.

Darwin's first great accomplishment was to displace typological thinking by what Mayr called *population thinking*. Population thinking *un-reifies* the species. Instead of a timeless *kind*, the species becomes just an *aggregation of individuals*. The species has a beginning, in an act of speciation, and sooner or later it will have an end, when it becomes extinct. Its boundaries – who is in, and who is not – are determined by pedigree: once the species has come into being, no individual may enter unless its parent or parents are already members, and no member can defect, except through death. For Darwin, what counts for a species as *population* is not the commonalities that its members share, but the *variation* among conspecifics. That is, the species as population is characterized not by a shared organization, but by the *statistical distribution of those features that differ* among members of the population. Thus, not only is the *species* no longer identified with an *ideal* organization but the very *real* organization of an *individual* is disregarded in Darwin's story, and the individual figures in it merely as a set of distinct features. From the point of view of population thinking, biological evolution is the story of the changes in the distribution in the population of these features over time, including the introduction of new features.[3]

The species as population is not composed of a fixed set of individuals: the members of the population change over time, through birth and death events. It is critically important to the success of Darwin's story that the features of new individuals are statistically related to the current distribution of features in the population. Fortunately, for features that are *heritable* this turns out to be the case. That is, absent changes due to the mechanisms of variation and selection described in the next paragraph, reproduction – whether it be sexual or asexual – does not change[4] the distribution of differing heritable features, which, as we have seen, Darwin's theory takes as the variable of interest in the species transformation story.

Darwin analyzed the change in feature distribution over time by distinguishing between two fundamental classes of mechanisms through which change happens: mechanisms of *variation* and mechanisms of *selection*. The former introduce *new* variant features that individuals in the population may possess, while the latter determine which features will *increase in frequency* in the population over time. New heritable features persist in the population, unless they are eliminated by selection mechanisms.[5] In *Origin*, he called attention to one particular selection mechanism, which he regarded as the primary determinant of the direction of change in feature distribution: *natural selection*. According to Darwin, individuals in the same species were always in competition among themselves to obtain the resources necessary to survive and reproduce. Thus, a heritable feature that helps individuals possessing it to get a reproductive edge over their conspecifics would tend to increase in frequency generation by generation. Such features came to be described as increasing the *fitness* of individuals who possessed them, and natural selection came to be conceived in terms of a stochastic process guided by a *fitness function*, whose value for a set of features represented the relative competitive reproductive advantage of an individual possessing this feature set.

According to the currently canonical version of Darwinian theory, the so-called neo-Darwinian synthesis that welded together ideas from Mendelian genetics to

[3] Of course, this begs some key questions, which Darwin did not address: just what constitutes a new *feature*, and how can it be integrated functionally with previously existing ones; or which new features – or distributional changes in existing features – constitute the origin of a new species? Biologists since Darwin have addressed these questions, sometimes supplementing but never successfully challenging the basic suppositions underlying population thinking.

[4] In expectation, with random mating in sexually reproducing species (that is, absent sexual selection, a selection mechanism). Of course, in sexually reproducing species, offspring will not have the same features as both their parents, and so the *realized* distribution after a new individual is born is not identical to what it was before the birth – it is conventional to refer to "random drift" as a selection mechanism when such random oscillations contribute to the directionality of change in the feature vector distribution.

[5] Here, as in the previous footnote, we follow the convention that classifies random drift as a selection mechanism.

Darwin's evolutionary theory in the first three decades of the 20th century, the key variation mechanisms for heritable features in biological evolution derive from genetic operations during reproduction. Thus, a particular innovation is initiated as a new variant *genotype*, which, in interaction with pre-existing structural or behavioral features and particular environmental contexts, happens to result in a new structure or a new behavior at the *phenotypic* level. This new structure or behavior may get incorporated in some kind of process with already existing behaviors, structures and environmental features, and this new process may provide a survival or reproductive advantage to the individual who possesses it. If so, by natural selection, the frequency of individuals with the innovation will increase over time in the population, and the innovation will count as a success.[6]

From the moment of *Origin*'s publication, Darwin's ideas were discussed everywhere, not just in the restricted circles of the natural historians.[7] This initial high level of interest ensured that many other scientists would continue to probe these ideas – to support them, oppose them, extend them. It took several generations for the initial *succès de scandale* to develop into scientific orthodoxy, but by the 1930s, this too had been achieved. How can we account for the great success of Darwin's theory of biological evolution? We think four reasons, described below, were primarily responsible. The first two of these account for the unusual degree of interest that Darwin's ideas encountered in the first decades after *Origin* and kept them under the spotlight of intense scientific exploration, and the second two were responsible for the construction of the scientific consensus around the Darwinian account as a foundation for a theory of biological innovation.

1.2.1 R1: A Non-Teleological Explanation for Structure-Function Fit

Darwin's theory provided the first really plausible alternative to the hypothesis of intelligent design as an explanation for the extraordinary match in the biological world between structure and function. It differed in two fundamental ways from intelligent design. According to intelligent design, biological organization is *immutable* and *teleological*: each structural feature was designed *in order to* carry out a particular function, and once designed, it need not – and did not – change. In contrast, in Darwin's story, structural change was the *key* to the match between structure and function. New variants might appear in any possible direction in feature space, but

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[6] Note that *how* the genotype contributes to the construction of the phenotype is not part of Darwin's account. This important problem, under the rubric of "evo-devo", is currently a very hot topic in biological research. Evo-devo extends rather than revises the Darwinian account, and the separation between variation and selection mechanisms serves as a strong constraint on the kinds of structures that evolution can produce – for example, new variations, which occur at the genotypic level, cannot be directed toward the provision of specific functions at the phenotypic level.

[7] See, for example, Desmond and Moore (1991), Chapter 33.

only those that provided an advantage with respect to the overarching functional imperatives – to survive and to reproduce – were retained through the generations.

The reaction to a non-teleological alternative to intelligent design was explosive. It empowered scientific radicals like Thomas Huxley and atheistic lay(wo)men like Harriet Martineau to take the initiative in dissolving the claims for divine causality that had subordinated natural history – and science more generally – to religion. Correspondingly, it deeply upset, even scandalized, proponents of traditional values, from scientists like Richard Owen and Louis Agassiz to clergymen like Samuel Wilberforce, who in an 1860 Oxford free-for-all discussion on Darwin's ideas asked Huxley from which side of his family was he descended from apes. Though debates of this sort generated substantially more heat than light, the idea of directional change without a directing intelligence became a central theme in the ongoing cultural battle between an emerging materialistic scientism and traditional deference to established authority and revealed religion. For scientists on both sides of this battle, finding evidence and arguments that bore on the plausibility of Darwin's ideas, whether to support or demolish theory, had a very high priority – and the guarantee of a large, very interested public should they accomplish a breakthrough in this quest.

1.2.2 R2: Demonstrating the Plausibility of Organizational Innovation from Gradual Feature Change: Two Analogies

However internally consistent Darwin's ideas were, they were certainly not directly demonstrable from empirical evidence. Indeed, to make his argument plausible, Darwin had to come to grips with a very difficult empirical problem: many natural historians were prepared to argue that the immutability of species was no hypothesis, but observable fact. From Aristotle to Linnaeus to Darwin, no observer of the natural world had seen a new species come into being. True, paleontologists had found what seemed to be fossilized remains of plants and animals that did not seem to belong to any known existing species, and enough progress had been made in the relative dating of geologic strata to convince most scientists that not all presumed life forms – living or fossil – had come into being in the same epoch. But the possibility of extinction and separate epochs of creation did not contradict the assumption that, once created, a species-as-ideal-organization didn't change. Where was the evidence for change?

Darwin answered this question with a spectacular rhetorical move, accomplished through the juxtaposition of two analogies. The first analogy was intended to show that biological form is indeed malleable.[8] Darwin reminded his readers of the wonders achieved by plant and animal breeders – in particular, dog and pigeon

[8] This analogy, as Darwin himself points out in the introduction to the sixth edition of Origin, had been introduced for this purpose by other authors before him. No other author, as far as we know, had coupled it as did Darwin with the analogy with Lyellian geology.

fanciers – in creating new breeds or varieties.[9] Of course, the breeder plays an essential role here, since he selects individuals to reproduce on the basis of the features he wants to favor. In the wild, Darwin asserted, competition to survive and reproduce takes the place of the breeder. Obviously, this *natural* selection is much less intense than the breeders' *artificial* selection, and consequently will require much more time to accrue observable differences in bodily structure or behavior. Here, Darwin introduces his second analogy: we know, he claims, from the revolutionary work of Charles Lyell in geology what can happen when presently observable microprocesses act over huge spans of time. As he puts it in *Origin*, "a man should examine for himself the great piles of superimposed strata, and watch the rivulets bringing down mud, and the waves wearing away the sea-cliffs, in order to comprehend something about the duration of past time, the monuments of which we see all around us." Given enough time, small quantitative changes can produce large qualitative change. So, the same process of differential reproduction, favoring particular features, which we can observe when breeders produce new varieties, can operate over Lyellian "geological time" to produce new species by natural selection.

With this argument, Darwin changed the status of the immutability of species from an empirical fact to a mere hypothesis, and an increasingly implausible one at that – as the torturous evasions of Owen around this issue in the years after 1859, ridiculed in later editions of *Origin*, testify.[10]

1.2.3 R3: Carving Nature at the Joints: The Variation–Selection Dichotomy

When Darwin decomposed the evolutionary process into variation and selection mechanisms, he knew almost nothing about how the former actually worked. He was convinced, though, that they satisfied two properties, which were really all his theory at its most abstract level required of them: they generated variant features independently of their potential functionality, and these features were heritable. These properties sufficed to justify his analysis of the *directionality* of evolution – and hence, in his theory, the origin of species – solely in terms of selection mechanisms, in particular natural selection. The research initiated by the rediscovery of Mendel's work around the beginning of the 20th century resulted in the identification and detailed explication of the genetics underlying evolutionary variation mechanisms such as mutation and cross-over.

As a result, it became clear that Darwin's decomposition was not merely an analytic or conceptual move, but really carved nature at the joints. As Darwin had foreseen, they were functionally orthogonal: the directionality of evolution was supplied just by selection, not variation, mechanisms. But much more was true. The principal variation and selection mechanisms incorporated into the neo-Darwinian synthesis differed from each other with respect to their *ontological level* and their

[9] Darwin admits that, like all analogies, this one is incomplete, since varieties aren't species: when interbred, their offspring are not sterile.

[10] See Desmond and Moore, 1991, Chapters 33 and 34.

characteristic *spatiotemporal scales*. The variation mechanisms involved random changes in the genome, which took place essentially instantaneously, while selection operated in individuals interacting with their biological and physical environments and occurred on a time scale of many generations. Moreover, variants that produced viable individuals with new phenotypic features upon which selection could operate were exceedingly rare, so rare that the time between such events was sufficiently long that selection could in general process them one at a time, attaining equilibrium frequencies with respect to a new innovation without interference from another.

The significance of these level and scale differences between variation and selection mechanisms was two-fold. First, they made it possible to *parallelize* evolutionary research: laboratory scientists explored the genetic basis of variation mechanisms, while field researchers investigated the past history and present operation of directional change through selection. Secondly, the absence of strong interaction effects between the two classes of mechanisms very much simplified the work of theoreticians who sought to put together their effects to deepen and extend evolutionary theory – in particular, towards a quantitative theory.

1.2.4 R4: Mathematization

Since Galileo, the epistemological gold standard of science has been the construction of mathematical theories that provide succinct description and quantitative prediction for empirical phenomena. By the end of the 19th century, physics was enshrined as the king of sciences – in large part, because it had married the queen, mathematics. Other emerging sciences, like chemistry and economics, did their best to emulate the king in this respect. Biology seemed hopelessly behind. Despite the efforts of a few fringe players like D'Arcy Thompson, it still resembled its ancestor, natural history, much more than its successful rival science, physics. Though the theory presented in *Origin* was far more general and precise than any other yet introduced in biology, it was anything but mathematical. With the incorporation of Mendelian genetics into evolutionary theory, the situation changed. Ronald Fisher, Sewall Wright and JBS Haldane pioneered the quantitative theory of population genetics, which provided the beginning of what has become a flourishing mathematical foundation for Darwinian evolutionary biology, with a consequent upgrading of its scientific status. In this theory, natural selection is represented by a fitness function, with a natural interpretation in terms of expected offspring from individuals with alternative genomic configurations; the stochastic components of the models derive from genetic theories that can be calibrated with frequencies from genetic experiments.

1.2.5 Darwinian Accounts

As with other successful scientific theories, Darwin's ideas have inspired scientists working on different problems than his. For example, biologists and cognitive scientists have developed interesting and fruitful theories based on Darwinian reasoning to explain phenomena ranging from the construction of immunological and neural organizations during individual ontogeny to cognitive processes like perceptual categorization and even induction.[11] Such theories begin with the identification of the essential elements of what we will call a *Darwinian account*: a relevant *population*; and *variation* and *selection mechanisms* for features that vary among individuals in the population. If the members of the population change over time, there must be some mechanism, corresponding to reproduction in evolutionary theory, that guarantees the stability of the frequency distribution of features in the population over time, absent the operation of the identified variation and selection mechanisms.

One notable example of a Darwinian account is Edelman's theory of neuronal group selection, which describes the construction during an individual's ontogeny of a neural organization that can support perceptual categorization, the basis for many innovative context-specific behaviors that the individual may generate during its lifetime. In Edelman's theory, the population consists of repertoires of neuronal groups, "collections of hundreds to thousands of strongly interconnected neurons."[12] These groups arise according to mechanico-chemical processes of cell division, movement, death and differentiation, which guarantee that "no two individual animals are likely to have identical connectivity in corresponding brain regions." These processes thus constitute the theory's variation mechanisms. Selection operates on the neural groups, as synaptic strengths increase or decrease, within and between the groups, in response to patterns of activation correlated via re-entrant signaling with sensory and motor activity. In this theory, the repertoires of neural groups are constructed via the variation processes and remain stable (unless they disappear) during the subsequent operation of selection, so there is no need for any mechanism corresponding to reproduction. Edelman's theory shows that biological evolution not only follows the Darwinian account, but that it "engineers" systems which themselves operate coherently with that account.

In general, the relation between successful theories based on a Darwinian account and the phenomena they purport to explain shares the characteristics we claim account for success of Darwin's theory: macrolevel function-carrying structure emerges from non-teleological interaction microprocesses; proposed variation and selection mechanisms are ontologically distinct and causally independent; fundamental aspects of the phenomena of interest are expressible in tractable mathematical or computational models. It is of course *conceivable* that a Darwinian account for some class of innovation phenomena might succeed even if none of the conditions of success for Darwin's theory hold, but it would seem prudent to

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[11] For example, clonal selection in immunology (Jerne, 1967), neural Darwinism (Edelman, 1987), classifier systems for induction (Holland, Holyoak, Nesbitt, & Thagard, 1989). In addition, there are some interesting and successful Darwinian accounts for particular social phenomena, for example Croft's (2001) theory of language change.

[12] Edelman (1987), p. 5.

assign a very low *a priori* probability to such an outcome – and to look elsewhere for the foundations of a theory of innovation in such a context.

Now, neither R1 nor R2 seem particularly relevant for human sociocultural innovation. In contrast to the biological world, the fit between structure and function in the social world is not so evident that it cries out for explanation. Rather, it is *function* itself that seems to need to be explained: what is the functionality associated with such social constructions as cathedrals, horror movies and dog shows? This is not a question that a Darwinian account is equipped to address.[13] Moreover, as far as R2 is concerned, it is quite unnecessary to demonstrate the existence of large-scale organizational innovation in the sociocultural context: we all *know* that social systems, and the kinds of agents and artifacts that inhabit them change, sometimes drastically and suddenly. Nor will a Lyellian analogy work to relate observable microprocesses to large-scale sociocultural innovation, for two reasons. First, it is unlikely that all or even most large-scale sociocultural innovation proceeds by the gradual accumulation of changes induced by microprocesses. Second, it is even more doubtful whether these microprocesses are themselves sufficiently stationary over long time scales that they could generate large-scale changes, without undergoing such significant transformations that their "observability" becomes irrelevant to predicting long-term effects.

We also can – at least provisionally – claim that R4, mathematization, has yet to tell in favor of a Darwinian account for sociocultural phenomena. As far as we know, the attempts to provide such an account have yet to introduce any new mathematics, beyond variations on population genetics and evolutionary game theory; and the mathematics that has been applied has yet to produce the kind of verifiable predictions and unifying conceptions that marked the work of Fisher, Wright, Haldane and their successors.

Thus, the main issue for a Darwinian account of sociocultural innovation is that raised by R3: do the foundations of a Darwinian account carve nature (or in this case, society) at the joints? We take this issue up in the next section.

1.3 A Darwinian Account for Sociocultural Innovation?

To give meaning to the question that provides the title to this section, we need to say something about what we mean by "sociocultural innovation". As it happens, the previous section refers to an interesting, if somewhat surprising, example of what we have in mind.[14] The example comes from Darwin himself, through the analogy

[13] Unless it imposes the Procrustean bed of subordinated functionality and defines the "master functionality" to which cathedral building, horror movies and dog shows are subordinated.

[14] Of course, Darwin's theory and the processes through which it became scientific orthodoxy offer another good example. Though at first sight it might seem very far removed from the dog fancy – after all, one seems to be just about concepts and the evidentiary standards of scientific research, while the other seems to be about the generation of new breeds of dog – in fact it shares all the key features that we identify with that example.

he introduces between natural and artificial selection, and in particular the “fancies” that were coming into prominence as a popular pastime and commercial enterprise in Darwin’s epoch – and which so intrigued Darwin for the sheer variety of animal forms the fanciers were able to generate.[15] In our discussion of this example, we highlight four features that are signatures of sociocultural innovation processes. After we describe these features and explore some of their implications, we confront our findings with the foundational requirements for a Darwinian account.

1.3.1 Artificial Selection and the Dog Fancy

As we saw, Darwin discussed artificial selection in *Origin* to highlight the wide range of heritable features that nature provides as grist for selection’s mill. Depending on the selection criterion used, artificial selection can generate varieties from the same ancestral stock that are eventually as dissimilar as, say, tiny Maltese dogs and huge Saint Bernards. For the purposes of Darwin’s argument, what is being selected is just a free variable: it could be any feature, as long as it is observable, heritable and stable over time. But if we are interested in analyzing artificial selection as a process of *sociocultural* innovation, then of course we need to understand what kinds of features are employed as selection criteria, and how they become established.

According to Darwin, there is a single primary functionality that underlies all selection criteria in natural selection: reproductive potential – the capacity to produce the maximum possible number of surviving and reproducing offspring. All other evolutionary functionality is *subordinated* to this primary functionality. For example, individuals must survive to reproduce, hence survival takes on (subordinated) evolutionary functionality in Darwinian terms – so long as the features that ensure it do not compromise reproductive potential. Similarly, the woodpecker’s sharp strong beak makes food gathering more efficient, and so enhances the survival of a (proto-) woodpecker that has this feature; thus, a sharp strong beak has (subordinated) evolutionary functionality for the woodpecker.

For much of human history, such subordinated functionality probably provides an adequate first-order explanation for the criteria employed in artificial selection as well. People used the plants and animals they domesticated and bred as *tools* to help themselves (or the social organizations of which they were a part) to carry out functions related to reproduction or survival (of the relevant individual or social organization): ensuring an adequate food supply, for example, or defeating enemies in combat. Any features that rendered domesticated plants and animals particularly effective with respect to such functionality could become a selection criterion for artificial selection – that is, the basis for differential treatment by their human masters that enhanced the fecundity of individuals possessing these features, either directly

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[15] Though Darwin was particularly interested in the pigeon fancy, we will mainly concentrate on the dog fancy, which has continued to grow in social and economic importance to the present day, although somewhere in the process the label “fancy” has largely disappeared from common usage – even though “Dog Fancy” is the name of a popular magazine for fanciers.

(e.g. by determining which seeds were planted, which animals were allowed to mate, or which offspring were not intentionally eliminated) or indirectly (e.g. by food allocation practices).

At some point, though, in the history of human interaction with domesticated plants and animals, a different kind of selection criterion emerged. These criteria were no longer subordinated to reproduction or survival. For example, some plants were bred to enhance the beauty of their flowers. Similarly, some breeds of dog probably arose from selection criteria related to their capacities to provide pleasant companionship for their human masters: already in ancient Rome, tiny Maltese dogs were simply household pets, noted – and almost surely selected[16] – for their affectionate temperaments and useless but luxurious silky coats.[17]

In England, in the mid-19th century, a new kind of non-subordinated selection criterion began to emerge, associated with a new kind of social activity, the dog fancy. In 1859, the same year that the first edition of *Origin* was published, the first official dog show was held in Newcastle, followed a few months later by another in Birmingham in which 80 dogs (and their human handlers) competed in 14 different classes. These competitions proved very popular, and they rapidly grew in number, as well as in the number of competitors and the size of the public who attended them. In the earliest competitions, the dogs were judged with respect to their competence in performing class-specific activities related to such subordinated functionalities as pointing, retrieving or herding. However, this quickly began to change, and in the final decades of the 19th century, the most prestigious competitions had a completely different kind of criterion: the winners were those animals that were judged to best exemplify the "standard" conformation (physical and temperamental) of their class! Thus, the selection criteria, both for the judges in conformation competitions and for breeders seeking to produce winning animals, was not only totally unrelated to Darwinian primary functionality, but depended on *attributions* about the *attributions of others*: what judges, and fanciers in general, believed were the ideal features of a particular class, and what determined how close they believed a given animal might be to this ideal.

Such selection criteria of course required considerable alignment among the attributions of the people who participated in the competitions – owners, breeders, judges and the public who paid to view the conformance competitions – about just what counted as a class and what constituted the ideal conformation for each class. And this raises an exquisitely social question: where did these attributions come from, and how did they come to be sufficiently aligned among fanciers to make conformation competitions possible, attractive and profitable?

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[16] Probably from ancestors selected for their subordinated functionality of eliminating vermin that could attack the master's food supply.

[17] A status they continued to enjoy in the Renaissance (and beyond). Carpaccio painted a beautiful diptych, in one frame of which a group of men hunt ducks in the Venice lagoon with the help of water spaniels – and in the other two women dreamily await their men's return on the terrace of a Venetian palazzo, accompanied by a fluffy, cuddly Maltese.

It is important to understand that, with just a few exceptions, what we now know as dog "breeds"[18] did not pre-exist the rise of the dog fancy and the conformance competition, even if dog *breeding* did, as we have seen. As we saw, the classes in competitions were initially defined by function, and sometimes also by size, not genealogy. For example, in the earliest competitions, spaniels were divided into "springer" and "field" classes, depending on whether the animals were trained to flush game or simply locate and retrieve it. Because of the requirements of their task, springers were generally larger and more agile that field spaniels, but it was perfectly possible for a dog to compete in the springer spaniel class in the same competition in which its sibling was entered in the field spaniel class. Moreover, because of the variety in form of dogs entered in the field spaniel class, some competitions began to distinguish between larger dogs, called "field spaniels" and smaller ones, called "cocker spaniels" (supposedly because they were used to hunt smaller prey, like woodcocks). As *conformance* competitions increased in popularity, the issue of judging criteria for classes like these became particularly rancorous, since winning these competitions did not depend on what the dogs did, but how they appeared.

The solution to these questions of rules and definitions lay in *organization* – and *negotiation* channeled by organizations. Fanciers, especially breeders, established societies that debated and established procedures for determining rules for entering, classifying and judging competitions and conventions for sponsoring or recognizing competitions based upon these rules. The first such societies were based upon interest in particular classes of dogs, but soon the desire for overall coordination led to the creation of a new national society, the Kennel Club, founded in 1873, which appropriated the responsibility to oversee all "official" dog fancy competitions. The following year, the Club published its first Stud Book, which included results of past competitions and rules and calendars for future ones. Moreover, the Kennel Club, working with the class-based societies, began to establish conformation *standards* for the classes it recognized. To handle entries in a standardized way, each individual dog was restricted to membership in one particular class. The basis of this enrolment quickly became genealogy. That is, the *classes* were transmuted into *breeds*. In 1880, the Kennel Club began to register dogs as "purebred" members of the newly standardized breeds.

All this, of course, goes exactly in the opposite direction to Darwin's move to *unreify* species. In effect, the dog fancy societies, coordinated by the Kennel Club, reified the *breed* – and endowed each breed with an ideal organization, expressed in its published conformation standard. This reification of the breed was not a recognition of some existing underlying *natural* reality, but rather, through the activities of the clubs, the competitions, and in particular the Kennel Club's breed registry, it *created* a new *social* reality.

[18] Defined by a particular set of characteristics that "bred true" and backed up by certified breed genealogies.