THE FRONTIERS COLLECTION

Caterina AM La Porta
Stefano Zapperi
Luciano Pilotti (Eds.)

UNDERSTANDING INNOVATION THROUGH EXAPTATION

Springer

THE FRONTIERS COLLECTION

The books in this collection are devoted to challenging and open problems at the forefront of modern science and scholarship, including related philosophical debates. In contrast to typical research monographs, however, they strive to present their topics in a manner accessible also to scientifically literate non-specialists wishing to gain insight into the deeper implications and fascinating questions involved. Taken as a whole, the series reflects the need for a fundamental and interdisciplinary approach to modern science and research. Furthermore, it is intended to encourage active academics in all fields to ponder over important and perhaps controversial issues beyond their own speciality. Extending from quantum physics and relativity to entropy, consciousness, language and complex systems—the Frontiers Collection will inspire readers to push back the frontiers of their own knowledge.

More information about this series at http://www.springer.com/series/5342

Caterina AM La Porta ·
Stefano Zapperi · Luciano Pilotti
Editors

Understanding Innovation Through Exaptation

Springer

Editors
Caterina AM La Porta
Department of Environmental Science
and Policy, Center for Complexity
and Biosystems
University of Milan,
Milan, Italy

CNR - Consiglio Nazionale delle Ricerche
Istituto di Biofisica
Genova, Italy

Innovation For Well-Being
And Environment (CRC-I-WE)
University of Milan
Milan, Italy

Stefano Zapperi
Department of Physics
Center for Complexity and Biosystems
University of Milan
Milan, Italy

Luciano Pilotti
Department of Environmental
Science and Policy
University of Milan
Milan, Italy

ISSN 1612-3018 ISSN 2197-6619 (electronic)
The Frontiers Collection
ISBN 978-3-030-45783-9 ISBN 978-3-030-45784-6 (eBook)
https://doi.org/10.1007/978-3-030-45784-6

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface: Why Read This Book

Twenty years ago, IBM's Deep Blue computer stunned the world by becoming the first machine to beat a reigning world chess champion in a six-game match. The supercomputer's success against an incredulous Garry Kasparov sparked controversy over how a machine had managed to beat a grandmaster. The possibility for modern computers to process large amounts of data in a short time is a strength that we lack as human beings. Kasparov later wrote in his book: "If I had to think whether this was a blessing or a curse that I became world champion when machines were really weak, and I ended my professional career when computers were unbeatable, I think it's more like a blessing. I was part of something unique". More recently in 2016, the strongest Go player, the South Korean Lee Se-dol, was beaten by the AlphaGo program, based on artificial intelligence. For years, Go was considered beyond reach even for the most sophisticated computer algorithms. The ancient board game is notoriously complex, with 10^{170} board configurations, more than all the atoms in the observable universe. Despite this, AlphaGo had apparently no problem in finding more effective moves than its human opponent.

These and other recent achievements of artificial intelligence may suggest that computers are already capable of producing innovative ideas. Is this really the case? While it is difficult to answer this question, we can take a step backward and try to understand how new ideas occur in the first place. Innovation, defined as the capability to create new ideas, creative thoughts or new imagination, is considered still to be a peculiar characteristic of human beings. Three main points emerge from this book: the importance for researchers to be free from any form of prejudice and look at the world with an open mind. Secondly, be ready to be contaminated by research in different fields and finally, mix together natural and artificial reality, abstraction and concreteness, rationality and emotion. As a consequence of this, a continuous interchange between exploration and exploitation, specialization and de-specialization emerges as a critical element for innovation.

The possibility to move randomly, jump into different and unrelated fields, use different methods and approaches, make mistakes are all part of the business. We have to keep in mind that information is always incomplete and our exploration of the world uses both rationality and irrational exploration of the unknown.

Exploration into the mechanisms producing innovation naturally leads to the concept of exaptation, introduced in evolutionary biology by Gould and Vrba in 1982. They described the possibility that already existing traits would be exploited for new purposes, throughout evolution. Observing exaptation in different areas of human activity has been shown to be extremely relevant to understand how human beings are able to produce innovation and find novel solutions for complex problems.

The present book discusses the role of exaptation in different disciplines including biomedicine, physics and materials science, economics, social sciences, computer science, psychology and architecture. We illustrate how progress in all those disciplines can be viewed through the lenses of exaptation, as a macroscopic picture of the world composed by many pieces all working together in a complex interconnected system.

The book starts with a chapter by Plevani and Sanguettoli, who describe the theoretical background underlying the original idea of expatation by Gould and Vrba and its impact on philosophy and biology. They also discuss the critique of exaptation due to the philosopher Daniel Dannett, showing that, in fact, this author implicitly accepted many conceptual implications of exptation. The following chapters present concrete examples of the relevance of exptation for "hard sciences", such as mathematics or physics. Micheletti illustrates in chapter "Nature-Inspired Optimization Methods: How Ants, Bees, Cuckoos and Other Friends May Improve the Work of Mathematicians" how it is possible to develop an algorithm that is able to enclose the main traits of the evolutionary success of a species or a society and reuse it. Zaiser and Zapperi discuss the importance of exaptation in theoretical physics and materials science, discussing how this concept is central in the field of materials discovery. Chapter "Exaptation for the Good and the Bad: Regeneration and Cancer" focuses on biomedicine considering the basic physiological process, such as regeneration, and pathological conditions such as cancer from the point of view of exaptation. All these chapters highlight form a different angle the common background of a core of elements or processes that are reused in different contexts.

In chapter "Quantifying Exaptation in Scientific Evolution", Ferreira et al. explore the notion that exaptation can be quantified from the usage of scientific ideas in domains other than the area that they were originally applied. In their original approach, the authors identify distinctive patterns of exaptation and expose specific examples of papers that display those patterns. The outcome of this new approach is the possibility to quantify exaptation phenomena in the context of scientific evolution. In chapter "Exaptation and Beyond: Multilevel Function Evolution in Biology and Technology", Andriani et al. discuss differences and similarities between the natural and the artificial world, showing that when exaptation is considered from a modular viewpoint, some of the differences that have plagued the analogy between natural and artificial evolution disappear. Along similar lines, chapter "The Role of Affordance Landscapes in Exaptive Innovations" explores different hypothesis with respect to the common idea of considering exaptation as the core ingredient of decision-making about innovation. The authors discuss the concept of affordance landscape, emphasizing the ability of living beings to prefigure landscapes to reach specific goals. This notion is, according to the authors, useful to shed light on the ability of living beings to reconceive the existing affordances to discover new uses for artefacts.

The following chapters deal with economics. In chapter "Mapping Exaptation as Source of Smart Specialization in European Regional Policy Between Tacitness and Codification", exaptation is shown to be a source of smart specialization within the European Regional Policy while in chapter "The Technology Second Chance: Leveraging Creativity by Convergence of Serendipity and Exaptation Processes", Leporini et al. start from some famous cases in technology showing how serendipity and exaptation are strictly interconnected. In particular, the authors highlight the importance of "convergence" in research and applied policy, considering two critical aspects: hybridization of knowledge and continuous contamination of extended specialization.

In chapter "Innovation-Oriented Programming: Software Development as a Medium for Exaptation and Implications for the Active Facilitation of Innovation Within Virtual Environments", David King explores the intriguing question of the role of exaptation in computer software discussing how innovations in that domain proceeds through the repurposing of data, algorithms and visualizations to problems other than the ones they were originally developed to solve. The departure from traditional programming paradigms and the implementation of development systems specifically oriented towards innovation appears to be very promising in this context. Preliminary experiments reported by King show that when explicit innovation-oriented programming systems and practices are leveraged, innovation can rapidly occur.

In chapter "Dancing with the Urban Exaptation", Longhi discusses how architecture results from a complex relationship between scientific, artistic, economic and political experiences. The author explains in this chapter this exaptive world using the metaphor of the dance to produce new multiple design alphabets from environmental, architectural, economic, social and technological contexts. Finally, in chapter "Exaptative Thinking as What Makes Us Human", the authors develop a theory of two kinds of self-organization and self-reproducing structures in living organisms and complex mind. They discuss how biology and psychological expiration events might play a critical role in these processes.

The book was conceived as an exhaustive monograph to the emerging interdisciplinary field of the exaptation. Its targeted readership is composed of graduate students in physics, biology, mathematics, economics, psychology and architecture. The book should also appeal to established researchers in humanities who wish to engage in a new science-driven interdisciplinary field. Most importantly, however, it is our hope that this book might be an inspiration for further innovation and ideas.

Milan, Italy

Caterina AM La Porta
Stefano Zapperi
Luciano Pilotti

Contents

The Evolution of Exaptation, and How Exaptation Survived Dennett's Criticism

Telmo Pievani and Filippo Sanguettoli

1 Introduction

In one of the concluding chapters of his last monumental work, the late palaeontologist Stephen J. Gould quoted Thomas H. Huxley in affirming that he was "prepared to go to the stake for exaptation", for this term, he continued, "stands in important contrast to adaptation, defining a distinction at the heart of evolutionary theory" (Gould 2002b: 1234).

Making things clearer about this distinction has been one of the main aims of Gould's overall reflection on the theory of evolution and its extension and revision, and this is why under the term 'exaptation' lies a whole set of interrelated concepts and theoretical perspectives. It should not surprise, then, that the debate concerning the concept of exaptation has historically been very harsh and can be seen, among the many within contemporary philosophy of biology, as one of the most famous and long-lasting: the reader can see its development throughout the years and the pages of various journals and books. In his reconstruction of the debate, Kim Sterelny (2001) speaks of two different views on evolution, embodied by Richard Dawkins and Gould, colliding on almost every relevant aspect of the evolutionary theory. Andrew Brown has even termed such disputes the *Darwin Wars* (Brown 2002).

The aim of this work is to offer a new perspective on this complex matter. In order to do so, we will proceed in three main steps. Firstly, we will provide a brief exposition of the theoretical background that accompanied the birth of the concept of exaptation. Then, we will take into consideration the strong critiques of the Gouldian position that philosopher Daniel Dennett developed in his *Darwin's Dangerous Idea* (Dennett 1995),[1] and the philosophical framework behind them. Taking them as a guideline, we will finally try to critically approach his position in two ways: from an

[1] Henceforth: DDI.

T. Pievani (✉) · F. Sanguettoli
Department of Biology, University of Padua, Padua, Italy
e-mail: dietelmo.pievani@unipd.it

C. AM. La Porta et al. (eds.), *Understanding Innovation Through Exaptation*,
The Frontiers Collection, https://doi.org/10.1007/978-3-030-45784-6_1

empirical point of view, we will show how the concept of exaptation can be a viable hypothesis whose implications have been seriously addressed in recent research; from a conceptual perspective, we will focus on Dennett's last work, *From Bacteria to Bach and Back* (Dennett 2017)[2] in order to show how, quite ironically, he has come to accept a few insights that were typical of the Gouldian position.

2 Exaptation: A Brief Archaeology

One of the chief problems of neo-Darwinian evolutionary theory is how to account for the apparent and often astonishing complexity of biological organisms and structures in a way that is consistent with our scientific knowledge of the world. In this regard, the process of natural selection (in its many forms) has been, and still is, one of the main instruments capable of explaining the coming into being of said complexity. In their famous *spandrels* paper, however, Gould and Richard Lewontin denounced what they believed to be the explanatory trend prevalent at their time.

They argued that biologists tended to embrace a strong version of natural selection as an optimizing agent, conceiving it either as the *sole* agent responsible for the modification of organisms or, at least, as *the* most important one, to which all the others could be reduced. It is beyond dispute that, in a certain sense, "eyes are for seeing and feet are for walking" (Gould 1997a); however, Gould thought that many were too hasty in assuming that organic traits were forged by natural selection to carry a specific function (that would have remained the same since the very beginning of the evolution of the trait), thus becoming too easily convinced of having found it. Gould argued that this had been a drawback of the success of the Modern Synthesis, which had resulted in an excessive focus on the role of natural selection as the main cause of evolution and on adaptation as the explanandum *par excellence* of evolutionary biology.

This way of thinking, that according to the authors "dominated evolutionary thought in England and the United States" (Gould and Lewontin 1979: 581) was criticized for two main reasons: firstly, it analysed the structure of an organism by 'atomizing' it into a bundle of traits defined by their function and then it proceeded to give an account of how said functions could have been favoured by natural selection from the beginning. This resulted in an underestimation of the causal power of organisms, which came to be conceived as passive entities in front of environments and their selective pressures; furthermore, in many cases this atomization at the organismal level was pushed even further by considering organisms and traits as 'vehicles' for genes, the only truly 'replicating' entities (Dawkins 1976).

Secondly, when and if the atomizing and functionalist strategy failed, the result was just to try out another 'adaptive story', always focusing on present utility and excluding other attributes of form. The authors suggested that, even if allowed in principle, other forces except natural selection where never taken seriously as explanatory

[2]Henceforth: BB.

hypotheses, even in cases of evident sub-optimality of parts. Instead of focusing on the production of 'adaptive stories', or adaptive 'just-so stories', Gould was much more interested in questioning how *limited* was the power of selection to change organisms, wondering if it was possible to find "alternatives to immediate adaptation for the explanation of form, function and behaviour" (Gould and Lewontin 1979: 590).

Even after this brief presentation, we can appreciate how behind the critique of the 'Panglossian' paradigm there was more at stake than the colour patterns in snail shells. As Gould once wrote, his critique can be traced back to three main theoretical roots:

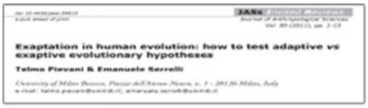
> The first arose from seven years' composition of *Ontogeny and Phylogeny* (1977), and my growing respect for the great European structuralist literature on laws of form (dating to such seminal thinkers as Goethe and Geoffroy). The second developed from a series of technical articles, written […] between 1973 and 1977, on ordered patterns in phylogeny that arise within purely random systems (but were previously attributed without question to Darwinian adaptation). Sociobiology did provide the third – as I struggled to understand what seemed so wrong about a speculative literature that reached conclusions about people so out of whack with my concepts of reality (Gould 1987a: 41)

We can thus individuate a philosophical root, coming from Gould's respect for the structuralist tradition in biology, which he read in an anti-functionalist fashion; an experimental root, that focused on structural homologies coming from purely casual systems and the internal constraints; and a political root, that is, his opposition to many socio-biological theories popular at his time, that offered a hyper-reductionist treatment of complex human behaviours. We believe that by disentangling these topics we can come to appreciate how much the difference between adaptation and exaptation—here not intended as mutually exclusive phenomena—touches the 'heart' of evolutionary theory.

2.1 A Dialectic Between Functions and Forms

Gould's interest in the structuralist tradition was motivated by his conviction that a purely functionalist approach to evolution was insufficient to explain the complex and, in a sense, dialectical relationship between function and form (Gould 2002b). This aspect of his thought can be seen clearly in the essay written in 1982 with palaeontologist Elisabeth Vrba (Gould and Vrba 1982). The authors proposed the general term *aptations* to indicate those biological traits that are somehow useful (*aptus*) for the fitness of organisms, and then identified two meanings and subsets of the concept: (1) the set of traits forged directly by natural selection for the same function they maintain in the present (*adaptations*); (2) then, the set of characters that, born for a certain reason or for no functional reason at all, where co-opted for a different or a new function.

They proposed to consider as *ad-aptations* those cases where the relation between structure and function was provable with evidence, and to use instead the term


Exaptation in human evolution: how to test adaptive vs exaptive evolutionary hypotheses
Telmo Pievani & Emanuele Serrelli

Taxonomy of evolutionary innovations

Process	*Character*	*Usage*
Natural Selection shapes the character for a current use.	Adaptation	Function
A character, previously shaped by natural selection for a particular function (an adaptation), is coopted for a new use.	Exaptation 1 (by cooptation)	Effect
A character whose origin cannot be ascribed to the direct action of Natural Selection (a non-aptation), is coopted for a current use.	Exaptation 2 (by non-aptation) or "spandrels"	Effect

Fig. 1 (A schematic representation of the differences between standard adaptations, exaptations and spandrels, with the proposal to distinguish two types of exaptation, frequently confused even in evolutionary literature)

ex-aptation to refer to a *functional shift* of preexisting structures that had a different function. While in the first case the function could be seen as the *raison d'etre* of the form, in the second the usefulness of the trait (*aptation*) did not precede but followed the organic structure or form (*ex*). Nevertheless, we should define such a taxonomy further (cfr. Fig. 1). We can distinguish two main processes of exaptation (Pievani and Serrelli 2011).

The first one comes from the need to separate the origin of a trait from its present fitness. Feathers could have been used to protect the bearer from cold temperatures (hence with a thermo-regulatory function) and only later be used to aid flight or for sexual selection, as it can be conjectured from traces of feathered and coloured dinosaurs unable to fly. The second meaning of exaptation covers instead the case of architectural *spandrels*, made famous by the now homonymous essay. The first meaning of exaptation, while important and very frequent, still assumes that the trait had *a* function, even if it changed during evolution and following the phylogeny of the species considered. The second one, instead, wants us to allow for the possibility of traits not developing for *any* function, in other words not being selected for a specific function.

Although less frequent, this second meaning of exaptation is very important, since it carries with it Gould's own study of the European tradition of the 'biology of form' (from Goethe to Haeckel) that had been neglected in the Anglo-American world due to a preference for a strict functionalism. In their article, Gould and Lewontin proposed to rethink the concept of *Bauplan*, that is, to see organisms as integrated wholes whose organic structure is not just a passive and plastic material upon which selection can act, but is a level of organization with proper constraints, past history and causal force. The term *spandrels*, taken from architecture, refers in fact to what the authors called a 'by-product' of a certain structure, that is, an element that does not come from a specific project (following the metaphor of architecture), but is bound to be present once a certain set of constructive rules has been fixed.

The authors wanted to give much more credit to those traits that did not arise for evident adaptive reasons at the beginning but as by-products of what Charles Darwin called 'laws of growth', and that we can now study in evolutionary developmental biology (evo-devo). We can recall one example given by Darwin himself: the sutures on the skull of many mammals seem perfectly 'adapted' to make the birth process easier, making it tempting to assume that they 'evolved for' this very reason. However, as Darwin noted (1859: 197) and ingeniously argued from a comparative analysis (the tree of life is the second pillar of any evolutionary explanation), skull sutures are present in reptiles and birds too, i.e. in animals that hatch from eggs. Most likely, these sutures came from a common ancestor of different taxonomic groups, due to ontogenesis (laws of growth), and were later opportunistically co-opted by mammals to make birth easier.

In this regard, the term 'function' should be reserved for the proper outcomes of adaptation, while for exaptation it is better to speak of 'effects'. It must be said that the reference to Darwin is not irrelevant, because the distinction of adaptations *strictu sensu*, exaptations by co-optation of already existing functional traits and *spandrels*, corresponds exactly to the three hypotheses that Darwin proposed in the final edition of *The Origin of Species* (1872) in order to explain how natural selection can produce very complex traits. Changes of function and tinkering with already existing material were the original Darwinian theoretical strategies for saving the idea that natural selection can make even very complex structures in a continuous and gradual way (Pievani 2013). Other scientists like François Jacob (1977) have then recovered this seminal idea.

2.2 *Contingency and Exaptation in a Hierarchical Perspective*

From these remarks it should be clear that, since the beginning, the notion of exaptation was not meant to replace the standard notion of adaptation, but to complement it by stressing the role of *functional redundancy* and *functional shifts* in evolution (cfr. Fig. 2). The relationship between adaptation and exaptation is in fact a complex one, that admits of interrelations and degrees: a certain trait can undergo an exaptation and then an adaptation 'founded' on the former, or vice versa (Gould and

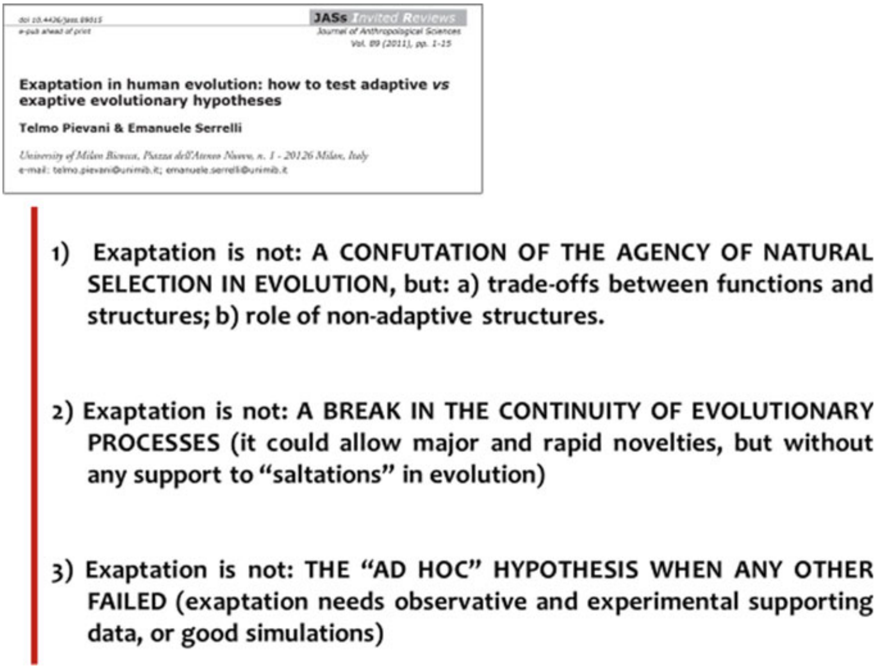


Fig. 2 (Exaptation is neither an anti-Darwinian nor a post-Darwinian concept; here depicted the relationships between exaptation, natural selection and gradualism, that is, the theoretical core of the current neo-Darwinian research programme in evolutionary biology)

Vrba 1982: 12). Once the feathers have been 'exapted' for flight (being evolved to satisfy completely different previous functions, such as thermoregulation and sexual choice), they have probably undergone an autonomous adaptive process that has made them better suited for that function. The same seems to be true for the evolution of limbs from fins, another very important evolutionary transition: as noted by biologist Michael Coates, the picture of the transition towards limbs that emerges from a detailed study of fossils and phylogenesis is increasingly complex and, while functional explanation may indeed be proposed for these changes, it does not allow for simple and unidirectional interpretations (Coates et al. 2002: 398–399). Many changes in the anatomy of tetrapods that were crucial for the fins-limbs transition have been found in animals that were still mostly aquatic, challenging the established notions that limbs evolved for terrestrial locomotion; furthermore, bony fishes as a whole share most of the same genes and developmental regulatory systems, and the same materials are deployed and used similarly in paired fin buds and limb buds. For this reason, the authors see digits as a new arrangement of fin radials, whose development co-opted more general patterns of gene regulatory activity (Coates et al. 2008: 577–583). We can say then that it is from the interplay between adaptations and functional co-optations that the amount of evolutionary possibilities always finds new strategies.

These examples allow us to appreciate the precise sense in which the process of natural selection was put into question by Gould: his approach aimed at conceiving the force of natural selection as a major factor among others, that can change the organism but is also *constrained* by structural limits and developmental rules as well. Instead of seeing organisms as 'free' to roam within an adaptive space, constrained only by the competition with others and by environmental limits, he argued that there are certain routes that natural selection cannot, or can with high improbability, act upon.

Gould suggested that organisms should be seen as biological 'polyhedra' capable of moving only by proceeding side by side, unlike billiard balls than can go in any direction according to the selective environmental accidents (Gould 1993: 422). However, the term *constraint* also has a positive meaning in this view: the organic exaptations and *spandrels* do not only limit the power of selection. Instead, precisely due to their lack of immediate function or due to their functional plasticity, they can constitute a 'reserve for potential exaptations' that can be exploited when environmental conditions change, allowing for transitions that could not have happened by simply improving already existing adaptations (Gould and Vrba 1982: 8). The fecundity of this view keeps showing itself even in recent studies: a review published this October in *Nature* (Levy 2019) analysed a series of studies showing that many important genes essential to survival did not evolve from preexisting, functional genes but from the combination of nonfunctional genetic sequences that lay in that portion of the genome that was once improperly called 'junk DNA'. A recent example of these newly termed 'de novo genes' is the antifreeze gene present in the Atlantic cod (*Gadus morhua*)—essential to its survival—that was shown, after an analysis of the fish genome, to have been built 'from scratch'. The cod, however, seems to be in good company: researchers have found many similar genes in the lineages they surveyed. The ability of organisms to acquire genes this way is certainly a sign of the role played by plasticity in evolution and its power to produce novelty against improbability.

This implication of the concept can be seen as seminal, since it allows us to appreciate one of Gould's most cherished topics: the role of *contingency* in evolution. As noted by Brandon and Misher (1987) and Alhouse (1998), the *spandrels* paper was not refuting the role of selection but arguing for a multiplicity of causal agents (both functional and structural), allowing arguments about which agents(s) should be seen as more explicative in a particular case. This is what we call *evolutionary pluralism*.

Evolution is hereby seen as the interplay between many different causal pathways that forge the contingent story of populations of individuals, full of suboptimal traits and unforeseeable tinkering or *bricolages*. If organisms are integrated entities, not separable into 'single traits', the frequency of correlations capable of producing non-adaptive traits, as Darwin already noted, can be very high: not only the white colour of bones, the redness of blood and male nipples (Gould 2002b: 1572), but also the form of the shell of many snails, among many others traits (Gould 1980). The more complex the organization of an organ is, the more likely it is to generate non-adaptive traits that can form the basis for future exaptations.

As Gould and Vrba mentioned in an article published a few years later (Gould and Vrba 1986), the concept of exaptation can receive new light if interpreted alongside a hierarchical perspective on evolution. The hierarchical theory, developed with palaeontologist Niles Eldredge in the 80s, has been developed over the course of the years even after Gould's death, proving to be a viable framework that can offer an updated perspective on many different fields of the life sciences, from both a theoretical and empirical point of view (Eldredge et al. 2016). Limiting ourselves to what concerns the present topic, we can stress that if the units of selection are not just single organisms bearing genes, but also multiple forms of 'unities' arranged in a hierarchical structure (groups, species, ecosystems, etc.), then we can allow for characters that were adaptive at the original level but can be interpreted as exaptive if considered from the point of view of other levels. These interactions between different levels have been termed *cross-level spandrels* and constitute one of the most promising applications of the concept, insofar as it admits a peculiar form of circular or 'downward' causation between evolutionary levels of change (Gould and Vrba 1986: 225).

Hierarchical theory gives proper attention to the causal power of the basic 'organismal-level', since it stresses the importance of behavioural tendencies that influence the heritability of traits by modifying key aspects of the life of organisms, like diet: a case that is particularly interesting in human evolution. Adaptation is then a phenomenon that happens at multiple causal levels (genetic, cultural and phenotypic) at the same time, generating possible cascades of exaptations at different levels (Pievani and Parravicini 2016).

2.3 Niche Construction as a Critique of the Adaptationist Programme

Another aspect of the critique of the strong adaptationist programme was put forward by Richard Lewontin in a series of essays published around the same years as the *spandrels* paper. In *The Organism as Subject and Object of Evolution* (Lewontin 1983a)[3] Lewontin argued that Darwinism had been successful in showing how organisms should be seen as 'objects' of evolution and its 'forces', like genetic mutation, genetic drift and natural selection, that are "autonomous and alienated from the organism as a whole" (Lewontin 1983a: 87). Lewontin proposed, however, that we now need to see organisms also as *subjects* as well as objects of evolution, with respect to both the production of individual phenotypes and their relations to the environment, because organisms actively participate in their own development and build the environments they encounter.

In a sense he was anticipating the concept of *niche construction* (Odling-Smee et al. 2003) that has become much more popular in recent years. By defending the

[3]For a more recent take on the matter, cfr. Godfrey-Smith (2017): *The Subject as Cause and Effect of Evolution*.

active role of organisms in mediating the selective pressures of their own environment, Lewontin wanted to criticize an excessive 'gene-centric' approach and also to question two strong principles of the adaptationist thinking. The first is the framework according to which the environment poses certain 'problems' that organisms have to 'solve' and that natural selection is the mechanism that allows them to do so, in a quite passive way. This approach implies that researchers ought to start from the 'problem' and then study the organism as a machine that is being built to solve it.

The second principle is the postulation of an environment per se, conceived *before* the presence of any organism actively living into it. Lewontin argued that the concept of *niche construction* puts radically in question both of them, insofar as it does not make sense to speak of the niche of a potential organism before the organism exists: niches are *defined* in practice by the organism's metabolism, anatomy and behaviour and for this reason it is incorrect to conceive an 'empty niche' that awaits the organism to evolve 'into' it (Lewontin 1983a: 98).

This contradiction, he argues, cannot be solved by admitting that the 'problem' preexists the solution. It is also impossible to conceive physical 'constants' of the environment as 'problems' that concern each organism: even gravitation, for example, is not applicable in practice to bacteria since they are very small in size and live in a liquid medium, while they are instead subject to the Brownian motion of molecules, that we human beings can safely ignore (Lewontin 1983a: 104).

3 Dennett's Defence of the *Panglossian Paradigm*

A few years after the publication of the aforementioned essays, the position advanced by Gould was harshly criticized by philosopher Daniel Dennett in an essay with the programmatic title *The Panglossian Paradigm Defended* (Dennett 1983). This started a heated debate that went on for many years[4]: Dennett moved his critiques to Gould in many books of his, especially in his *Darwin Dangerous Idea* (Dennett 1995), where he devoted almost two whole chapters to a refutation of Gould's positions, presenting himself as a proud adaptationist. Since his critiques can be seen as paradigmatic in many senses, we will now examine them and try to give a proper answer updated to the current scientific literature, 25 years later.

As a way to begin this analysis, it could be useful to apply a bit of 'reverse engineering' to Dennett's philosophical position, in order to better understand his own project against Gould and exaptation. Much of the prominent work done by Dennett in his field, the philosophy of mind, can be traced back to his critique of the common knowledge we have of ourselves—our 'folk psychology', as he calls it—and to a background assumption that often accompanies it, the myth of the *Cartesian*

[4]Cfr., for example, Lewontin (1983b), Eldredge (1983) (in response to the target article by Dennett), Gould (1992), Dennett (1992), Gould (1997a, b), Dennett (1997); then the reader can find an explicit rejection of Gould's position in most of Dennett's books, notably, Dennett (1987), Dennett (1995), Dennett (2017).

Theatre. This kind of reasoning, which Dennett criticizes effectively in many books (notably Dennett 1991a) can be summed up in the conception according to which the human mind is a *representational centre* that governs thought and actions due to its intentionality, the capacity to refer to things and states of the world.

This kind of theory of mind is often at the centre of the *manifest image* (Sellars 1965) of the world that we, as persons, inhabit and share with others. To be precise, Dennett has never been an 'eliminativist' towards the manifest image[5]: his position requires him to show how to retain many of the philosophical attributes of the manifest image (such as the freedom of the agent, one of Dennett's main goals) without committing himself to a Cartesian ontology of the subject. The solution to this problem has been a commitment to a particular form of *functionalism*, that sees meaning and intentionality as defined by their function and not by ontological considerations. His theory of the *intentional stance* can be seen on this regard as a way of preserving our 'mentalistic' talk without endorsing the ontological assumption according to which when we say that 'Smith *believes* something' there is a Cartesian subject that represents and endorses this belief. The same is true even with respect to animals, which can be treated as *intentional systems* (Dennett 1971).

The intentional stance is then a sort of theory of the mind that we have come to endorse and that must be explained in functionalist terms: we *assume* a certain degree of rationality in other beings as a strategy "to organize data, explain interrelations and generate questions to ask Nature" (Dennett 1983: 353). This methodological treatment of intentionality, however, was not enough to complete Dennett's project: he needed also a way to explain away ontological implications about 'minds' and to show that a functional classification of 'mental' states was enough. This led him to develop his interest in Artificial Intelligence, as a way of showing how complex tasks whose completion was normally attributed to a form of 'original intentionality' in human mind could be done by 'sharing' this higher-level intentionality of the 'man in the brain' with many unintentional 'homunculi'. In this regard even artefacts can be studied intentionally (methodologically speaking), while admitting that you can reach a level where

> the homunculi are no more than adders and subtracters; […] by the time they need only the intelligence to pick the larger of two numbers when directed to, they have been reduced to functionaries who can be replaced by a machine (Dennett 1978a: 80)

As this passage clearly shows, this approach sees the intentional stance as a way of describing the behaviour of an entity without any form of ontological mind, describable in purely functional terms. It is by recognizing this feature of his thought that we can understand Dennett's enthusiastic endorsement of Richard Dawkins' metaphor of the *selfish gene*: his refutation of the Cartesian conception was completed by recognizing that even our intentionality was phylogenetically 'derived', since we humans were *like* machines designed by nature to transmit and perpetuate our genes (Dennett 1987: 298). This ultra-Darwinian and gene-centric perspective on

---

[5]Cfr., for example, his reply to P. Churchland (Dennett 1991b), and his critique of Harris' position (Dennett 2017: 394, fn. 368).

evolution was in fact approached by Dennett as a way to show how the 'original' intentionality of mind, instead of being an 'all-or-nothing' phenomenon that stood in the way of a proper naturalization, could be traced back to the anonymous work of a myriad of non-intentional processes, in the same way that the apparent 'intelligent' design of organism could be created by "cascades of selective processes lacking any intelligence" (BB: 68).

Dennett's defence of strong adaptationism was thus philosophically motivated: from this point of view, the cognitive psychologists who, as 'intentionalists', assume that other living beings have intentional states (that is, possess a degree of *rationality*), are ideologically in the same boat as evolutionary biologists who, as 'adaptationists', assume that everything they find in nature is adaptive (that is, has a *reason* to function the way it does). In other words, there is the strictest connection between the intentional stance, the optimality stance and adaptationist thinking (Dennett 1987: 277): in this way instead of crediting the subject (man or other animal) with the rationale of their own actions we can translate the view of it *"from the individual to the evolving genotype"* (Dennett 1983: 351). In this way Dennett could employ the intentional stance without admitting the Cartesian theatre: the subject represents reasons that he was not the source of, while 'Mother Nature' could be seen as the source of them, but without being capable of representing anything.

3.1 The Critiques of the Concept of Exaptation in DDI

These considerations can shed light on how evolution was depicted in *Darwin's Dangerous Idea*[6]. There Dennett affirmed that Darwin's merit was not to have simply described the evolution of organisms through the tree of life model (descent with modifications), but to have argued that all happened *through natural selection*, the only unintentional and blind agent that can explain the coming into being of complex structures. In fact, what is 'dangerous' about the Darwinian idea of selection is that, like a universal acid, it is applicable not only to biology, but to our whole vision of the world (DDI: 77), serving the purpose of Dennett's own critique of the *Cartesian Theatre*.

Evolution by natural selection is then described through three main metaphors: first, it is for him an *algorithmic process*, that is, "a certain sort of formal process that can be counted on—logically—to yield a certain sort of result whenever it is 'run' or instantiated" (DDI: 50). Given a certain frequency of variations, a population with enough members and a lot of time, the Darwinian algorithm must produce complex structures out of simpler materials in a purely automatic way. Nature works, in this respect, *as if* it were an *engineer*, to the point where Dennett dedicated an entire chapter to defending the second metaphor, according to which *Biology means*

[6]The theorical position presented in the book received a few critiques not only from Gould (Gould 1997a, b): cfr., for example, the review by Orr and Dennett's reply: Orr (1996b, c); Dennett (1996); Orr (1996a) and also Alhouse (1998). For a defence of Dennett's position see Carroll (2004).

Engineering (chapter VIII). Given his commitment to optimality assumptions, he affirmed that the correct way to reconstruct the evolutionary history of organisms is through the 'reverse engineering' approach. By this he meant that we should first individuate the function of a certain trait and then reconstruct the environmental problem whose 'solution' was provided by that adaptive function, treating organisms as machines subject to a never-ending 'research and development' process.

Finally, evolution by natural selection, in this sense, is essentially a gradual process of functional refinement that proceeds by serial accumulations: it works as a *crane* (third metaphor), capable of lifting organisms through the 'design space', a (likely) Platonic space of ideal forms (the 'library of Mendel') that selection can reach by improving organic designs (DDI: 80). Anything that is not a *crane* working with bottom-up causation is for him a *skyhook*, a term used to indicate mystical appeals to unnatural forces. The radical opposition between *skyhooks* and *cranes* is stressed over and over throughout the book: it seems that the fear of falling back into a 'Cartesian' conception of mind lead Dennett to accept a strong dichotomy between a purely mechanical account of evolution, on one side, and a mystical faith in a prime mover on the other, without a middle way in between. In this *aut-aut* sense, one is either a 'Darwinian fundamentalist' (Gould 1997a) or a creationist, and this is the 'fundamental truth' of Darwinism (Dennett 2006: 2).

If this analysis is correct, it can safely be said that Dennett's disagreement with Gould had deeper roots than just the role of natural selection in contemporary evolutionary theory. Dennett's own research in the philosophy of mind led him to a form of strong *functionalism* that was in sharp contrast with Gould's reflection on the 'philosophy of form' and structuralism. Furthermore, Dennett's interest towards Artificial Intelligence supported the 'reverse engineering' hypothesis, that could be seen as the very target Lewontin was attacking with his defence of the concept of *niche construction*.

It is then quite natural and consequent that Dennett criticized every aspect of the Gouldian position that we have previously presented: he depicted Gould as a 'failed revolutionary', thus proclaiming the death of the Modern Synthesis without being able to offer any alternative to it, since removing adaptationism from its place is tantamount to 'refuting Darwinism' itself (DDI: 249). Put briefly, Dennett defended all those aspects of the Modern Synthesis that Gould was criticizing at the time (gene-centrism, exclusive focus on selection, adaptationism, gradualism and the reverse engineering approach) since he could not allow the undermining of the notion of nature as an optimizing agent.

For our purposes here, we can restrict his critiques to three main points related to exaptation:

(1) He maintains that it is impossible to distinguish an adaptation from an exaptation correctly, since every exaptation presupposes a previous adaptation.
(2) He allows for an evolutionary role played by constraints and spandrels, but he marginalizes it, saying that the only way to discover them is through reverse engineering. Following this perspective, we can show the correctness of non-adaptive hypotheses only after having all the possible adaptive alternatives tested. Saying

that a trait did not arise for any apparent function is absurd for Dennett, since it would be like calling for nothing less than a skyhook, a metaphysical hole in the mechanical process of evolution.

(3) Finally, he is entirely critical of Gould's defence of the concept of evolutionary *contingency*: putting contingency at the centre of evolutionary explanations is for Dennett tantamount to leaving it to mere chance. He even implies that Gould's hidden aim is to oppose the Darwinian perspective in order to give the "*mind* some elbow room, so it can *act,* and be *responsible* for its own destiny instead of being the mere effect of a mindless cascade of mechanical processes" (DDI: 300). So, the Cartesian conception of the mind remains the overarching polemical target for Dennett, even though Gould never thought in Cartesian terms.

We can take these objections to exaptation as a guideline and divide them into *experimental* and *conceptual* ones. The experimental ones will be answered through a confrontation with recent experimental evidence and empirical studies, 25 years after this philosophical debate. As regards the conceptual issue, we will look at BB and decide whether or not Dennett himself has changed his position during the years and after Gould's death.

4 Exaptation as an Operational Concept

The first critique we can examine concerns the alleged indistinguishable nature of exaptations and adaptations, and the indispensable character of optimality assumptions. One of the authors of this paper (Pievani) and Emanuele Serrelli (2011) call this the *non-operationality objection* and show how to reply to it in detail through a pluralistic approach. Even those scholars who accept the conceptual utility of the exaptation hypothesis are in need of differentiating it from adaptations. By examining some empirical studies, we suggest a few ways to differentiate the two concepts with more clarity, showing how exaptation can be an 'operational' and not only a 'theoretical' concept (Pievani and Serrelli 2011: 16–17).

(1) Instead of taking adaptation as a null hypothesis that does not need independent testing, researchers could *devise detailed mathematical and biomechanical models to test the real relationships between a function and a structure*. For example, in a very interesting study published in *Nature* (Barve and Wagner 2013) the authors analysed the ability of a metabolic reaction network to synthesize biomass from a single source of carbon and energy. They applied complex computational models to sample many metabolic networks randomly, that could sustain life on any given carbon source but contain an otherwise random set of known biochemical reactions. The authors verified that once a certain system is set to synthetize a certain source of carbon, it becomes capable of acting on other sources that were not the direct 'target' of selection. For this

reason, they have shown how "any adaptation in these metabolic systems typically entails multiple potential exaptations. Metabolic systems thus contain a latent potential for evolutionary innovations with non-adaptive origins" (Barve and Wagner 2013: 205).

(2) *Testing for effective correspondence between structure and function in living and fossil species*. Adopting the 'tree thinking' perspective, to employ both a synchronic and diachronic perspective at the same time can reinforce the adaptive or exaptive hypothesis with more accuracy. If the distribution of a trait was random regarding behaviour and lifestyle, an adaptive hypothesis would be undoubtedly weakened. On the contrary, the 'convergence approach' (Kivell and Begun, 2007) can potentially give strong support to an adaptive hypothesis.

(3) *Exploring multiple functions of a structure* and *structural alternatives for the considered function.* Exaptations refer to a functional redundancy that allows for gradual shifts between functions. For example, Shimizu and Macho (2007) state that researchers have considered scallops primarily as a crack-stopping mechanism. Now experimental studies reveal that the latter function has been overestimated: scallops prevent delamination of enamel, as their primary function, with crack-stopping as an indirect effect. On the other hand, the existence of actual structural alternatives for the same function can weaken the structure-function correspondence necessary for a strictly adaptive hypothesis.

(4) *Enlarging phylogenetic context to improve knowledge*. From this point of view, even the most famous 'adaptive story' can be questioned: as noted by Tecumseh Fitch, the adaptive basis for the form of the giraffes' neck is questioned when noticing that almost every mammal has seven neck vertebrae, even the apparently 'neckless' narwhal (Fitch 2012: 618). It would have been a 'simpler' strategy to add new vertebrae with the augmentation of the length of the neck, but that did not happen. Since that trait is not present in birds or reptiles, it is likely that it is a constraint fixed in early mammals, and that it would have been too costly for natural selection to act upon it. For this reason, it should be said that the *length* of the neck is an adaptation, while "other correlated traits such as the number of the vertebrae and the form of the larynx nerve were due to developmental constraints and were not optimized during the evolution of the long neck" (Fitch 2012: 619).

(5) *Improving knowledge concerning ontogenetic and developmental processes underlying organic structure:* adaptationist views often rely on the assumption of direct genetic control upon structures. However, this assumption became less central in recent years because of new advancements in developmental biology: the increasing attention to the role of epigenetics in acting as a mediator between genotypes and phenotypes, for example, is putting in question the assumption that selection can act directly on genes. As an illuminating example, a study that appeared a few years ago in *Nature* (Ataman et al. 2016) has shown a gene (OSTN) expressed in the bones and muscles of mice and other mammals that, over the course of evolution, was re-functionalized to act in the neurons of primates. OSTN encodes a secreted protein that is involved in

glucose metabolism in the muscles and bones of mice; then the authors over-expressed or repressed OSTN in human neuronal cultures, and discovered that the expression of the gene regulates the shape of dendrites—the branched parts of neurons that receive and integrate synaptic information from other neurons. Then the authors supposed that the same gene had been 'co-opted' in primates for a different function: this result suggests that, in primates but not in other mammals, OSTN might regulate structural changes that neurons undergo during learning. Given the fundamental importance of neural plasticity in primates and *Homo sapiens*, such an approach could be seminal for our comprehension of the evolution of genetic regulation (Burns and Boeke 2008).

These considerations ask researchers to adopt a different set of guiding questions, as philosopher of biology Elizabeth Lloyd notes. An adaptationist approach takes as a guiding question: "what is the function of this trait?" (Lloyd and Gould 2017: 54), whose consequence is that cases of exaptations can have the role of 'null hypotheses' at most. In a pluralist approach, instead, there should be more questions from the start. Lloyd proposes the following: "What evolutionary factors account for the form and distribution of this trait? How did this trait come to be present in this population? And does this trait have a function?". These guiding questions (that call for the joint approach of different evolutionary disciplines) maintain a key aspect of the concept of exaptation.

In fact, even if the effects of exaptations and spandrels can contribute to the total fitness of the organism, it should be highlighted that they are not simply the *solution of an adaptive problem*, but are maintained "mostly through other mechanisms, such as developmental constraints or […] other structural mediums as by-products or genetic correlations" (Lloyd and Gould 2017: 51). In this regard Fitch notes that disciplines such as Evo-Devo put into question the Dennettian metaphor of nature as a chess player that 'hides' moves from us (DDI: 252), since they allow us to 'read the rules' by studying developmental processes. Furthermore, other inferences can be made after a detailed study of phylogenesis and ontogenesis together (Fitch 2012). For this reason, he believes that the 'adaptation hypothesis' should not be the default assumption but "an onerous concept to be invoked only after a pluralistic set of plausible non-adaptive hypotheses (chance, constraints, spandrels, exaptation, phenotypic plasticity) have failed" (Fitch 2012: 616).

Finally, it is interesting to note that those aspects of evolutionary theory that were put forward by Gould as 'correctives' with respect to the strong 'adaptationist' core of the Modern Synthesis have become much more central recently. Many scholars have become critical towards that perspective and advanced the need for an 'Extended Evolutionary Synthesis' (EES) (Pigliucci and Müller 2010). As Müller notes (2013), many of the key concepts employed in this approach where anticipated in Gould's thought and owe to him a strong debt, since he was one of the first theorists to criticize the Modern Synthesis as the standard view. He wished for its development and reformation when it was certainly uncommon in the field: he anticipated models and concepts like niche construction, soft-inheritance (Avital and Jablonka 2000), phenotypic plasticity (Jablonka and Lamb 2005) and mostly the role of constraints in evolution.

These recent lines of research (still Neo-Darwinian, but in an extended sense) have put in question the assumption that natural selection "is a sufficient descriptor for all directionalities in phenotypic change and that most characters are independently adaptive" (Müller 2013: 10–11), calling instead for a pluralistic and less gene-centred approach to evolution. While it is indeed a debated topic still today, with distinguished scholars on both sides (for a confrontation between 'reformists' and 'conservatives' about the legacy of the Modern Synthesis, see Laland et al. 2014), we can safely say that the Gouldian 'revolutions' were not just a baseless approach (as Dennett maintained), but theorical insights that could open different research pathways. We can say that exaptation has had its empirical revenge 25 years later.

5 From Bacteria to Bach and the Conceptual Objections

As a second part of our strategy, it is now our purpose to make a confrontation between DDI and BB in order to see how Dennett's view changed regarding some of the conceptual problems we have mentioned here. To do so, we will have to read between the lines of the text. Actually, Dennett explicitly reiterates his sharp critiques of Gould (who unfortunately cannot reply) in his recent book. He affirms that the *spandrels* paper was an "unfair caricature of the use of optimality assumptions in biology" (BB: 41). He defends reverse engineering (BB: 42) and invites the reader to abandon Gould's 'ecumenical' view of the evolution of culture, adopting instead that of Richard Dawkins (BB: 210). However, we will argue that this critique remains quite superficial, by examining three conceptual features that are important to Dennett's arguments throughout the book: his use of the concept of *Umwelt*; the analysis of the phenomenon of 'de-Darwinization'; and the development of his thought concerning the metaphor of organisms as machines.

5.1 The Concept of Umwelt and Its Relationship to Natural Selection

One of the key concepts that are found in his latest book and that were completely absent in DDI is that of *Umwelt*. He also heavily applies the concept of *niche*, which in DDI appeared only marginally. Dennett describes the *Umwelt* of an organism as "the behavioural environment that consists of all the things that matter to its well-being" (BB: 86). These objects make up the 'ontology' of the organism, which is also described, along with Gibson's (1979) concept of *affordance*, as "what the environment offers the animal for good or ill". Each species has its own ontology: the sun is in the ontology of a bee, but not of a bacterium, for example. We in fact learn that the various *affordances* of an *Umwelt* constitute what Dennett calls the *semantic information* available for a certain organism, defined as a 'distinction that makes a difference': any situation or state of affairs that elicits a differential response from the organism counts as information for it and its species.

Umwelts are not static, but they change over time due to the activity of the organisms and the changing environment: the more instruments are available for a certain being, the more semantic information becomes available, and with that come new differential responses and capacities to discriminate and individuate entities. While it is true that for Dennett the *Umwelt* comprehends the problems 'faced and solved' by the organism, this topic has a different ring than in DDI. We are in fact told that the *semantic information* is receiver relative and does not have independent measure (BB: 127), that it cannot be properly described in physical terms (BB: 134), and that it arises in the relationships between organism and environment, which should be conceived as a 'virtuous circle' (BB: 120).

Furthermore, in the same environments there can be very different niches, since what counts for an organism as information can be useless for another. Dennett is brilliant at thematising how the same physical medium can count as a completely different 'signal' depending on the organic 'threshold' it passes through. He uses the concept of *soft-inheritance* and openly speaks of behavioural traits that lead genetic development and of the role of organisms in building their own environment. As we have seen, these conceptual features of the concept of *Umwelt* are very close to Lewontin's idea that we should not see the organism as receiving a set of problems from a preformed environment considered independently of its inhabitants, but that the environment exists only *with respect to* the organisms that inhabit it. The 'virtuous circle' that Dennett describes is also very close to the idea that it is not the environment per se, but the *organism-environment differential relationship* that defines the 'traits' being selected.

Could this endorsement of the concept of niche lead to a reconsideration of the role of selection? The answer seems, at least partially, yes; we can appreciate this feature if we look at Dennett's analysis of the phenomenon of 'de-Darwinization', to which he dedicates a whole chapter of the book. While in DDI he was fond of describing a single 'design space' that selection was responsible to explore, and marginalized any phenomenon that departed from the ubiquitous natural selection, now he utilizes Peter Godfrey-Smith's concept of 'Darwinian spaces' (Godfrey-Smith 2009) to present the evolutionary environment as a space with different degrees of closeness to the evolutionary 'norm' exemplified by the bacterium. He calls these departures 'de-Darwinizations'. We learn that these are present at many levels of the biosphere, not just in *Homo sapiens* but also in other animals: examples include human cells (less Darwinian that their prokaryotic 'ancestors') (BB: 142) and communities of bacteria.

When he deals with the de-Darwinization brought about by culture and socialization, we see a beautiful diagram in which humans occupy the higher part, but there also are many intermediate levels among which Dennett counts even mushroom groups and 'societies' of aspen groves (BB: 150). He also dedicates a decent amount of space to the phenomenon of 'animal traditions' (Avital and Jablonka 2000)[7].

Proceeding along these lines, Dennett asserts that instead of trying to draw bright lines that separate mere pseudo-Darwinian phenomena from phenomena that exhibit all three of the 'essential' features of natural selection, "we contrive gradients on which we can place things that are sorta-Darwinian in some regard or another" (BB: 139). It should not surprise, then, that here Dennett openly speaks of evolution as a phenomenon that can reach different 'peaks' of 'sorta-Darwinism' depending on the environment and on the starting conditions: the 'blind watchmaker' peak is seen as a case seldom reachable, while in more 'rugged' landscapes evolution admits only local peaks (BB: 139).

There is certainly a sharp contrast with DDI, where Gould was accused of advocating for *skyhooks* for having stressed more or less the same points. In fact, it is quite striking to notice that the examples of genetic drift and the role of chance that Dennett makes in these pages are almost identical to the ones presented by Gould and Lewontin in the *spandrels* paper.

5.2 Dennett's 'Conversion' on the Brain-Computer Metaphor

Finally, we arrive at what constitutes perhaps the most interesting development in Dennett's thought: his critique of a mechanical conception of the brain. He dedicates a whole chapter to illustrate this difference. He criticizes the conception that sees the brain as a rudimentary computer, and the functionalist assumption of AI (BB: 153)—that he himself used to defend, as he admits—according to which "any living organ is really just a very sophisticated bit of carbon-based machinery that can be replaced, piece by piece or all at once, by a non-living substitute that has the same input-output profile" (BB: 157).

He says that he has come to find problematic the solution that we have quoted above, proposed in *Brainstorms* (Dennett 1978b), on how to handle the 'homunculus temptation' or, as described here, the *Cartesian Theatre*. Now Dennett states that new developments in various fields of science led him to reformulate a key part of his thought to the point where he wants to "emphasise the conversion" (BB: 161). He openly rejects the terms 'committee' and 'machine' since they suggest a "profoundly unbiological sort of efficacy" (BB: 162), and prefers to describe neurons as competent agents, playing enterprising roles, capable of a form of nano-intentionality (Fitch 2008). While machines are 'parasitic' on external energy, living things provide energy for themselves and are made of parts (like cells) that are themselves alive. They can

[7]It should be noticed that the authors here are critical of the concept of 'meme' as presented by Dawkins and explicitly link their work to Lewontin (1983a); they are also critical of a 'first problem-then solution' model of natural selection advocated as prime agent, and of the gene as 'recipe' to build something (Avital and Jablonka 2000: 68–78).

defend and repair themselves, constituting a system of units, which is open to the environment in which its body situates it.

Concerning the brain, the difference between neurons and circuits is that the former are in key respects autonomous on their own. Furthermore, the brain's most important feature is its plasticity: its capacity to reassign functions to different areas and to repair itself (BB: 159). Plasticity is important because it shows that the reassignment of functions is not 'imposed' by a 'politburo' form of top-down control, but by a bottom-up coalition of living entities. For this reason, the model previously endorsed by him applied "the wrong kind of hierarchy" (BB: 165), like a bureaucracy that suppresses innovation and exploration of possibilities (we have seen how seminal the concept of 'hierarchy' has been in Gould's reflections).

We have a significantly different Dennett here, with relevant philosophical consequences. This is a radical conversion: if our reconstruction is right, it touches more than a few of Dennett's key concepts and problems. His new concept of hierarchy is very close to the Gouldian one, insofar as it shows that in many cases a flexibility between structure and function is the preferable condition. Ever-changing environments call for 'incomplete designs' that can be 'tuned to the circumstances' (BB: 164), whereas the previous mechanical model (based on optimality and specialization) could have been a bad evolutionary strategy in many cases. This necessity of local adaptations calls for a plurality of levels of learning, some of which can be in the genes and others behavioural, as we have seen. Dennett's reformulation of the organism-machine metaphor even leads him to accept the "undeniable message of evo-devo", according to which

> the production of the next generation of any organism is not a straightforward matter of following a blueprint or recipe laid down in the genes; it is a construction job that must rely on local R&D that depends on the activity of (myopic) local agents that conduct more or less random trials as they interact with their surroundings in the course of development (BB: 164–165).

Summing up our analysis so far, we have seen that Dennett allows for brain plasticity and for a flexibility in the structure-function mapping. He rejects now the conception of genes as blueprints, calling instead for complex developmental processes. He puts in question the mechanical metaphor to a certain degree, preferring to refer to hierarchies of interrelated systems. He stresses that in the same environment there can be both different niches and different selective forces, acting at the same time with different degrees of efficacy.

As we tried to show, these arguments have philosophical consequences and are very close to the ones Gould used, namely against adaptationism and its functionalist metaphor of selection as a 'universal algorithm', as the reader can see in Gould (1997a). No wonder that, while in DDI Dennett criticized the 'Burgess Shale' argument for contingency (Gould 1989), contending that it would have been possible to rewind the tape of evolution 'algorithmically' with Alife models (DDI: 212), now he denies that a 'master algorithm' could exist since what the 'algorithm' of selection can act upon is only the "adjacent possible" (BB: 365), an expression (coined by theoretical biologist Stuart Kauffman) that ironically captures very well Gould's conception of the role of contingency in evolutionary history.

As a concluding remark, it is interesting to note that in the article that started the whole debate, Dennett referred polemically to Lewontin's review of *The Mismeasure of Man* (Gould 1981), where Lewontin claims that

> It is not easy, given the analytic mode of science, to replace the clockwork mind with something less silly. Updating the metaphor by changing clocks into computers has got us nowhere. The wholesale rejection of analysis in favour of obscurantist holism has been worse. *Imprisoned by our Cartesianism*, we do not know how to think about thinking (Lewontin 1981: 16)

Dennett suggested that Lewontin's opposition to the 'clockwork model' of mind was only due to his lack of interest in computer science. Now, after more than a few years of reflection on both artificial intelligence and evolutionary theory, Dennett has ended up doing exactly the same.

6 Conclusion: Homo Sapiens as an Exaptive Species

It is not by chance that Dennett's position gets closer to Gould's when it comes to the analysis of the evolution of culture. The concept of exaptation proves, in fact, to be very useful in those fields where it is hard to individuate a specific function for the objects studied, like, for example, in the study of the complex evolution of culture and technology (Larson et al. 2013: 498). In these cases, an adaptationist approach runs the risk of missing the intrinsic complexity of the phenomenon studied, since the most peculiar trait about human culture is its capacity to modify its own nature and its aims, adapting to phenomena of its own creation.

This is especially true in the case of technology. As William B. Arthur notes in an informative book dedicated to the evolution of technology (Arthur 2009), the system of technologies that a certain 'age' makes use of constitutes a complex structure, made by interrelated parts. Each instrument or set of instruments are built from preexisting technologies that are put to new uses, in a cumulative and continuous process that has many similarities with the evolution of species. Everything starts with the discovery of a natural phenomenon that is firstly studied and put under control (from the use of fire to the electromagnetic field): this first step is often rudimentary but then a new space is open for a technological development that proceeds by 'combinatory evolution' (Arthur 2009: 12).

The author stresses that technology always has a hierarchical structure, similar to that of a tree (Arthur 2009: 33): the heart of a certain system of instruments is the one put to the 'main' use (e.g.: the control of a certain phenomenon), but it is always accompanied by auxiliary parts that have themselves a certain set of autonomous applications, and so forth. In this regard, the functional organization of interrelated parts is a property that biological structures have in common with technological ones. As in the case of biological organisms, this hierarchy makes very likely that in any given technological system there are subparts that can be dissociated and put to a separate use, or that have no use at all.

According to Arthur's reconstruction, the first technology is described by a more or less abstract principle and is then developed and perfected by combining already existing instruments, in a sort of 'hybridisation' that proceeds by adding always new principles of use. This sort of 'evolutionary bricolage' is for Arthur the basis of technological evolution, as a sort of *working architecture* being modified from inside out by playing with constraints and preexisting features, in a continuity of change arising from the creative use of what already exists. This is what the author calls *adaptive stretch* (and that we could call 'technological exaptation' (Pievani and De Biase 2016: 31). This implies that deliberate projects are bound to be just *a* part of the development of new technologies: an equally and perhaps more important part is given by the creative use of the already existing items in a different way by changing the context of use.

In this sense, the phenomenon of exaptation can be seen as almost ubiquitous in the history of technology. From the phonograph to GPS, from the Internet to the radio, it is rare that an invention maintained the use that its creators had in mind, to the point that the uses of a given technology with regard to different contexts are bound to give birth to unpredictable exaptations (Dew et al. 2004).

This 'exaptive' view of technology is particularly fruitful if applied to the concept of niche construction, since *Homo sapiens* can be seen as the constructor of techno-cultural niches, experiencing and promoting gene-culture coevolutionary processes (Laland et al. 2010; Fisher and Ridley 2019). More generally, we could speak of a *gene-technology coevolution*, seeing *Homo sapiens* as an essentially techno-symbiotic species (Pievani and Di Biase 2016: 60). This concept of niche is a good instrument to weaken the image of a 'clockwork mind', to use Lewontin's expression: the fault of many socio-biological reconstructions is that they have a mechanical model of behaviour that turns human beings into 'adaptive automata' with Palaeolithic 'behavioural modules' in the brain.

As John Dupré rightly notes, this model that takes an element out of its context and makes it the 'cause' of behaviour is still a 'Cartesian' account that simply replaces the duality of body and soul with that of brain and behaviour (Dupré 2010: 297). The fault of this model is to see human beings as mechanical systems in which information is embedded from outside. As even Dennett admits today, a more fruitful strategy is to see our behavioural capacities as being proper of an 'open' (and hence 'living') system. In this way, we can accept a circular causality where the 'machinery' of the organism is both *caused* by the environment but is also an *effect* of its own behaviour.

Our genome did not change much from the time of our ancestors, and neither did our brains: what did evolve was our technological capacity that moved evolution to the level of culture[8]. In this regard, we can conclude by saying that all the factors that we mentioned, which enlarge the neo-Darwinian 'core' based on genetic variation and

[8]Due to their plasticity and the fact that their development continues for almost two-thirds after birth, an 'alphabetized' brain that has grown up in a certain technological environment can be proved to be biologically different from a brain that did not (cfr. Dehaene et al. 2015): this very capacity of the brain can be seen as the source of numerous 'neural exaptations' or neural recycling that start from the technological niche and act upon it.

selection, seem useful to better understand the evolution of the human species: epigenetics, phenotypic plasticity, developmental constraints, functional shifts, macroevolutionary factors that happen on a large scale, the interplay between the different levels at which the evolutionary process happen, and especially the study of how organisms construct their own niches. This extended and more ecological evolutionary theory, faithful to Darwin's pluralistic spirit (Eldredge et al. 2016), is what we need in order to understand the co-evolution of technologies and human beings. For a fruitful scientific comprehension of both biological and cultural evolution, the concept of exaptation still stands out as a pillar of the most updated evolutionary approach.

7 Attributions

Both authors are responsible for the content of this paper. Particularly, Telmo Pievani is the author of Chaps. 1, 3 and 5. Filippo Sanguettoli is the author of Chaps. 2 and 4.

References

Alhouse J (1998) *The tragedy of a priori Selectionism: Dennett and gould on Adaptationism.* Biol Philos 13(3):359–391
Arthur BW (2009) *The nature of technology.* What is and how it evolves. Penguin Books, London
Ataman B (2016) *Evolution of Osteocrin as an activity-regulated factor in the primate brain.* Nature (539):242–247
Avital E, Jablonka E (2000) Animal traditions: behavioural inheritance in evolution. Cambridge University Press, Cambridge
Barve A, Wagner A (2013) A latent capacity for evolutionary innovation through Exaptation in metabolic systems. Nature 500:203–206
Brandon RN, Mishler BD (1987) Individuality, pluralism, and the phylogenetic species concept. Biol Philos 2(4):397–414
Brown A (2002) The darwin wars: the scientific battle for the soul of man. Simon and Schuster, New York
Burns KH, Boeke JD (2008) Great exaptations. J. Biol 7(5)
Coates MI, Jeffery JE, Ruta M (2002) Fins to limbs: what the fossils say. Evolut Dev 4(5):390–401
Coates MI, Jeffery JE, Ruta M (2008) ever since owen: changing perspectives on the early evolution of tetrapods. Ann Rev Ecol Evolut and Syst (39):571–592
Carroll J (2004) Modern darwinism and the pseudo-revolutions of Stephen jay Gould, in literary darwinism. Routledge, London
Darwin C (1859) On the origin of species by means of natural selection or the preservation of favored races in the struggle of life, 6a ed. 1872, London, Murray
Dawkins R (1976) The selfish gene. Oxford University Press, Oxford (1989) Rev. ed
Dehaene S et al (2015) *Illiterate to literate: behavioural and cerebral changes induced by reading acquisition*. Nat Rev Neurosci 16
Dennett DC (2006) The selfish gene as a philosophical essay. In: Grafen A, Ridley M (eds) Richard dawkins: how a scientist changed the way we think. Oxford University Press, Oxford, pp 101–115
Dennett DC (1971) Intentional systems. J Philos 68(4):87–106

Dennett DC (1978a) Brainstorms: philosophical essays on mind and psychology. Bradford Books, Montgomery, Vt
Dennett DC (1978b) Brainstorms. Philosophical Essays on Mind and Psychology. Montgomery, Vt., Bradford Books
Dennett DC (1983) Intentional systems in cognitive ethology: the panglossian paradigm defended, and taking the intentional stance seriously. Behav Brain Sci 6(3):343–390
Dennett DC (1987) The intentional stance. MIT Press, Cambridge, Mass
Dennett DC (1991a) Consciousness explained. Little—Brown and Co., Boston
Dennett DC (1991b) Real patterns. J Philos 88(1):27–51
Dennett DC (1992) Confusion over evolution: en exchange. New York Rev (1992, 14th January
Dennett DC (1995) Darwin dangerous idea. Simon and Schuster, New York
Dennett DC (1997) Darwinian fundamentalism: an exchange. New York Rev Books, 14th August, pp. 34–37
Dennett DC (2017) from bacteria to bach and back. W. W Norton, New York
Dennett DC (1996) The scope of natural selection: the author replies to "Dennett's Strange Idea". Boston Rev Mag 21
Dew N, Sarasvathy SD, Venkataraman S (2004) The economic implications of exaptations. J Evolut Econ (14):69–84
Dupré J, How to be naturalistic without being simplistic in the study of human nature. In De Caro M, McArthur A (eds), Naturalism and Normativity, New York, Columbia University Press
Eldredge N, Pievani T, Serrelli E, Temkin Y (eds) (2016) Evolutionary theory: a hierarchical perspective. The University of Chicago Press, Chicago
Eldredge N (1983) A la recherche du docteur pangloss. Behav Brain Sci 6(3):361–362
Fisher SE, Ridley M (2013) Culture, genes, and the human revolution. Science 340:929–930
Fitch TW (2008) Nano-intentionality: a defense of intrinsic intentionality. Biol Philos 23(2):157–177
Fitch TW (2012) Evolutionary developmental biology and human language evolution: constraints on adaptation. Evol Biol 39:613–637
Gibson JJ (1979) The ecological approach to visual perception. Houghton Mifflin, Boston
Godfrey-Smith P (2009) Darwinian populations and natural selection. Oxford University Press, Oxford
Godfrey-Smith P (2017) The subject as cause and effect of evolution. Interf Focus 7:20170022
Gould SJ (1977b) Ontogeny and phylogeny. Harvard University Press, Cambridge (Mass.)
Gould SJ (1980) The panda's thumb. W. W Norton, New York
Gould SJ (1981) The mismeasure of man. W. W. Norton, New York
Gould SJ (1987) An urchin in the storm. Essays about books and ideas. W. W Norton, New York
Gould SJ (1989) Wonderful life. The Burgess shale and the nature of history. W. W. Norton, New York
Gould SJ (1992) Confusion over evolution. New York Rev, 1992, 19th November
Gould SJ (1993) Eight little piggies. W. W. Norton, New York
Gould SJ (2002b) The structure of evolutionary theory. Harvard University Press, Cambridge (Mass.)
Gould SJ, Lewontin RC (1979) The spandrels of san marco and the panglossian paradigm: a critique of the adaptationist programme. In Proceedings of the royal society of London, Series B, Biological Sciences, Vol. 205, No. 1161, The Evolution of Adaptation by Natural Selection, pp 581–598
Gould SJ, Vrba ES (1986) The hierarchical expansion of sorting and selection: sorting and selection cannot be equated. Paleobiology 12(2):217–228
Gould SJ (1997a) Darwinian fundamentalism. New York Rev Books, 1997, 12th June
GOULD, S.J., 1997b, *Evolution. The Pleasure of Pluralism,* New York Review of Books, 1997, 26th June
Gould SJ, Vrba ES (1982) Exaptation. A missing term in the science of form. Paleobiology 8(1):4–15
Jacob F (1977) Evolution and tinkering. Science 196(4295):1161–1166

Jablonka E, Lamb MJ (2005) evolution in four dimensions. genetic, epigenetic, behavioral, and symbolic variation in the history of life. The MIT Press, Cambridge (Ma.)
Kivell TL, Begun DR (2007) Frequency and timing of scaphoid-centrale fusion in hominoids. J Human Evol 52:321–340
Laland K et al (2014) Does evolutionary theory need a rethink? Nature 514:161–164
Laland KN et al (2010) How culture shaped the human genome: bringing genetics and the human sciences together. Nat Rev Genet 11:137–148
Larson A, Stephens PA, Tehrani JJ Layton RH (2013) Exapting exaptation. Trends Ecol Evol 28(9):497–498
Levy A (2019) How evolution builds genes from scratch. Nature 574:314–316
Lewontin RC (1981) The inferiority complex. New York Rev of Books, 22nd October
Lewontin RC (1983) The organism as subject and object of evolution. Scientia 118:63–82
Lewontin RC (1983b) Elementary errors about evolution. Behav Brain Sci 6(3):367–368
Lloyd EA, Gould SJ (2017) exaptation revisited: changes imposed by evolutionary psychologists and behavioral biologists. Biol Theor 50:50–65
Müller GB, Beyond spandrels: stephen j. gould, evodevo, and the extended synthesis. In Danieli GA et al (eds), Stephen J. Gould: The Scientific Legacy, Springer, Italia
Odling-Smee J, Laland KN, Feldman MW (2003) Niche construction. the neglected process in evolution. Princeton University Press, Princeton
Orr HA (1996°) Allen Orr replies. Boston Rev Mag 21
Orr HA (1996b) Dennett's dangerous Idea. Evolution 50:467–472
Orr HA (1996c) Dennett's strange idea. Boston Rev Mag 21
Pievani T (2013) *Anatomia di una rivoluzione. La logica della scoperta scientifica di Darwin*, Milano-Udine, Mimesis Edizioni
Pievani T, De Biase L (2016) Come saremo. Per una Ecologia della Tecnologia, Torino, Codice Edizioni
Pievani T, Parravicini A (2016) Multilevel selection in a broader hierarchical perspective. In Eldredge N, Pievani T, Serrelli E, Temkin I (eds) 2016, evolutionary theory: a hierarchical perspective, Chapter: 8, The University of Chicago Press, pp 174–201
Pievani T, Serrelli E (2011) exaptation in human evolution: how to test adaptive vs exaptive evolutionary hypotheses. J Anthropol Sci 89:9–23
Pigliucci M, Müller GB (2010) Evolution—the extended synthesis. The MIT Press, Cambridge (MA)
Sellars WS (1963) Philosophy and the scientific image of man. In: Sellars W (ed) Empiricism and the philosophy of mind. Routledge & Kegan Paul Ltd, London, pp 1–40
Shimizu D, Macho GA (2007) Functional significance of the microstructural detail of the primate dentino-enamel junction: a possible example of exaptation. J Human Evol 52:103–111
Sterelny K (2001) Dawkins vs gould: survival of the fittest. Icon Books, Cambridge

Nature-Inspired Optimization Methods: How Ants, Bees, Cuckoos, and Other Friends May Improve the Work of Mathematicians

Alessandra Micheletti

1 Introduction

Nature-inspired optimization algorithms have become increasingly popular in recent years, to solve, at least in an approximate way, many mathematical problems. Apart from some well-known optimization techniques which are based on the imitation of physical phenomena (e.g., Simulated Annealing), most of these recent (heuristic) algorithms are often based on swarm intelligence, that is, the ability of swarms of animals of self-organization themselves, based on simple individual behavioral rules. Other paradigms are instead based on the emulation of the individual behavior of specific animals, which have brought to the evolutionary success of the corresponding species.

The development of such nature-inspired optimization methods, also called *Computational Intelligence*, is caused by an increasing awareness among scientists that interactions between mathematicians and biologists or ecologists may bring to scientific progress in both fields. In fact, quantitative biology and the introduction of mathematical models to explain biological phenomena may, on one side, provide more a deep insight into such phenomena, but also the observation of nature and of its mechanisms of self-optimization is inspiring mathematicians and computer scientists to develop effective ways to solve difficult or computationally expensive mathematical problems.

Optimization problems of increasing complexity arise more and more frequently nowadays, due to the deluge of data that is produced by the modern "digital society". Challenging mathematical problems may arise from different applications (see e.g., Micheletti et al. (2016) for a case study in material science, Rancoita et al. (2011) for an application to biomedicine, Micheletti et al. (2010) for an application to rescue services, Micheletti et al. (2020) for an application to agro-economics) or even

A. Micheletti (✉)
Department of Environmental Science and Policy, Universitá degli Studi di Milano, via Saldini 50, 20133 Milan, Italy
e-mail: alessandra.micheletti@unimi.it

C. AM. La Porta et al. (eds.), *Understanding Innovation Through Exaptation*,
The Frontiers Collection, https://doi.org/10.1007/978-3-030-45784-6_2

from different scientific theoretical disciplines, for example, remembering that the maximum likelihood principle, used in Statistics to estimate unknown parameters, is based on the maximization—that is optimization—of the likelihood function.

In this complex context, classical optimization techniques cannot be applied, due to the quantity of data to be processed in a limited computational time. Thus either techniques which split the problem into a family of smaller and simpler subproblems are used (*distributed optimization*), or we give up to the possibility to find the global optimal solution and we apply heuristic algorithms which may provide a suboptimal solution, which, under general conditions, is a good approximation of "the best one".

In principle, Computational Intelligence (CI) consists of any science-supported approaches and technologies for analyzing, creating, and developing intelligent systems (Xing and Gao (2016)). Unlike Artificial Intelligence, that is based on the knowledge derived from human expertise, CI mostly relies on the collection of nature-inspired computational paradigms (Bozorg-Haddad (2018), Du and Swamy (2016)).

One of the pioneering algorithms that was developed following a biological-inspired paradigm is the so-called *Ant Colony Optimization (ACO)*, that was introduced by Marco Dorigo and his group (Colorni et al. (1992), Dorigo (1992), Dorigo and Stützle (2004)) in 1992 and that gave origin to a wide research sector that nowadays involves a large scientific community. The original ACO algorithm was designed to solve the traveling salesman problem, a typical optimization problem in which the goal is to find the shortest round-trip to link a series of cities, or nodes on a graph.

After ACO, many other algorithms have been developed which are borrowing some traits of the behavior of animals, which have brought to the evolution and survival of their species.

Every optimization method is based on the definition either of a cost function, that should be minimized, or of a fitness or utility function, that should be maximized. Many of the nature-inspired algorithms are actually either *swarm intelligence algorithms* or *evolutionary algorithms*. In both cases at each iteration, there is a "population" or "swarm" of individuals which explores the space of the parameters on which the fitness function depends. In swarm intelligence algorithms, the number of individuals forming the population is usually fixed across iterations, and the individuals tend to move in the direction of the best-fitted one, keeping some individual independence to explore the entire region of interest. In the evolutionary algorithms, the size of the population can vary across iterations, since each individual, or a couple of individuals, can reproduce itself, creating a new generation, and individuals may die. The individuals who have a larger fitness are the most likely to survive and to reproduce in the next generation. This mechanism clearly emulates natural selection. At the end of both types of algorithms, the individual with the highest fitness, or with the minimum cost function, provides the solution to the optimization problem.

In the following sections, we will shortly outline the main characteristics of some well-known nature-inspired algorithms, avoiding to enter too deeply into the mathematical details, and focusing in particular on the biological traits that have been emulated by mathematicians to set up new effective optimization methods.

2 Swarm Intelligence Algorithms

Swarm intelligence algorithms are agent-based models, where a swarm of agents move to explore the space of the solutions to the problem, keeping an individual freedom of movement, but having a tendency to "follow the best" agent. Playing with the characteristic parameters of the algorithms, it is then possible to drive the "swarm" in the direction of the optimal solution. The size of the swarm (i.e., the number of agents) is here fixed, and is clearly directly related to the computational costs of the algorithm.

In the following, we describe some swarm intelligence methods which have been studied across the past 30 years. Anyway other methods of this kind are available, based on the imitation of the behavior of other animals. See, for example, Bozorg-Haddad (2018) for examples and further details.

2.1 The Smell of Ants

As already mentioned, one of the first optimization paradigms inspired by animal behavior is the *Ant Colony Optimization (ACO)*, introduced by Marco Dorigo in 1992 (Colorni et al. (1992)). We will here describe its original formulation, that was directly inspired by the the behavior of ants colonies. Anyway nowadays ACOs form a well-known family of optimization algorithms, with many differences from the original formulation and which can solve a wide range of optimization problems.

Many species of ants have a very effective strategy to search for their food, minimizing the efforts for transportation to their nest. Ants start moving from their nest randomly in the surrounding territory. When an ant finds some food, it comes back to the nest bringing the food with it. During their walk, ants release a trace of pheromone, that can be sniffed by other ants, which are attracted by its smell. Anyway pheromone evaporates, thus after some time its smell is reduced. In this way, ants that walk further from the nest to capture the food will have a smaller chance to attract other ants along their walk, since their trace of pheromone will be exposed to evaporation for a longer time than the trace left by ants which are crossing smaller distances. In this way, the shortest path from the nest to the food is automatically selected by the ants, after some time.

This behavior was imitated by mathematicians to solve the well-known problem of the "Traveling Salesman". It consists in finding the shortest round path on a graph to visit a given set of nodes and is a typical problem which arises, for example, in applications to logistic, when the costs to move tracks along a set of routes to accomplish some deliveries must be minimized. The traveling salesman problem is a computationally hard problem to be solved (technically, it is called an NP-hard problem), since the number of possible paths to be explored, to look for the optimum, explodes when the number of nodes increases. It can be equivalently formulated also as "looking for the shortest path joining two points", with some constraints on the nodes to be visited. The idea of Dorigo and his group was then to ideally identify the two points to be joined as the locations of the nest and of the closest food of an ant colony. Then the movement of the ants is simulated on the graph as a random walk starting from the nest, with an higher probability to cross the edges which have associated an higher amount of pheromone. The walk is thus coupled with the evolution of pheromone, which is left on the edges of the graph by the walking ants, and which evaporates with an exponential decay, according to a suitable differential equation. The two driving parameters, speed of pheromone evaporation, and the probability that an ant will follow the higher trace of pheromone, must be suitably tuned to solve the optimization problem and find the minimum path.

2.2 Bees and Flowers

The *flower pollination algorithm (FPA)* was proposed by Yang (2012). This metaheuristic algorithm is inspired by the pollination phenomenon of flowering plants in nature. Almost 90% of flowering plants exploit biotic pollination, in which the pollens are transferred by pollinators such as insects or other animals. Each pollinator prefers to sit on a specific type of flowers, thus there is usually a specific pollination coupling between plants and animal species.

For biotic pollination, the pollinators such as flies, birds, and bats can fly long distances. Thus, they can be considered as “global pollinators”. Their movements can be described as a *Levy flight*, which is a type of flight where movement happens mainly in a limited region, with some major jumps, from time to time. Instead, insects who are not spanning big distances from their nest, like bees, can be considered as “local pollinators”, and their movements are more regular and limited to a well-defined region.

In FPA, a flower and its location form a solution of the optimization problem. Thus, the optimization algorithm starts by defining a population of pollinators, whose locations are the flowers that are visited (i.e., the candidate solutions to the optimization problem). The two phenomena of global and local pollination are randomly alternated among subsequent iterations, tossing a coin at each iteration. The global pollinators use the Levy flight to move between flowers (i.e., they explore wider regions of the parameters space), while the local pollinators move according to a random walk on the flowers in their surrounding. At each iteration, the fitness of each flower, that has been visited by the pollinators, is computed and the best solution is recorded, and, if it is better than those found in the previous steps, it is updated. After a fixed number of iterations, the solution of the optimization problem is the location of the visited flower with the best fitness.

2.3 Bats and Their Sonars

Bat-inspired algorithm is a metaheuristic optimization algorithm developed by Yang (2010). This algorithm is based on the behavior of microbats that use echolocation to detect obstacles. There are over 900 species of bats in nature. Their size ranges from the tiny bumblebee bat (of about 1.5–2 g) to the giant bats with a wingspan of about 2 m and weight up to about 1 kg. Microbats typically have a wingspan ranging from 4.5 to about 20 cm. Most bats use some form of echolocation; among all species, microbats use echolocation extensively while megabats do not (Richardson (2008)). These bats emit a very loud sound pulse and listen for the echo that bounces back from the surrounding objects (see Fig. 1). Their pulses vary in properties and can be correlated with their hunting strategies, depending on the species. Most bats use short, frequency-modulated signals to sweep through about an octave, while others more often use constant-frequency signals for echolocation. They are also able to adapt the frequency of the signals to the distance of the detected object.

Ultimately, from the echoes, the bats can determine the size of objects, their distance, and, when objects move, how fast they are traveling. The bat algorithm is inspired by the main traits of this echolocation strategy, and its main ingredients are the following.

- The algorithm starts by locating a swarm of bats in the space of parameters of the cost or fitness function.
- All bats use echolocation to sense distance, and the location of a bat x_i corresponds to a solution vector of the optimization problem under consideration.
- Bats fly randomly with velocity v_i at position x_i with a varying ultrasound frequency (from a minimum f_{min} to a maximum frequency f_{max}) and loudness A to search for prey. They can automatically adjust the frequencies of their emitted pulses and the rate of pulse emission r depends on the proximity of the target.
- Loudness varies from a large positive value A_0 to a minimum constant value A_{min}, while pulse emission rate r varies from a lower constant value to a higher value.

A bat's motion is governed by two modes of flight. The first mode is the *global search step* or *guided flight mode* in which all bats are directed toward the bat with the best location (that is, the solution with the best fitness or minimum cost value). The velocity of movement of each bat is modulated by the frequency of the signal that the bat is producing. By directing the bats to the best one, it enables them to exploit more the possessed information and seek for a better solution, while moving to a region "richer of preys".

The second mode of flight is the *local search step*: a new location for each bat is randomly generated locally, that is in a small neighborhood of its location, by using a function depending on the average loudness $\bar{A}$ of all bats in the swarm.

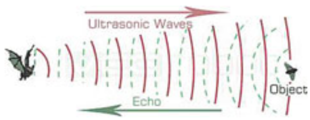


Fig. 1 Echo mechanism by which a bat detects the presence of prays or obstacles

The control of the auto-switch between the first and the second mode of flight is random as well, and is obtained by the tuning of two parameters: the loudness A_i and the pulse rate r_i of each bat. These parameters are updated during the iteration process: the loudness decreases while the pulse rate increases as the bat gets closer to its prey, that is, as the fitness of its location increases.

The final solution to the optimization problem, after a given number of iterations, is the location of the best bat.

2.4 Grey Wolf Life

Grey Wolf Optimization (GWO) is a quite recent metaheuristic optimization algorithm, which was introduced in 2014 by Mirjalili et al. (2014). GWO is inspired by social hierarchy and the intelligent hunting method of grey wolves. Usually, grey wolves are at the top of the food chain in their environment. Grey wolves usually live in packs composed of 5 to 12 individuals, where there is a strict social hierarchy (see Fig. 2).

The leaders of a pack (alpha) are male and female wolves that are mainly responsible for making decisions for their pack, such as sleep place, hunting, and wake-up time. Other individuals of the pack must obey the decision made by the alpha couple. The level next to alpha in the social hierarchy of grey wolves is beta and the role of betas is to help alphas in making decisions. Betas can be either male or female wolves and they are the best candidate to substitute an alpha when one of them becomes old or dies. Each beta must respect the alphas, but he/she can command other lower classes. Beta is the consultant of alpha and responsible for disciplining the pack. The beta reinforces the orders of alphas and gives alphas the feedback.

The next level in the hierarchy is delta. The wolves at the level of delta obey the alpha and beta wolves and dominate the last lower class, the omega wolves. The deltas

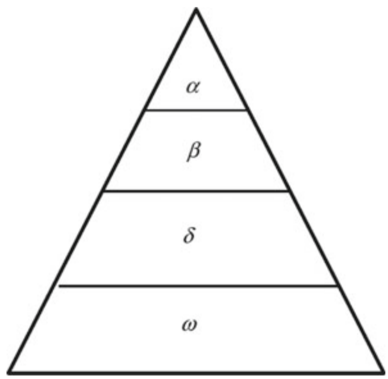


Fig. 2 Structure of the social hierarchy of grey wolves

act as scouts, sentinels, hunters, and caretakers in the pack. Scouts are responsible for looking after boundaries and territory and also they should alarm the pack in facing danger. Sentinels are in charge of the security establishment. Hunters help alpha and beta in hunting and preparing food for the pack, while caretakers should look after the weak, ill, and wounded wolves. Elder deltas are the experienced wolves that are candidates to become beta and alpha.

The weakest level in a pack of grey wolves is omega that plays the role of scapegoat. The wolves at the level of omega have to obey other individuals' orders and they are the last wolves that are allowed to eat food. Omegas seem to be the least important individuals in the pack, but without omegas, internal fight and other problems in the pack equilibrium can be observed. Sometimes, omegas play the role of a babysitter in the pack.

In addition to the social hierarchy, group hunting is one of the interesting social behaviors of grey wolves too. Grey wolves hunting includes the following three main parts (Muro et al. (2011)):

(1) Tracking, chasing, and approaching the prey.
(2) Pursuing, encircling, and harassing the prey until it stops moving.
(3) Attacking the prey.

These two main traits of the behavior of grey wolves packs (social hierarchy and hunting technique) are emulated in the GWO algorithm.

The GWO algorithm starts by positioning the wolves of the pack in the parameter space, without any initial hierarchical distinction. In order to model the hierarchy, at each step the wolf with the best position (highest fitness or lowest cost) is labeled as α, the second-best wolf is labeled as β, the third-best wolf is labeled as δ and all other wolves are labeled as ω. It is supposed that the α, β, and δ wolves have better knowledge about the potential location of prey (i.e., the optimal solution). Therefore, in the next iteration, the other search agents (including the omegas) are obliged to update their positions according to the position of the best search agents. Thus the α wolf will move randomly in a small disk centered in its previous location, the β and the δ wolves will move in disks of increasing radii, and the ω wolves will move in the direction of the weighted mean location of the first three wolves. Then the hierarchy is evaluated again and the iterations proceed.

The optimal solution coincides with the position of the α wolf in the last iteration.

3 Evolutionary Algorithms

Evolutionary algorithms differ from swarm intelligence methods in the natural paradigm that is imitated. They rely on the simulation of different generations of individuals, where the best-fitted individuals will give birth to identical copies of themselves in the next generation, while the others will evolve into a different form, or even die. Thus, differently from the swarm intelligence algorithms, in the evolutionary algorithms the size of the population of agents that explore the parameters space may change across subsequent iterations and can then have the advantage to reduce the computational costs. The most famous class of evolutionary algorithms are the *genetic algorithms*, which imitate the phenomenon of genes duplication, and which are nowadays a well-known and effective method applied to problems of artificial intelligence and machine learning. Other evolutionary methods, like the Cuckoo method, have more recently been developed, which imitate animal behavior, similarly to the swarm intelligence methods.

3.1 Genetic Algorithms

Genetic algorithms (GA) are the firstly developed and the most famous family of evolutionary algorithms, which emulate the biological phenomena of genetic evolution and natural selection, in order to solve optimization problems (Spall (2003), Holland (1992)). DNA and chromosome duplication are at the basis of the life cycle of cells of living beings. When a cell gives origin to another cell, the DNA chain inside the cell duplicates, so that at the end of the duplication process we have two identical copies of the original cell. Sometimes anyway some random change may take place: it may happen a *mutation* in a chromosome, which means that one of the (couples of) basis forming the DNA sequence is substituted by a different one; or it may take place the phenomenon of the *cross over*, that is, that two neighboring chromosomes exchange among each other a small part of their constituting DNA chains. These two phenomena imply that a new generation of chromosomes, with a given probability, will not be exactly equal to the parent one. Typically if the mutations or the crossover have produced a cell with improved characteristics, with respect to the parent cell, it will survive and reproduce more frequently than cells that have undergone to less advantageous changes.

The central idea in the algorithmic application of a GA is to move a set (population) of chromosomes from an initial collection of values to a point where the fitness function is optimized. Chromosomes here represent a candidate solution to the optimization problem. Usually, solutions (i.e., numbers, or vector of numbers) are represented in binary form, so that each chromosome is composed of suitable sequences of zeros and ones. Each digit is called *gene*. This kind of representation is very convenient to emulate a mutation, which consists in transforming a 0 into a 1 or vice versa. Also, the crossover is imitated by exchanging sequences of digits of the same length between two chromosomes (see Fig. 3). GA then imitates the phenomena of *selection* and *elitism* to produce the next generation of chromosomes: starting

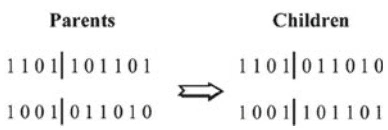


Fig. 3 How a GA imitates the crossover phenomenon

from an initial population of N chromosomes, in the next generation only a subset $N_e < N$ of them will produce offsprings identical to themselves, and these N_e elitist chromosomes will be chosen among those which show the highest fitness. The other chromosomes will undergo mutation and crossover to produce their offsprings. This method ensures to explore sufficiently the space of the solutions, but at the same time makes the chromosomes converge to the solution with the highest fitness, moving across different generations.

3.2 The Terrible Cuckoo

Rajabioun (2011) proposed a new evolutionary algorithm called *cuckoo optimization algorithm (COA)*, which was inspired by the life of cuckoos. Cuckoos belong to the group of birds species that detached themselves from the challenge of nest-making and use a cunning way to raise their families. These birds are called “Brood Parasites” and they never build a nest. They lay their eggs in other species' nests and wait for them to take care of their children. A mother cuckoo destroys the host's eggs and lays her own eggs among others in the nest, then flies away from the location fastly. This process takes hardly more than 10 s. Cuckoos mimic the color and the patterns of existing eggs carefully so that new eggs in the nest look like the previous eggs. Each female cuckoo is specialized in specific species of birds. Some of the birds recognize cuckoos eggs and sometimes they even throw the eggs out of the nest. Some of them completely leave the nest and build a new one. Actually, cuckoos continuously improve their mimicry of the eggs in the target nests and host birds learn new ways to recognize the stranger eggs as well. This struggle for survival among different birds and cuckoos is a constant and continuous process. Furthermore, cuckoo eggs hatch earlier than their host's eggs. In most cases, a cuckoo chick throws the host's eggs or the host's chicks out of the nest and then makes the host provide a food suitable to its growth and begs for food again and again.

Similar to other evolutionary methods, Cuckoo Optimization Algorithm (COA) starts with an initial population. The cuckoo population, in different generations, is composed of two types of individuals: mature cuckoos and eggs.

Each cuckoo has some eggs that will be laid in other species' nests, that is, in different locations of the parameter space. Some of these eggs that are more similar to the host's eggs (i.e., have a larger fitness) are more likely to be raised and turned into adult cuckoos. Other eggs, with a smaller fitness, are detected by the host and are destroyed. The rate of the raised eggs shows the suitability of the area, that is, the possible presence of the maximum of the fitness function in the surrounding. Then the survived cuckoos explore their neighborhood and possibly immigrate to a better environment and start reproducing and laying eggs. Cuckoos' survival effort hopefully converges to a state where there is only one cuckoo society, all with the same fitness values. Their location coincides with the detected maximum point of the fitness function.

References

Bozorg-Haddad O (2018) Advanced optimization by nature-inspired algorithms, 1st edn. Springer Publishing Company, Incorporated

Colorni A, Dorigo M, Maniezzo V (1992) Distributed optimization by ant colonies. MIT Press, pp 134–142

Dorigo M (1992) Optimization, learning and natural algorithms. PhD thesis, Politecnico di Milano

Dorigo M, Stützle T (2004) Ant colony optimization. MIT Press

Du KL, Swamy MNS (2016) Search and optimization by metaheuristics: techniques and algorithms inspired by nature. Birkhäuser Basel, 1st edn

Holland JH (1992) Adaptation in natural and artificial systems. University of Michigan Press, Ann Arbor, MI, 1975. second edn

Micheletti A, Aletti G, Ferrandi G, Bertoni D, Cavicchioli D, Pretolani R (2020) A weighted χ^2 test to detect the presence of a major change point in nonstationary markov chains. Stat Methods Appl

Micheletti A, Morale D, Rapati D, Nolli P (2010) A stochastic model for simulation and forecasting of emergencies in the area of Milano

Micheletti A, Nakagawa J, Alessi AA, Morale D, Villa E (2016) A germ-grain model applied to the morphological study of dual phase steel. J f Math Ind 6(1):12

Mirjalili S, Mirjalili SM, Lewis A (2014) Grey wolf optimizer. Adv Eng Softw 69:46–61

Muro C, Escobedo R, Spector L, Coppinger R (2011) Wolf-pack (canis lupus) hunting strategies emerge from simple rules in computational simulations. Behav Process 88(3):192–197

Rajabioun R (2011) Cuckoo optimization algorithm. Appl. Soft Comput 11(8):5508–5518

Rancoita PMV, Giusti A, Micheletti A (2011) Intensity estimation of stationary fibre processes from digital images with a learned detector. Image Anal Stereol 30(3):167–178

Richardson P (2008) The secrete life of bats. Natural History Museum London

Spall JC (2003) Introduction to Stochastic search and optimization, 1st edn. John Wiley & Sons Inc, USA

Xing B, Gao WJ (2016) Innovative computational intelligence: a rough guide to 134 clever algorithms, 1st edn. Springer Publishing Company, Incorporated

Yang X (2010) A new metaheuristic bat-inspired algorithm. Springer, Berlin Heidelberg, Berlin, Heidelberg, pp 65–74

Yang XS (2012) Flower pollination algorithm for global optimization, vol 7445. Lecture Notes in Computer Science. Springer, Berlin, Heidelberg

Exaptation in Physics and Materials Science

Michael Zaiser and Stefano Zapperi

1 Introduction

The term *exaptation* was introduced in evolutionary biology by Gould and Vrba as an extension to the well-established concept of adaptation (Gould and Vrba 1982). According to the classical view of Darwinian evolution, species *adapt* to the environmental conditions by selecting randomly acquired advantageous traits. Species, therefore, increase their global fitness in a process in which new traits are constantly generated by random mutations while only advantageous ones are fixated in the population. Gould and Vrba proposed to distinguish between traits that arise *de novo* and those that were already present but which may acquire a new advantageous function, increasing the overall fitness of the species (Gould and Vrba 1982). This last process of repurposing existing traits for new functions was defined as exaptation.

Examples of exaptation in biology are abundant and are discussed in other chapters of the present book. Here, we would like to discuss how the biological concept of exaptation can be *exapted* (Larson et al. 2013) to analyze discovery processes in physics and materials science. In the context of materials discovery, the general idea is that new materials are often not discovered out of nowhere but by recognizing and exploiting new possibilities offered by existing materials. A process of this kind has been described by various authors as a driving mechanism for technological innovation in general (Andriani and Cattani 2016) (see also other chapters in the present book). Here, we argue that scientific progress in theoretical physics and materials science often follows similar patterns.

M. Zaiser
Department of Materials Science, Institute of Materials Simulation,
Friedrich-Alexander-Universität Erlangen-Nürnberg, Dr.-Mack-Str. 77, 90762 Fürth, Germany
e-mail: michael.zaiser@fau.de

S. Zapperi (✉)
Department of Physics, Center for Complexity and Biosystems, University of Milan, via Celoria 16, 20133 Milan, Italy
e-mail: stefano.zapperi@unimi.it

C. AM. La Porta et al. (eds.), *Understanding Innovation Through Exaptation*,
The Frontiers Collection, https://doi.org/10.1007/978-3-030-45784-6_3

2 Exaptation in Theoretical Physics

Historical and epistemological studies on the advancement of science often concentrate on revolutionary theories creating a paradigm shift, such as quantum mechanics replacing classical mechanics or general relativity overcoming Newtonian gravitation (Kuhn 1962). One could thus rephrase the history of theoretical physics in evolutionary terms as an ensemble of new theories and ideas that are proposed and tested with experimental facts. Theories that agree with the experiments are retained, while other unsuccessful theories are rapidly forgotten. But are all fundamental discoveries in theoretical physics entirely new?

Several examples support a more nuanced interpretation of the progress of theoretical physics. Take for instance the celebrated mechanism proposed by Peter Higgs in 1964 to explain why gauge bosons have a nonvanishing mass (Higgs 1964). This is certainly a fundamental and influential theory that almost dictated the agenda of experimental particle physics for decades until the Higgs particle was finally revealed at CERN just a few years ago. Was the Higgs theory a new theory? As nicely discussed by Witten 2016, Philipp Anderson, two years before Higgs' paper, proposed the same mechanism in the nonrelativistic form to describe superconducting materials. Hence, the Higgs mechanism could be viewed as an exaptation of the Anderson mechanism, which was transposed from nonrelativistic superconductors to relativistic subatomic particles. The Higgs theory is certainly an important discovery but it did not arise out of nowhere. It exploited an already existing mathematical theory which, however, related to a different phenomenon.

The Higgs story is just one of the many examples in theoretical physics where important progress occurs by exploiting already existing theories and giving them a new meaning and function. Another example of exaptation—this time from particle physics to condensed matter physics—is provided by the renormalization group theory of phase transitions which was developed by Kenneth Wilson in the 70s (Wilson 1971). The theory had a tremendous impact on statistical mechanics and condensed matter physics in the following decades and explained how materials suddenly change symmetry when external control parameters—such as temperature or pressure—are tuned to a critical point. For example, it explains how liquids evaporate at the liquid-gas critical point or how paramagnetic materials become ferromagnets at the Curie temperature.

The renormalization group is based on the observation that at the critical point the system is scale invariant and thus would look the same when viewed at different magnification scales. To take a concrete example, an observer looking at the domain structure of a ferromagnetic material sees different structures depending on the magnification of the microscope used. But when the temperature is equal to the Curie temperature, the pictures are statistically equivalent regardless of magnification (see Fig. 1, top). The renormalization group exploits this scale invariance to compute how important physical observables change when external conditions are tuned away from the critical point.

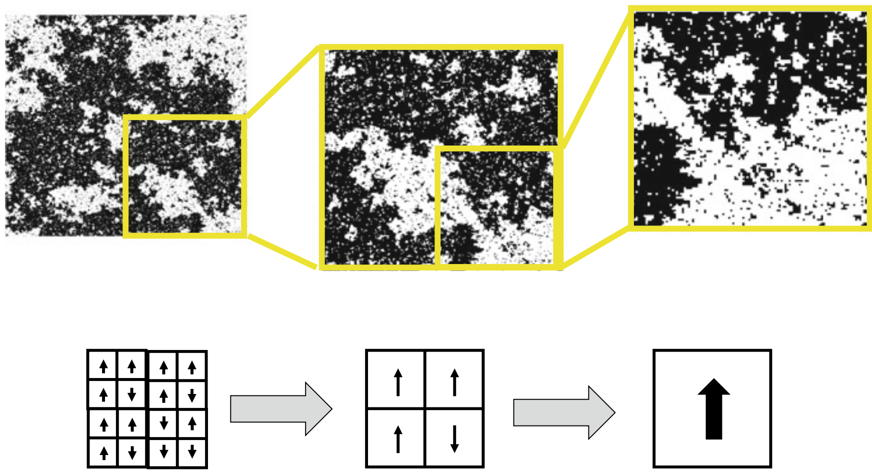


Fig. 1 The top panel displays a configuration of the critical state of the Ising model, a well-studied model of the paramagnetic–ferromagnetic phase transition. When a portion of the image is magnified it looks statistically similar to the whole image. The process of magnification can be repeated many times highlighting the scale invariance of the configuration. Here the Ising model was simulated with the code of Matt Bierbaum https://mattbierbaum.github.io/ising.js/. The bottom panel shows block spin transformations, in which sets of 4 spins are repeatedly replaced by coarse-grained block spins. Thanks to scale invariance, critical exponents can be estimated by iterative applications of the block spin transformation and the subsequent rescaling of the Ising model parameters

The basic ingredients of the renormalization group transformation exploited by Wilson to deal with a problem in condensed matter physics were already available, but in particle physics. The renormalization group had been introduced in the mid-50s by Gell-Mann and Low (1954), Stuckelberg and Petermann (1953), and others (Bogoliubov and Shirkov 1955) in the context of relativistic quantum electrodynamics, where it describes the flow of coupling constants as the cut-off length scale is changed. The full potential of the renormalization group became, however, apparent a decade later, when Kadanoff introduced the concept of *block spin* in statistical mechanics, providing a mathematical and visual representation of the act of changing the microscope magnification (Kadanoff 1966) (see Fig. 1, bottom). Wilson combined the block spin idea with the renormalization group theory to make quantitative predictions of several experimentally testable properties of phase transitions (Wilson 1971), a discovery for which he received the Nobel prize in 1982.

If we look closely, several important discoveries in theoretical physics are the result of exaptation. Ideas and theories developed in a given context are often transferred to a completely different field and used to explain unrelated problems. Another example comes from our own research activity. At the end of the 90s, one of us developed a theory of the Barkhausen effect (Zapperi et al. 1998) which describes the noise emitted by ferromagnetic materials when they are being magnetized. A key observation was that the largest noise pulses were dependent on the amplitude of the demagnetizing field, the magnetic field produced by a magnetized body. A decade later, the second of us showed that the same general mechanism describes the magnitude of the largest strain bursts in micron-scale plastic deformation (Zaiser and Nikitas 2007; Csikor et al. 2007). Going from magnetism to micromechanics, one has to replace the demagnetizing field with an internal stress field. While the physical quantities describing the two problems (i.e., magnetic field and stress) are different, the mathematical structure of the theory remains the same and can thus be *exapted* from one problem to the other.

3 Materials Genomes: Accelerating Evolution—Accelerating Exaptation

The discovery of materials with new structural or functional properties has been an essential driving force in the history of human civilization. Throughout centuries and millennia, materials discovery has followed a steady path, often based on trial and error, with fundamental breakthroughs triggering historical changes. From the first tools made of stone over the discovery of bronze and iron to the much more recent discovery of silicon-based electronics, periods of human history have been named after the material that was the key ingredient of technological progress. Materials discovery has been based on both adaptation and exaptation mechanisms. Take, for instance, the history of copper: It was probably discovered around 9000 BC and employed for making tools. Around 3500 BC, pure copper was progressively replaced by alloys with superior mechanical properties, such as bronze, obtained from copper and tin (adaptation). With the advent of the Iron Age, copper and its alloys have gradually fallen out of use in applications where high strength and hardness are important. However, the superior corrosion resistance and easy workability of the material have kept it "alive" in a range of applications ranging from jewelry over music instruments to kitchen utensils. Finally, with the advent of electricity in the nineteenth century, copper has found new and widespread use thanks to its very good conductive properties (exaptation).

In recent times, Materials Science has become a well-established academic discipline where systematic approaches to materials development and materials discovery are being sought. Trial and error now can be performed on large scales through combinatorial approaches (McFarland and Weinberg 1999), made possible by combining high-speed material synthesis with high-throughput (HT) materials screening. The purpose of combinatorial materials research is to accelerate the path of evolution. New materials were once painstakingly synthesized and characterized one at a time, while at present high-throughput methods allow us to synthesize and test thousands of different samples almost simultaneously. Computational methods are helping this discovery process by calculating the electronic, mechanical, or thermodynamic properties of a vast array of materials, both existing or only hypothetical (Curtarolo et al. 2013), thus allowing for screening of potentially useful material compositions prior to entering the often less rapid and more costly process of actual materials synthesis. Materials properties are then stored in large databases that can be interrogated to identify materials which are most suited for a particular task. As an example, we show in Fig. 2 an array of possible intermetallic compounds obtained by binary combination of metallic elements (Curtarolo et al. 2013). The top left triangle of the matrix visualizes the results of numerical simulations made to assess the stability of the corresponding intermetallic compound, while the bottom right triangle reports the comparison with experiments. Observing the matrix we can see which combinations of elements yield viable binary intermetallics.

The process of high-throughput materials discovery is very similar to adaptation in biological evolution: a large set of possible traits is generated and the most successful are then selected. This analogy did not escape the attention of policymakers, leading in the United States to the creation of the "Materials Genome Initiative" whose aim is to "discover, manufacture, and deploy advanced materials twice as fast, at a fraction of the cost" (https://www.mgi.gov/), and in the P.R. of China to the foundation of numerous institutes for "Materials Genome Engineering" at leading research universities.

The usefulness of large annotated databases for the development of new materials and processes through evolutionary adaptation was vividly illustrated in an investigation by Raccuglia et al. (2016). These authors trained a machine learning algorithm on a large data set documenting failed or unsuccessful attempts at the hydrothermal synthesis of a specific class of inorganic-organic hybrid materials (templated vanadium selenites). By using machine learning to identify those traits that are likely to make the synthesis reaction fail, they then used the accumulated knowledge to predict new successful reactions. Hence, previous apparently useless knowledge was reused to produce something new and useful. This process may be envisaged as an analog of accelerating evolutionary adaptation by means of targeted intervention, i.e., genetic engineering, which accelerates adaptation by identifying and removing unfavorable traits.

Where there is evolution, there is exaptation: Materials may be screened, developed, and optimized with a given purpose in mind, but then prove their actual usefulness in a completely different context. We illustrate the process of exaptation-driven materials discovery by two recent examples. Over the past decade, a new class of alloys has received much attention in the materials community. Different from traditional alloys, these so-called high-entropy alloys (HEAs) combine a large number of elements (typically five) into a chemically disordered crystalline structure which is stabilized by configurational entropy against ordering. This idea offers a vast range of combinatorial possibilities for new alloy compositions: Unlike the 435 possibilities for binary mixtures shown in Fig. 2, the number of possible quintenary mixtures of the 95 metallic elements in the periodic table is of the order of 50 millions, precluding systematic investigation by conventional trial-and-error approaches even if high-throughput methods are used. High-entropy alloys were originally envisaged as promising structural materials for high-strength applications: The chemical disorder of these materials leads to extreme strength, and Gludovatz et al. (2014) demonstrated that, as temperature decreases, both the strength and the fracture toughness of such

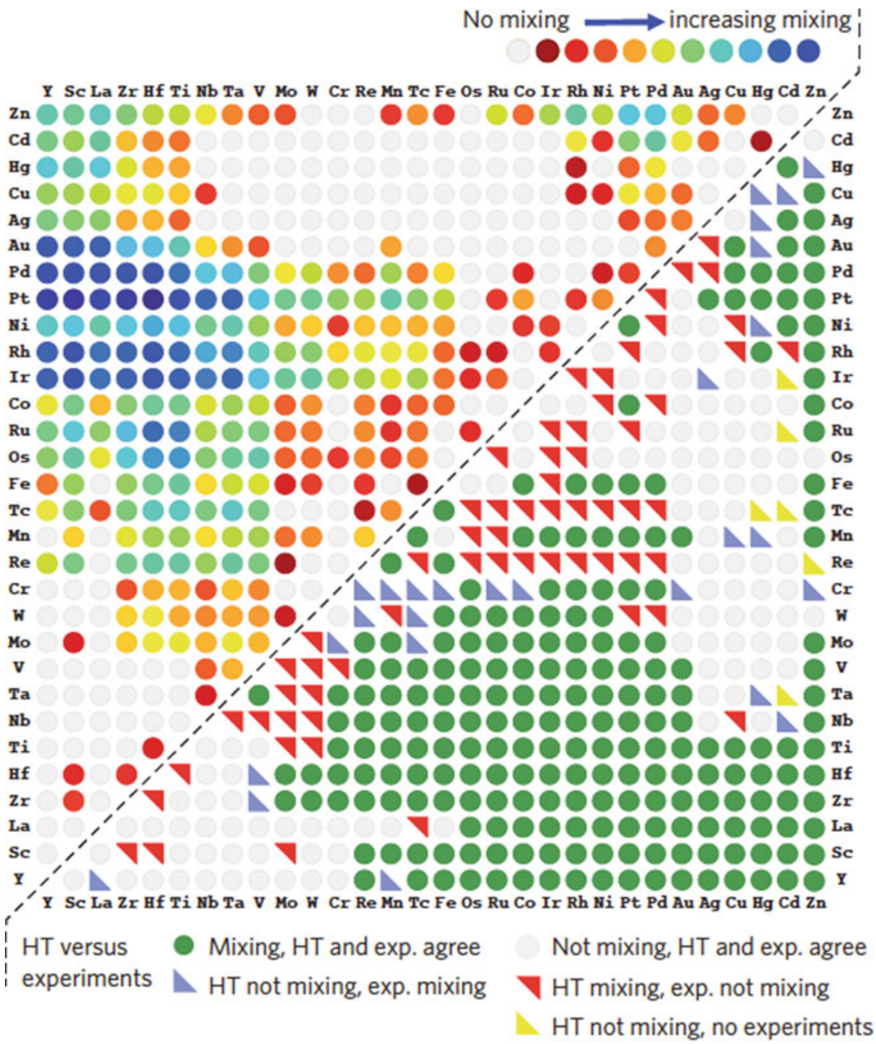


Fig. 2 High-throughput analysis of binary intermetallic mixtures. Top left triangle: ordering tendency of the mixture. Grey circles indicate no ordering, whereas darker blue circles indicate the increasing capability to form stable binary compounds. Bottom right triangle: comparison of HT versus experimental results. Green and grey circles denote agreement between calculations and experimental data on the existence (green) or absence (grey) of stable compounds. Purple (red) triangles indicate disagreement of HT predictions of compound absence (existence) versus experimental existence (absence). Yellow triangles indicate unavailable comparison data. Reprinted from Curtarolo et al. (2013)

allows may increase, in stark contrast to conventional materials such as steel which embrittles at low temperature. However, high cost and difficult processing have as yet prevented the industry-scale application of HEAs. At the same time, it is being realized that the HEA paradigm offers unprecedented possibilities to tune surface chemistry: HEAs are being rediscovered as novel catalyst materials. As an example, exaptation of the CoMoFeNiCu HEA as a novel catalyst showed an efficiency for ammonia decomposition that exceeds the performance of conventional catalysts based on the rare and expensive noble metal Ruthenium by a factor of 20 (Xie et al. 2019).

Materials exaptation need not happen accidentally but may be conducted in a systematic manner. Tshitoyan et al. illustrated this possibility by using state-of-the-art techniques for natural language processing to mine the materials science literature (Tshitoyan et al. 2019). These authors demonstrate, using the example of thermoelectricity, that important knowledge about a given functional materials property might be contained in papers that do not investigate this property at all: By looking at associations of materials properties reported in a large set of published papers, one may discover new interesting properties in materials studied for completely different purposes. To illustrate this point, Tshitoyan et al. (2019) analyzed the literature on thermoelectric materials published up to the year 2009, in conjunction with papers that investigate the particular material $CuGaTe_2$ but do *not* consider its thermoelectric properties. This analysis led to the prediction that $CuGaTe_2$ should show a strong thermoelectric effect. Indeed the material, whose thermoelectric properties were first documented in 2012 (Plirdpring et al. 2012), is now considered as one of the most successful thermoelectric materials.

From this perspective, rather than being a mere tool for accelerating the evolutionary adaptation of materials, materials genomics conducted via development and automated analysis of large databases may be envisaged as a vehicle for targeted and systematic materials exaptation. Over millennia of human civilization, materials scientists and in earlier times metallurgists have developed a vast range of materials and processes. Some ancient processes show amazing results when viewed under the transmission electron microscope of the modern materials scientist: take the medieval damascene metallurgist who may have inadvertently discovered the secret of how to wrap the ultra-hard yet brittle cementite phase of a high-carbon steel into tough carbon nanotubes (Reibold et al. 2006). Systematic exaptation of materials properties, whether contained in databases, documented in the literature, or contained in archeological artifacts, may rediscover such processes and find new applications for old materials. Most materials and processes developed over time were, in one sense or another, not fit for purpose: such is the fate of most research. However, it may often be more fair to say that the intended purpose did not match the actual material. Through data mining, analysis, and classification, materials for which properties and process data are well documented can be rapidly exposed to new “environments” and thus the vast desert of initially unsuccessful materials research may become an essential resource for exaptation-driven materials discovery.

4 Biologically Inspired Materials

Biological organisms in the natural world are often required to meet a variety of challenges. Over time, evolution produced remarkable materials and structures providing ready-made solutions for current engineering problems (Studart 2015). Thus creating artificial materials and structures inspired by their natural counterparts has become a field with great potential for technological innovation (Qin et al. 2014).

To give just a few examples, consider the self-cleaning surfaces of lotus leaves providing inspiration for super-hydrophobic surfaces (Feng et al. (2002)), the strongly adhesive feet of Gecko inspiring micro-fabricated adhesives (Geim te al. 2003) or the beetle exoskeleton that can be exploited for light interference (Lenau and Michael Barfoed 2008). In the quest for materials that combine strength and toughness, two characteristics that are often mutually exclusive (Launey and Ritchie 2009), one might look at bone and nacre (Hamza 2013), a composite material produced by some mollusks for their inner shell. Finally, a potentially even more damage tolerant biological structure is the dactyl club of the marine crustaceans stomatopods, a hammer-like structure that is able to smash other sea creatures (Weaver et al. 2012).

Fundamental differences exist between the design principles observed in nature and those employed by engineers. The selection of elements used in biology is much smaller than that used in engineering, since most biological structures are made out of polymers or polymer–ceramic composites (Fratzl 2007), which does not represent an obvious choice for building large-scale durable structures. In contrast, engineers assemble materials picking from the entire periodic table, carefully selecting atomic-scale structures best adapted to the desired macroscopic property. Biological materials present complex mechanical behavior, but it is possible to identify structural design principles underlying the mechanical properties of many natural materials (Dimas et al. 2013). For instance, the extraordinary mechanical properties of biological materials often result from a hierarchical structural organization as in the sea sponge ridge (Aizenberg et al. 2005) or the coral (Hamza 2013).

Nature grows structures and their components using biologically controlled, and therefore random, self-assembly (Fratzl 2007), while typical artificial manufacturing processes rely on the fabrication of identical components. This very different design philosophy means that there is much that we can learn from natural structures and materials. Indeed, the overlap between technological and biological solutions to similar problems is still low. For example, the overlap between human technologies and the design of arthropod cuticles that cope with radiation has been estimated to be 20% (Vincent 2005). There are thus many possibilities to use exaptation of natural processes for developing new engineering approaches. An interesting playground to explore the combination of geometry and mechanics to induce direct motion is provided by carnivorous plants such as Dionea muscipula (Forterre et al. 2005) or Drosera capensis, whose closure mechanism has been exploited to develop new metamaterial structures (La Porta et al. 2019) (see Fig. 3). Another example is the snap-through instability used by the leaf of Dionea muscipula, which is reminiscent

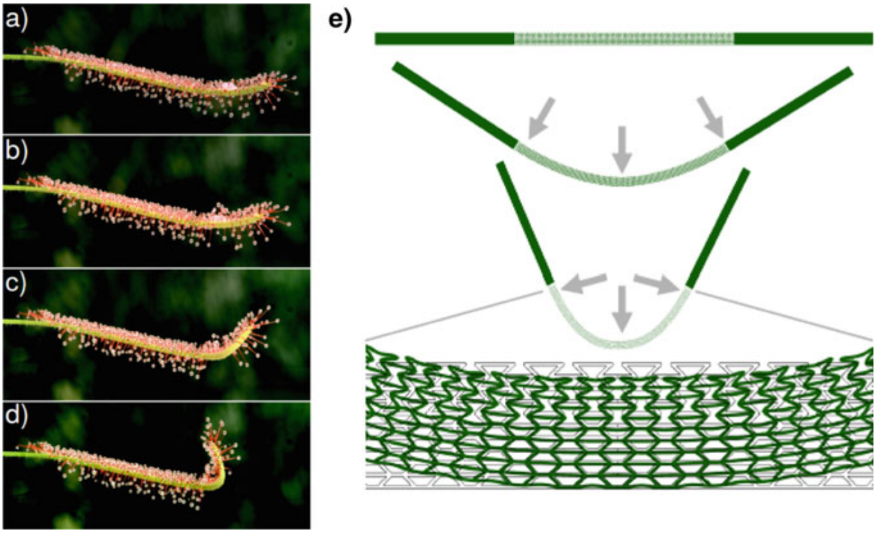


Fig. 3 The closure mechanism of the carnivorous plant Drosera capensis (**a**–**d**) can be exploited to design a metamaterial structure based on the same principle (**a**). Adapted from La Porta et al. (2019)

of the mechanism recently implemented in soft fluid actuators (Overvelde et al. 2015) and in mechanical metamaterials with a tunable response to loading (Rafsanjani and Bertoldi 2017).

5 Conclusions

In this chapter, we discussed how the concept of exaptation provides a good description of the process by which important scientific progress arises from previous results. To illustrate this point, we discussed several examples related to advances in theoretical physics in the past century. We then showed that biological evolution provides at the same time a good description of the general process of materials discovery and inspiration for new discoveries. Current strategies for material discovery are often mimicking evolutionary processes, both adaptive and exaptive. Finally, one can exapt evolution itself by using specific solutions obtained by biological evolution in the design of new materials and structures.

Acknowledgments This work was supported by the Alexander von Humboldt Foundation through the Humboldt Research Award. SZ thanks for hospitality the Friedrich-Alexander-Universität Erlangen-Nürnberg where this chapter has been written.

References

Aizenberg J, Weaver JC, Thanawala MS, Sundar VC, Morse DE, Fratzl P (2005) Skeleton of euplectella sp.: structural hierarchy from the nanoscale to the macroscale. Science 309(5732):275–278

Andriani P, Cattani G (2016) Exaptation as source of creativity, innovation, and diversity: introduction to the special section. Ind Corp Change 25(1):115–131

Autumn K, Liang YA, Hsieh ST, Zesch W, Chan WP, Kenny TW, Fearing R, Full RJ (2000) Adhesive force of a single gecko foot-hair. Nature 405(6787):681–685

Bogoliubov NN, Shirkov DV (1955) Application of the renormalization group to improve the formulae of perturbation theory. Doklady AN SSSR 103:391–394

Csikor FF, Motz C, Weygand D, Zaiser M, Zapperi S (2007) Dislocation avalanches, strain bursts, and the problem of plastic forming at the micrometer scale. Science 318(5848):251–254

Curtarolo S, Hart GLW, Nardelli MB, Mingo N, Sanvito S, Levy O (2013) The high-throughput highway to computational materials design. Nat Mater 12(3):191–201

Dimas LS, Bratzel GH, Eylon I, Buehler MJ (2013) Tough composites inspired by mineralized natural materials: computation, 3d printing, and testing. Adv Funct Mater 23(36):4629–4638

Feng L, Li S, Li Y, Li H, Zhang L, Zhai J, Song Y, Liu B, Jiang L, Zhu D (2002) Super-hydrophobic surfaces: from natural to artificial. Adv Mater 14(24):1857–1860

Yoël Forterre, Skotheim JM, Dumais J, Mahadevan L (2005) How the venus flytrap snaps. Nature 433(7024):421–5

Fratzl P (2007) Biomimetic materials research: what can we really learn from nature's structural materials? J Royal Soc Interface 4(15):637–642

Geim AK, Dubonos SV, Grigorieva IV, Novoselov KS, Zhukov AA, Shapoval SY (2003) Microfabricated adhesive mimicking gecko foot-hair. Nat Mater 2(7):461–463

Gell-Mann M, Low FE (1954) Quantum electrodynamics at small distances. Phys Rev 95(5):1300

Gludovatz B, Hohenwarter A, Catoor D, Chang EH, George EP, Ritchie RO (2014) A fracture-resistant high-entropy alloy for cryogenic applications. Science 345(6201):1153–1158

Gould SJ, Vrba ES (1982) Exaptation—a missing term in the science of form. Paleobiology 8(1):4–15

Hamza S, Slimane N, Azari Z, Pluvinage G (2013) Structural and mechanical properties of the coral and nacre and the potentiality of their use as bone substitutes. Appl Surf Sci 264:485–491

Higgs PW (1964) Broken symmetries and the masses of gauge bosons. Phys Rev Lett 13(16):508

Kadanoff LP (1966) Scaling laws for ising models near t c. Phys Physique Fizika 2(6):263

Kuhn TS (1962) The structure of scientific revolutions. Chicago and London

La Porta CAM, Lionetti MC, Bonfanti S, Milan S, Ferrario C, Rayneau-Kirkhope D, Beretta M, Hanifpour M, Fascio U, Ascagni M et al (2019) Metamaterial architecture from a self-shaping carnivorous plant. Proc Natl Acad Sci 116(38):18777–18782

Larson G, Stephens PA, Tehrani JJ, Layton RH (2013) Exapting exaptation. Trends Ecol Evol 28(9):497–498

Launey ME, Ritchie RO (2009) On the fracture toughness of advanced materials. Adv Mater 21(20):2103–2110

Lenau T, Barfoed M (2008) Colours and metallic sheen in beetle shells-a biomimetic search for material structuring principles causing light interference. Adv Eng Mater 10(4):299–314

McFarland EW, Weinberg WH (1999) Combinatorial approaches to materials discovery. Trends Biotechnol 17(3):107–115

Overvelde JTB, Kloek T (Sep 2015) D'haen JJA, Bertoldi K (2015) Amplifying the response of soft actuators by harnessing snap-through instabilities. Proc Natl Acad Sci U S A 112(35):10863–8

Plirdpring T, Kurosaki K, Kosuga A, Day T, Firdosy S, Ravi V, Snyder GJ, Harnwunggmoung A, Sugahara T, Ohishi Y et al (2012) Chalcopyrite cugate2: a high-efficiency bulk thermoelectric material. Adv Mater 24(27):3622–3626

Qin Z, Dimas L, Adler D, Bratzel G (2014) Buehler MJ (2014) Biological materials by design. J Phys Condens Matter 26(7):073101

Raccuglia P, Elbert KC, Adler PDF, Falk C, Wenny MB, Mollo A, Zeller M, Friedler SA, Schrier J, Norquist AJ (2016) Machine-learning-assisted materials discovery using failed experiments. Nature 533(7601):73

Rafsanjani A, Bertoldi K (2017) Buckling-induced kirigami. Phys Rev Lett 118(8):084301

Reibold M, Paufler P, Levin AA, Kochmann W, Pätzke N, Meyer DC (2006) Carbon nanotubes in an ancient damascus sabre. Nature 444(7117):286–286

Stuckelberg E, Petermann A (1953) La normalisation des constantes dans la theorie des quanta. Helv Phys Acta 26:499–520

Studart AR (2015) Biologically inspired dynamic material systems. Angewandte Chemie Int Edn 54(11):3400–3416

Tshitoyan V, Dagdelen J, Weston L, Dunn A, Rong Z, Kononova O, Persson KA, Ceder G, Jain A (2019) Unsupervised word embeddings capture latent knowledge from materials science literature. Nature 571(7763):95–98

Vincent JFV (2005) Deconstructing the design of a biological material. J Theor Biol 236(1):73–78

Weaver JC, Milliron GW, Miserez A, Evans-Lutterodt K, Herrera S, Gallana I, Mershon WJ, Swanson B, Zavattieri P, DiMasi E et al (2012) The stomatopod dactyl club: a formidable damage-tolerant biological hammer. Science 336(6086):1275–1280

Wilson KG (1971) Renormalization group and critical phenomena. i. Renormalization group and the kadanoff scaling picture. Phys Rev B 4(9):3174

Witten E (2016) Phil anderson and gauge symmetry breaking. In Pwa90: a lifetime of emergence, pp 73–89. World Scientific

Xie P, Yao Y, Huang Z, Liu Z, Zhang J, Li T, Wang G, Shahbazian-Yassar R, Liangbing H, Wang C (2019) Highly efficient decomposition of ammonia using high-entropy alloy catalysts. Nature Commun 10(1):1–12

Zaiser M (2007) Nikitas N (2007) Slip avalanches in crystal plasticity: scaling of the avalanche cut-off. J Stat Mechs: Theory Exp 04:P04013

Zapperi S, Cizeau P, Durin G, Stanley HE (1998) Dynamics of a ferromagnetic domain wall: Avalanches, depinning transition, and the barkhausen effect. Phys Rev B 58(10):6353

Exaptation for the Good and the Bad: Regeneration and Cancer

Caterina AM La Porta

1 The Most Important Ingredients of Regeneration

The integrity of an organism is a key biological ingredient and is closely related to the capability to successfully repair an injury. Regeneration is actually defined as the capability to replace a damaged or lost part of the body after an injury without any loss of function or scar. Regenerative processes are present in almost all Metazoa (Alvarado and Tsonis 2006) since they are an essential function of a multicellular organism. Plants are also very good at this process (Pulianmackal et al. 2014). In fact, plants possess a high capacity to regenerate, which has long been utilised for clonal propagation in the form of cutting and grafting (Hartmann et al. 2010; Melnyk et al. 2015). Plants are very versatile while in Metazoa the regenerative process decreases with the increase of the presence of a more specialised immune system. In fact, It has been shown that, through evolution, the development of an immune system is followed by a concomitant loss of regenerative capacity (Godwin and Rosenthal 2014; Godwin et al. 2014). One of the main characteristics of the adaptive immune system is to distinguish between self and non-self and the process involved in regeneration from proliferation to migration and remodelling appears to be in conflict with the mechanisms triggered by immunity while regeneration helps proliferation. In fact, these two processes have different final goals: immunity tries to hinder the growth in the body of external guests (bacteria, virus, etc.) while regeneration helps proliferation. We well know that mammals cannot regenerate amputated body parts

C. AM. La Porta (✉)
Department of Environmental Science and Policy, University of Milan, via Celoria 26, 20133 Milan, Italy
e-mail: caterina.laporta@unimi.it

Center for Complexity & Biosystems (CC&B), University of Milan, via Celoria 26, 20133 Milan, Italy

Innovation for Well-Being and Environment (CRC-I-WE), University of Milan, via Celoria 26, 20133 Milan, Italy

C. AM. La Porta et al. (eds.), *Understanding Innovation Through Exaptation*, The Frontiers Collection, https://doi.org/10.1007/978-3-030-45784-6_4

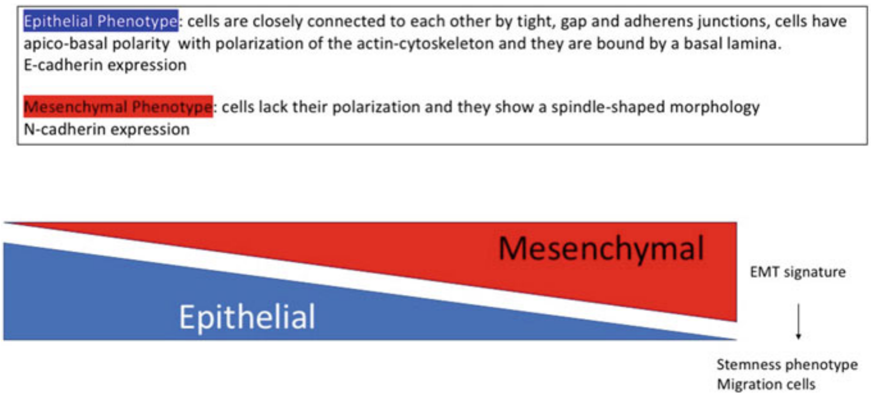


Fig. 1 Most important features of Epithelial and Mesenchymal cells

and regeneration capability is limited to post-injury regeneration (Mescher and Neff 2005; Mescher et al. 2017). A good model of this phenomenon in mammals is liver regeneration after partial hepatectomy (PH), where the original mass of the liver is re-established in direct proportion to the amount of tissue removed (Gilgenkrantz and Collin de l'Hortety 2018) (Fig. 1).

2 Exaptation in Regeneration

The main question that my group investigated in the past 3 years is to understand if the capability to regenerate in mammals was due to completely different molecular pathways with respect to animals having a simple immune system but high regenerative capacity such as *Hydra* (*Cnidaria*), *Planaria* (*Platyhelminthes*) and *Sea Cucumber* (*Echinodermata*). In other words, why did mammals loose this function during evolution? Do mammals have some signature of this capacity in organs able to regenerate? In other words, do mammals use a new strategy to regenerate or do they use a serendipity strategy explored by simpler organisms?

Hydra polyps belong to *phylum* of *Cnidaria* and is able to regenerate completely thanks to high proliferative stem cells that allow them to rebuild the entire body. In fact, it is possible to dissociate Hydra to the single cell level and observe that the cell can regenerate a complete body axis from aggregates of cells, behaving as a natural organoid. A recent paper shows stem cell differentiation trajectories at the level of single-cell resolution, building the first gene expression map of the Hydra nervous system with a comprehensive molecular description of the Hydra (Siebert et al. 2019).

Planarias are a group of flatworms with a great capability to regenerate due to proliferating cells (neoblasts) (Wagner et al. 2011; Reddien and Alvarado 2004). In a recent paper, it was shown that clonogenic neoblasts (cNeoblasts) were able to produce cells that differentiate into neuronal, intestinal and other known postmitotic cell types (Wagner et al. 2011) and single transplanted cNeoblasts restored regeneration in lethally irradiated hosts (Reddien and Alvarado 2004). Interestingly, *planarias* can prevent starvation using their own energy (de-growth process) (Reddien and Alvarado 2004).

Sea Cucumber belongs to Echinoderms and also has a great capability to regenerate a wide spectrum of body parts, e.g. their body wall, the nervous system, and internal organs, such as the digestive system, reproductive organs and respiratory trees. Regarding digestive system, this is the first organ to regenerate. There is very little information available on the mechanism used by these animals for regeneration. In a recent paper, a genomic evolution study was carried out leading to new clues to morphological evolution and visceral regeneration (Zhang et al. 2017).

To address why mammals lost this function during evolution and if mammals have still some signs of this capacity, we used the following strategy: first, we considered the very complete assembled transcriptome of *Hydra magnipapillata*, a paradigm for animal regeneration, being able to reconstruct missing body structure without scarring, *Schmidtea mediterranea* that represents the main model organism for the group of planarians, bilaterally symmetric Platyhelminthes that can be easily found in freshwater, and *Apostichopus japonicus* which among the number of Echinodermata possesses a good regenerative capacity (Fumagalli et al. 2018). Then, for each species, we considered both the reference and the regenerating transcriptome, obtained in the same experiment as a function of time (Fumagalli et al. 2018). We also considered mouse and rat liver regeneration after PH as illustrative of tissue regeneration in vertebrates and mammals (Stewart et al. 2013; Xu et al. 2010; Pibiri et al. 2015). What we found is that there is a common set of differentially expressed genes and relevant shared pathways that are conserved across species during the early stage of the regeneration process. Therefore, mammals use genes already used by these ancients organisms rearranging them in a different context (Fumagalli et al. 2018). In particular, I want to point out that we identified a signature associated to the Epithelial–Mesenchymal Transition (EMT), which in mammalian cells is involved in the plasticity of the cells allowing them to rapidly migrate towards the injury ensuring a fast wound closure and an effective regeneration process (Agata et al. 2007). Our results thus show that the complex tissue repair strategy that we have in mammals is related to the regeneration capacity present in those distant species. New biological process is created by exaptation rearranging part of old information in a new context. Increasing the complexity of the organisms, the immune system became more sophisticated and it was like a tug-of-war between the preservation of the integrity of the organism and the immune response against the non-self. It results in the end to the loss of regeneration with the exception of some tissues. In this tissue, we find a reminder of regeneration signature present in high regenerative capacity animals (Fumagalli et al. 2018). This kind of study helps us to highlight the differences between us and these high regenerative organisms and in the near future it is tempting to speculate that further investigating non-conserved genes, we could understand the key ingredients to establish this function. This would be useful for future regeneration therapies.

3 Most Important Ingredients of Cancer

Cancer cells are not alien but they are cells that acquire a profound independence from the other cells and a different relationship with the environment (La Porta and Zapperi 2017, 2018). Cancer, on the other hand, is highly heterogeneous and epigenetic changes help tumour heterogeneity (Easwaran et al. 2014).

Epigenetic changes are changes in the phenotype that do not involve alterations in the DNA. In Greek, *epigenetics* implies something that is "on top of" or "in addition to" the traditional basis for inheritance. From the biological point of view, there are many mechanisms at the basis of epigenetics including miRNAs and histone modifications (La Porta and Zapperi 2018).

In human melanoma, our group showed recently the capability of human melanoma cells to overshoot aggressive markers during their growth (Sellerio et al. 2015). This mechanism was demonstrated to be controlled by a complex network of miRNA, confirming the tight control of this process by the cells. The direct and more important consequence of these findings, is that the cells seem to have an intrinsic capability to change in the dependence of the environment that leads to a plasticity of the tumour cells (Sellerio et al. 2015). Plasticity of tumor cells was also demonstrated in other tumours including breast cancer (Wahl and Spike 2017). The direct consequence of these features is that cancer can adapt to different environments changing and becoming more aggressive and resistant to specific treatments, leading to difficulties in getting successful treatment.

The main question that my group investigated in the past years is to understand if tumour plasticity is created by something new or is due to exaptation of the same ingredients tossed in a different way. In biological language, we should search for a signature of aggressiveness to predict the future of a specific tumour due to its peculiar characteristics. This perspective leads, as a direct consequence, to the building of a precision medicine where we are able to know exactly the biological characteristics of a specific tumour and to treat each specific tumour in the best way available.

4 Exaptation in Cancer

How do cancer cells manage to become plastic? Cancer cells did not invent something new but they use the same ingredients that non-tumour cells usually exploit, tossing these ingredients in a different manner. It is possible to create different flavours starting from the same ingredients mixing them in different amounts and getting different cooked meals. EMT is one of the most important ingredients that allows cells to be plastic and to change their phenotype. As discussed in the previous section, mesenchymal genes control the shape and the migratory capacity of the cells helping them spread and acquire a metastatic phenotype (La Porta and Zapperi 2017). In a recent work, my group analysed the emergence of hybrid E/M states by studying the gene regulatory network underlying EMT/MET (Font et al. 2018), building on previous work on Boolean networks (Steinway et al. 2015). Modulating the gene regulatory network underlying EMT/MET, tumour cells can change their phenotype and adapt to the environment. EMT plays a crucial role in development of many tissues and organs in the developing embryo (Thiery et al. 2009). Therefore, the same mechanism can be used in a different way to get different results.

5 Exaptation and the Era of Big Data in Biomedicine

The possibility to use exaptation of genes to create serendipity or the occurrence of an unplanned fortunate discovery is a concept that happens in biology and in the development of diseases. In cancer, the capability of tumour cells to become metastatic starts from the exploration of many states through the heterogeneity of the cells that can involve the presence of more aggressive and resistant cells. The possibility to analyse a big number of single cells allows us to explore the landscape of the cells and, in particular, for tumour cells, the possibility to find the best combination leading to serendipity in that microenvironment. Our recent paper explored this direction (Font et al. 2018).

Exaptation is also used to discover new drugs. In fact, biomarker discovery is the search for measurable biological indicators of a phenotypic trait of interest and is indeed one of the fundamental data analysis problems in computational biology and health care. Therefore, the concept of exaptation that is proposed as a characteristic element of technological change and an important mechanism by which new markets for products and services are created by entrepreneurs is the same mechanism that brings innovation in biology and in the development of pathologies. The era of Big Data helps in the analysis of tonnes of data and allows us to discover mechanisms of exaptation more easily and in more complex situations, such as metabolic pathways, genome organisation, etc.

All this knowledge that is coming up in these years will help us to understand better the diseases and to find out innovative solutions bypassing classical biology and wet lab. The wet lab will still be useful to validate the results but, as it is happening in physics, an approach based on exaptation can speed up the discovery of the new findings and can help to investigate innovative solutions in silico. Another interesting consequence is that the technology in medicine also appears to be influenced by exaptation and, in this connection, innovation will probably speed up in the upcoming years. When I say technology, I think of the way to get information perhaps from electroencephalography (EEG) with functional magnetic resonance imaging (fMRI) in the brain. This information can help us understand what is the mechanisms used by our brain to organise and store information and can help also in discovering common features with our ancestor, understanding why we diverged from them, and in the long term can help to answer complex questions such as what is the meaning of consciousness and what is a neurological disease. All these problems are interesting challenges and exaptation can help find out new ideas and understand complex biological systems through serendipity.

6 Acknowledgments

The project was supported by funding from the Center for Complexity and Biosystems of UniMI. The research leading to these results has received funding from AIRC under IG 2019—ID. 23141 project—P.I. La Porta Caterina.

References

Agata K, Saito Y, Nakajima E (2007) Unifying principles of regeneration I: epimorphosis versus morphallaxis. Dev Growth Differ 49:73–78

Alvarado A, Tsonis P (2006) Bridging the regeneration gap: genetic insights from diverse animal models. Nat Rev Genet 7:873–884

Easwaran H, Tsai HC1, Baylin SB (2014) Cancer epigenetics: tumor heterogeneity, plasticity of stem-like states, and drug resistance. Mol Cell 54:716–727

Font Clos F, Zapperi S, La Porta C (2018) Topography of epithelial–mesenchymal plasticity. PNAS 115:5902–5907

Fumagalli MR, Zapperi S, LaPorta C (2018) Regeneration in distantly related species common strategies and pathways. NPJ Syst Biol Appl 4. https://doi.org/10.1038/s41540-017-0042-z

Gilgenkrantz H, Collin de l'Hortety A (2018) Understanding liver regeneration from mechanisms to regenerative medicine. Am J Pathol 188:1316–1327

Godwin JW (2014) The promise of perfect adult tissue repair and regeneration in mammals: learning from regenerative amphibians and fish. BioEssays 36:861–871

Godwin JW, Rosenthal N (2014) Scar-free wound healing and regeneration in amphibians: immunological influences on regenerative success. Differentiation 87:66–75

Hartmann HT, Kester DE, Davies FT, Geneve R (2010) Hartmann & Kester's plant propagation: principles and practices, 8th edn. Prentice-Hall, Englewood Cliffs, NJ, USA

La Porta CAM, Zapperi S (2017) Complexity in cancer stem cells and tumor evolution: towards precision medicine. Semin Cancer Biol 44:3–9

La Porta CAM, Zapperi S (2018) Explaining the dynamics of tumor aggressiveness: at the crossroads between biology, artificial intelligence and complex systems. Semin Cancer Biol 53:42–47

Melnyk CW, Schuster C, Leyser O, Meyerowitz EM (2015) A developmental framework for graft formation and vascular reconnection in Arabidopsis thaliana. Curr Biol 25:1306–1318

Mescher AL, Neff AW (2005) Regenerative capacity and the developing immune system. Adv Biochem Eng Biotechnol 93:39–66

Mescher AL, Neff AW, King MW (2017) Inflammation and immunity in organ regeneration. Dev Comp Immunol 66:98–110

Pibiri M, Sulas P, Leoni VP, Perra A, Kowalik MA, Cordella A, Saggese P, Nassa G, Ravo M (2015) Global gene expression profile of normal and regenerating liver in young and old mice. AGE 37:9796

Pulianmackal AJ, Kareem AVK, Durgaprasad K, Trivedi ZB, Prasad K (2014) Competence and regulatory interactions during regeneration in plants. Front Plant Sci 11. doi.org/10.3389/fpls.2014.00142
Reddien PW, Alvarado SA (2004) Fundamentals of planarian regeneration. Annu Rev Cell Dev Biol 20:725–757
Sellerio AL, Ciusani E, Bossel Ben-Moshe N, Coco S, Piccinini A, Myers CR, Sethna JP, Giampietro C, Zapperi S, La Porta CAM (2015) Overshoot during phenotypic switching of cancer cell populations. Sci Rep 5:15464
Siebert S, Farrell JA, Cazet JF, Abeykoon YL, Primack AS, Schnitzler CE, Juliano CE (2019) Stem cell differentiation trajectories in Hydra resolved at single-cell resolution 365:eaav9314
Steinway SN, Zañudo JGT, Michel PJ, Feith DJ, Loughran TP, Albert R (2015) Combinatorial interventions inhibit TGFβ-driven epithelial-to-mesenchymal transition and support hybrid cellular phenotypes. NPJ Syst Biol Appl 1, Article number: 15014
Stewart R, Rascón CA, Tian S, Nie J, Barry C, Chu LF, Ardalani H, Wagner RJ, Probasco MD, Bolin JM, Leng N, Sengupta S, Volkmer M, Habermann B, Tanaka EM, Thomson JA, Dewey CN (2013) Comparative RNA-seq analysis in the unsequenced axolotl: the oncogene burst highlights early gene expression in the blastema. PLoS Comput Biol 9:e1002936
Thiery JP, Acloque H, Huang YJ, Nieto MA (2009) Epithelial-mesenchymal transitions in development and disease. Cell 139:871–890
Wagner DE, Wang IE, Reddien PW (2011) Clonogenic neoblasts are pluripotent adult stem cells that underlie planarian regeneration. Science 332:811–816
Wahl GM, Spike BT (2017) Spike cell state plasticity, stem cells, EMT, and the generation of intra-tumoral heterogeneity. NPJ Breast Cancer 3:14
Xu C, Chen X, Chang C, Wang G, Wang W, Zhang L, Zhu Q, Wang L, Zhang F (2010) Transcriptome analysis of hepatocytes after partial hepatectomy in rats. Dev Genes Evol 220:263–274
Zhang X, Sun L, Yuan J, Sun Y, Gao Y, Zhang L, Li S1, Dai H, Hamel JF, Liu C, Yu Y, Liu S, Lin W, Guo K, Jin S, Xu P, Storey KB, Huan P, Zhang T, Zhou Y, Zhang J, Lin C, Li X, Xing L, Huo D, Sun M, Wang L, Mercier A, Li F, Yang H, Xiang J (2017) The sea cucumber genome provides insights into morphological evolution and visceral regeneration PLoSBiol 15:e2003790

Quantifying Exaptation in Scientific Evolution

M. R. Ferreira, N. Reisz, W. Schueller, V. D. P. Servedio, S. Thurner, and V. Loreto

1 Introduction

The rediscovery of a new function for a given object or concept can be just as important as its discovery. This phenomenon is known as *exaptation*, and the related verb is *to co-opt*. It characterises the process of acquiring new functions for which a trait, which originally evolved to solve one problem, is co-opted to solve a new

M. R. Ferreira · N. Reisz · W. Schueller · V. D. P. Servedio · V. Loreto (✉)
Complexity Science Hub Vienna, Josefstädter Str. 39, 1080 Vienna, Austria
e-mail: vittorio.loreto@gmail.com

M. R. Ferreira
e-mail: marcia.ferreiragoncalves8@gmail.com

N. Reisz
e-mail: reisz@csh.ac.at

V. D. P. Servedio
e-mail: servedio@csh.ac.at

M. R. Ferreira
TU Wien (Vienna University of Technology), 1040 Vienna, Austria

S. Thurner
Section for Science of Complex Systems, Center for Medical Statistics, Informatics and Intelligent Systems (CeMSIIS), Medical University of Vienna, 1090 Vienna, Austria
e-mail: stefan.thurner@muv.ac.at

Complexity Science Hub Vienna, 1080 Vienna, Austria

International Institute for Applied Systems Analysis (IIASA), 2361 Laxenburg, Austria

Santa Fe Institute, Santa Fe, NM 85701, United States

V. Loreto
Sony Computer Science Lab, Paris, 6, Rue Amyot, 75005 Paris, France

Sapienza University of Rome, Piazzale Aldo Moro2, 00185 Rome, Italy

C. AM. La Porta et al. (eds.), *Understanding Innovation Through Exaptation*,
The Frontiers Collection, https://doi.org/10.1007/978-3-030-45784-6_5

problem Gould and Vrba (1982). The definition is similar to the concept of *preadaptation* Bock (1959). However, since this term may suggest teleology, Vrba and Gould urged scholars to replace that term by exaptation. The idea of exaptation was also proposed to distinguish the concept from *adaptation* Darwin (2004). While exaptations are traits that have applications that deviate from their original purpose Gould and Vrba (1982), Kauffman (2000), adaptations have been shaped by natural selection for their current use Bock (1959), Darwin (2004). One canonical example of exaptation in biology is the evolution of feathers. It is often argued that feathers were not originally developed for flight, but emerged in the reptilian ancestors of today's birds for thermal regulation Gould and Vrba (1982). Other examples include the ability of a metabolic reaction network to survive on different food sources which can allow adoption of alternative substrates Barve and Wagner (2013). Exaptation events seem to be important to give birth to adaptive innovations, diversity and, more generally, to complex traits Barve and Wagner (2013).

Gould and Vrba propose exaptations have adaptive and non-adaptive origins: *preaptation* and *nonaptation*. Preaptation refers to characteristics or traits that are adapted and 'selected' for one evolutionary purpose (adaptations). These are later co-opted to serve another purpose leading to an increase in the fitness of the co-opted trait. Thus, preaptations are adaptations that have undergone a significant change in function Gould and Vrba (1982), Lloyd and Gould (2017). Another source of exaptation is nonaptation. Nonaptation refers to traits that emerge through a process of trial and error that generates lots of 'leftover' features (e.g., DNA, molecules, cells) Gould and Vrba (1982). These concern the effective use of co-opted leftover traits to serve a particular function, but whose origin cannot be ascribed to the process of 'natural selection' Gould and Vrba (1982). Nonaptations are byproducts of the evolution of some other trait Darwin (2004) that do not add to the fitness of the co-opted trait Lloyd and Gould (2017), Gould and Vrba (1982). In summary, adaptations, preaptations, and nonaptations are essential processes that drive the evolution of living matter, cells, humans, organisms, and biological ecosystems. They allow us to understand the adaptive and non-adaptive origins of biological novelty.

Recently, the notion of exaptation has been applied to the study of technological change Bonifati (2010), Dew et al. (2004). One set of studies have focused on the development of technological speciation narratives Dew et al. (2004), Levinthal (1998), Andriani and Cohen (2013) and niche construction theory Dew and Sarasvathy (2016). Other studies focused on the adoption of technology Rogers (2010), its commercial application Schumpeter (1939), and its economic impact Dew and Sarasvathy (2016), but not on the origin of those inventions Fleming and Sorenson (2004). Small-scale studies of technological exaptation abound in the management and innovation literature (e.g., Yong Tan and Tatsumura. (2015), Dew and Sarasvathy (2016), Cattani (2005), Rosenman (1988)). These studies point to the role of chance such as serendipitous discovery of a new function Andriani and Cohen (2013). Serendipity (accidental circumstances leading to fortunate findings) and exaptation (a shift in the function of something) are intricately related by the fact that accidental discoveries that contribute to the redeployment of a component in a different context lead to a shift in the function of that component. A related stream of research has attempted to model the dynamics of invention mathematically by analysing specific knowledge spaces Tria et al. (2014), Loreto et al. (2016), Thurner et al. (2010), Klimek et al. (2010), Klimek et al. (2012), Hidalgo and Hausmann (2009), Tacchella et al. (2012), Servedio et al. (2018), Kauffman (1993), Gabora (2013). The aim of these studies is not to explain why some entities produce more innovations than others (productivity), or what influences the ability of these entities to produce them, but how knowledge evolves in a mechanistic view. These studies have provided evidence for the existence of innovation bursts in national economies Thurner et al. (2010), Klimek et al. (2012), the rediscovery of publications leading to the emergence of new scientific fields Thurner et al. (2019), Van Raan (2004), and the novel combination of components as a source of everyday novelties Tria et al. (2014). Few attempts focused on explicitly quantifying exaptation, one notable exception being Andriani et al. (2017), where it is estimated that about 40% of pharmaceutical drugs have started as something else.

Similarly, many scientific discoveries find applications that are not foreseen from the outset. The scientific context is particularly relevant for the study of exaptation since it encompasses a variety of human activities where knowledge is frequently rediscovered and re-used. In scientific evolution processes, different disciplines may come together, "to tell one coherent interlocking story" Watson (2017), or a field may subdivide into new disciplines. Both may form the basis on which concepts can further recombine. The recent use of statistical physics to examine people's behaviour in crowds, traffic, or stock markets is an example of co-opting theories and techniques to the social sciences. Research on laser technologies Bonifati (2010), pharmaceuticals Andriani et al. (2017), and fibre optics Cattani (2005) keep expanding their scope of application in very diverse fields. This kind of repurposing may enhance (though not necessarily) the fitness of entities Gould and Vrba (1982). Exaptation in the context of science thus refers to a diversification logic, where publications build on an existing knowledge base and succeed in entering other fields by creating new scientific niches or sub-fields. We thus interpret exaptation in science as how research insights from publications in one field are co-opted (i.e. cited) by publications from different scientific domains.

To arrive at a formal understanding of exaptation in science and technology we start by briefly reviewing related perspectives on the origins of innovations.[1] We then attempt to detect the fingerprints of exaptation by using publication data indexed in the APS (American Physical Society) database, which contains over 450,000 articles in the field of physics. We use the direct citation network to construct clusters of publications that represent sub-fields of physics. Citations have been considered as a proxy for academic relevance, with citation-based indicators offering approximate information about the scientific impact of publications Sugimoto and Larivière (2018). We focus on seminal publications that initially appear in a given domain and later receive acknowledgements and new functions from other domains. The idea of func-

[1] It is not our aim to provide an in-depth discussion and definition of the concepts of novelty, innovation, or invention, which can be found elsewhere Erwin and Krakauer (2004), Arthur (2007); these terms will be used interchangeably throughout this chapter.

tion is critical here because it reflects knowledge-use of specific research outcomes in different scientific contexts. By investigating the "citation paths" of individual publications across different domains, we quantify both their overall importance, as well as their impact on the structure of the field of physics as a whole.

The chapter is structured as follows. In Sect. 1, we introduce the concept of exaptation as a theoretical concept and clarify the scientific context in which we will use it in this chapter. In Sect. 2, we describe the data and the empirical approach. In Sect. 3, we present results. Finally, in Sect. 4, we conclude the chapter and summarise our results and proposal in this area of research.

1.1 Exaptation in Science and Technology

A growing number of scholars in the area of innovation theory propose exaptation as the ultimate source of novelty. They argue that exaptation can explain the emergence of markets, technologies, and technical functions Dew and Sarasvathy (2016), Cattani (2005), Andriani et al. (2017), Mokyr (1991). In their view, exaptation leads to *technological speciation* or the creation of *technological niches* Andriani and Cattani (2016). In technological speciation processes, new technology develops from the effective transfer of existing knowledge to a new situation, where the transferred knowledge is interpreted and exploited in new ways Cohen and Levinthal (1990). Famous cases that illustrate this pattern include Corning Inc., a company that used its long-standing experience on glass engineering to deliver ground-breaking fibre-optic work that has transformed the telecommunications landscape Watson (2017), or the microwave, which was discovered by chance through the repurposing of parts of a radar system Rosenman (1988). Often, a distinction is made between radical and incremental innovations. While radical innovations transform the technological landscape, incremental innovations are minor improvements in existing technologies Dewar and Dutton (1986). Exaptation has been associated with radical innovations leading to the creation of new technological niches Andriani and Cohen (2013). Most empirical studies of exaptation in those contexts have been limited to small-scale or narratives of specific technologies.

In the context of science, contributions to the study of invention have used scientific publications, and metadata, such as author affiliation, organisation, location, and citation linkages to assess novel research outputs. Citation network analysis has been used extensively. Uzzi et al. (2013) used co-citation linkages from publications in various fields to differentiate between typical and atypical co-citations. Atypical co-citations are papers that are rarely cited together. They found that high-impact publications were usually not those that had the most atypical or novel combination of ideas, nor those that used typical combinations of ideas, but papers that cite a mix of new and conventional ideas. This result implies that, while originality is a crucial feature of high-impact science, the building blocks for new ideas are often embodied in existing knowledge Uzzi et al. (2013). Further, papers with high novelty as measured by atypical combinations tend to be less cited at the start, but are more likely to be cited after several years after publication Stephan et al. (2017). Other studies, which highlight the role of recombining ideas in driving innovation, suggest that older, seminal works are more likely to inspire ground-breaking science Kuhn (1962).

The combination of different theories, fields, and tools is also central to interdisciplinary research Wagner et al. (2011). Interdisciplinarity is likely to lead to more 'innovative' research Thurner et al. (2019), which is associated with higher levels of citation impact Larivière et al. (2015). Furthermore, the citation influence of papers is enhanced by the thematic distance (i.e. cognitively different fields) from the articles they cite Klavans et al. (2013). Yet, such outputs often face more resistance than mainstream publications (i.e. publications drawing mainly on the knowledge of a single field), thus requiring more time to get recognised by the wider scientific community Thurner et al. (2019). This idea relates to the "first-mover" advantage where mediocre papers will often receive more citations early on, than a later excellent one Newman (2009). There is, however, conflicting evidence that interdisciplinary research obtains higher citation rates at the level of journals in natural and medical sciences Levitt and Thelwall (1984), research departments Rinia et al. (2002), and in the field of biomedicine Larivière and Gingras (2010). This evidence shows that the relationship between novel research—as defined by interdisciplinary combinations—and impact depends on the characteristics of the fields and type of analysis involved Larivière and Gingras (2010).

2 Methodology

To track scientific progress, we use the APS dataset APS (2020), which includes publications in the leading physics journals since 1893. Following Blondel et al. (2008), we apply the Louvain algorithm to design an alternative classification scheme that clusters the set of all publications (articles and reviews) in the APS between 1893 and 2017 into research areas. The method is based on first determining pairs of publications that cite one another, and second, on clustering publications into a research area. The procedure uses a directed citation network where nodes consist of publications and links consist of citations between publications. Each publication belongs to a unique research area. We disregard the direction of the links in the network and exclude publications without citations.

Figure 1 shows the distribution of cluster sizes. For several clusters the number of publications is very small. For practical reasons we excluded clusters that have less than 10 publications. This method allows us to examine the influence of publications that belong to a specific field on other papers pertaining to different fields. This information is essential to determine whether a paper has been co-opted by papers in another field. This also allows us to trace the bibliographic properties of the citing publications.

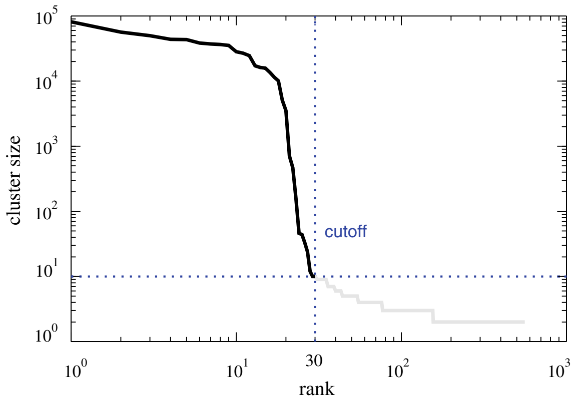


Fig. 1 Cluster size versus rank. The number of APS articles in a cluster as a function of the rank of the clusters. Clusters were detected by the Louvain algorithm applied to the citation network. We cluster all articles appeared in APS from 1893 to 2017. In our analysis, we remove the articles belonging to clusters with less than 10 articles. These removed clusters constitute a few percent of all articles

2.1 Quantifying Exaptation

To quantify the idea of functionality, we define a quantity that we call *forward normalised entropy* (FNE), S_i, of a generic article a_i. In Fig. 2, we consider the articles citing a_i (red circle), each belonging to a cluster, C_n, here we use all papers published in APS until 2017. Denoting by A_i the set of articles citing a_i and by C_n the clusters in the system, we define $p_{i,n} = |C_n \cap A_i|/|A_i|$. In other words, $p_{i,n}$ is the fraction of articles citing the reference article a_i, that belong to cluster C_n. We define the normalised forward entropy, S_i, as:

$$S_i = -\frac{1}{\log N_i} \sum_{n=1}^{N_i} p_{i,n} \log p_{i,n} \ , \tag{1}$$

where N_i is the number of clusters for which $p_{i,n} > 0$. We call S_i a forward entropy because it is computed based on articles published after a_i and citing a_i.

It gives information on how heterogeneous the composition of the citing articles is in terms of cluster composition. If an article is cited by articles belonging to only one cluster, i.e. it belongs to a well-defined scientific field, $S_i = 0$. If a paper has $S_i = 1$, then its citations are uniformly distributed among different areas. Therefore, the forward entropy can be thought of as a score for interdisciplinary impact.

To estimate the effective number of clusters from which the paper a_i received citations, we consider the Inverse Participation Ratio (IPR) I_i of article a_i:

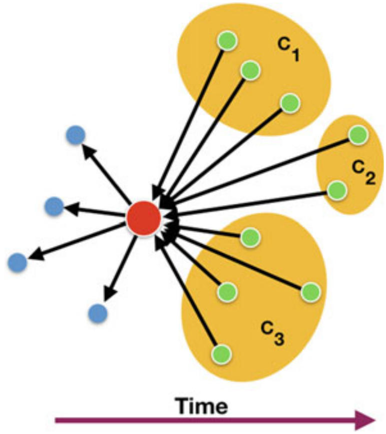


Fig. 2 Definition of normalised forward entropy cartoon. Circles represent published articles and arrows stand for citations. Only those articles and links are displayed, which are relevant for the entropy definition. The article a_i denoted with the large red circle cites four papers (blue circles at its left side) and has been cited by nine papers (green circles on its right side). These nine articles belong to three different clusters C_n depicted as orange ovals. Denoting with p_n the fraction of articles of cluster n in the whole citation pool of the red article, we have $p_1 = 1/3$, $p_2 = 2/9$ and $p_3 = 4/9$. According to Eq. (1), the normalised forward entropy is then $S_i = (-1/3 \log 1/3 - 2/9 \log 2/9 - 4/9 \log 4/9)/ \log 3 \approx 0.966$. The IPR for a_i is $I_i \simeq 2.79$

$$I_i = \left(\sum_{n, p_{i,n}>0} (p_{i,n})^{-2} \right)^{-1} . \tag{2}$$

Its value approximates the number of effective clusters citing a_i. We calculate the forward entropy and IPR for every year, by considering only those articles published in a given year, and citing a_i. In this way, we can follow the trajectory of an article over time, keeping track of the scientific areas it belonged to.

3 Results

We considered all publications in the APS database until 2017 and selected the top 200 most cited ones. The reasons for using highly cited publications are both conceptual and pragmatic. First, we assume that exaptation results from the significant adoption or acknowledgement of a paper. This implies that a co-opted publication should have a high citation impact. Second, a large number of citations enhances the statistical significance of the results. To identify distinctive patterns of exaptation, we looked at the yearly number of citations versus the forward normalised entropy (FNE), S_i, and the IPR, I_i, for all articles. We present a few examples with a well-defined signature of exaptation.

Before that, let us clarify how this pattern should ideally look like. A good candidate article for exaptation, say a_{ex}, ideally belongs to a well-established field and is disciplinary in nature. If the paper initially received citations only by papers in the same scientific sub-field, then its FNE score, S_i, would be zero. We hypothesise that at some point in time, the number of citations to a_{ex} starts increasing and possibly remains in the same scientific sub-field. At a later stage, the article may start receiving citations by papers from other scientific sub-fields, causing S_i to increase. The very fact that papers are co-opted in another scientific sub-domain also brings more citations to a_{ex}. If the new citing domain is highly productive, i.e., with many published papers, then S_i may eventually decline, as most of the citations will now come from the new citing field, overshadowing the original one. Eventually, while the citation rate of the paper will start to decrease as a natural consequence of ageing, its FNE, on the contrary, may increase slightly as other fields may become interested in the article and grow in relative importance.

The paper *The band theory of graphite*, published in 1947 Wallace (1947) seems to follow the hypothesised pattern of exaptation. Before taking a closer look, let us first dig into the graphene background. Graphite is a material made up of carbon atoms arranged in parallel hexagonal layers. Like the diamond, it is an allotropic form of carbon. While graphite is a conductor at room temperature, the diamond is an insulator. To understand why the carbon atoms with different crystal geometries are conducting or insulating it is necessary to understand how electrons behave once an electrical potential is applied. One of the great success of quantum mechanics was the possibility to understand these phenomena. The electronic structure of simple materials became computable right after the formalism of quantum mechanics was established. The geometry of graphite suggests that its electronic properties can be incrementally determined by first analysing a single layer of carbon—what is today known as *graphene*—and then by considering the mutual interaction between layers. As Wallace wrote in his manuscript Wallace (1947):

> Since the spacing of the lattice planes of graphite is large (3.37Å) compared with the hexagonal spacing in the layer (1.42Å), a first approximation in the treatment of graphite may be obtained by neglecting the interactions between planes, and supposing that conduction takes place only in layers.

Wallace did not consider the possibility that a hexagonal layer of carbon atoms could exist by itself and used it as a mere tool to solve the "more complicated" problem for the three-dimensional graphite. As recently pointed out in a review essay on graphene Castro Neto (2009):

> It was P. R. Wallace, who in 1946 wrote the first papers on the band structure of graphene and showed the unusual semi-metallic behaviour in this material (Wallace 1947). At that point in time, the thought of a purely 2D structure was a mere fantasy and Wallace's studies of graphene served him as a starting point to study graphite, a very important material for nuclear reactors in the post-World War II era.

Let us see now why the seminal paper of Wallace on graphene can be considered an example of exaptation according to the pattern highlighted above. Figure 3, shows two panels of the yearly number of citations versus the forward normalised entropy

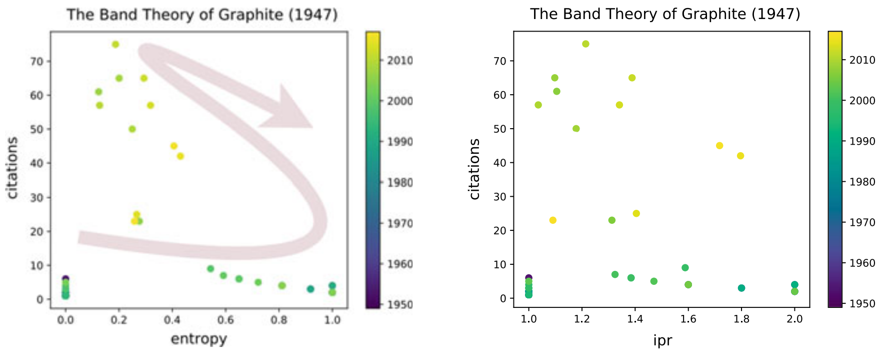


Fig. 3 A typical pattern for exaptation of an important paper. Left: yearly number of citations vsersu the forward normalised entropy of the paper of Wallace (1947). Each circle represents a different year, and the time-evolution is marked with a colour code, from dark tones (older) to light ones (newer). The ideal dynamics of citations and entropy over time for an exapted paper is also depicted by a thick arrow. The paper starts in one field ($S_i = 0$), then is exapted in another field leading to an increase of S_i; then, citations grow since the paper gets more popular while S_i decreases, since the new field prevails; eventually, the number of citations decreases as an ageing effect while S_i increases again, since the paper is rediscovered in the older field. Right: yearly number of citations versus IPR of Wallace (1947)

Fig. 4 Word clouds of the two communities citing Wallace's paper. WordClouds (2020) were generated by merging all the titles belonging to the main two clusters citing the graphite/graphene article. Stop words, numbers and punctuation marks were removed. Font size is proportional to the logarithm of the number of occurrences of words. The composition of the main cluster (graphene) with 613 articles citing Wallace's graphite article Wallace (1947) is shown on the left; the second important cluster (electronic structure properties) with 33 articles is on the right

(FNE) S_i (left), and the IPR, I_i (right). The paper starts with a small number of citations and a very small FNE (bottom-left corner of the plot in the left panel). After that, the pattern follows a very peculiar "S-shaped" trajectory, mirroring the following three situations: (i) the adoption by another field leading to an increase of S_i, (ii) the growth in the number of citations while S_i decreases, (iii) the decrease of the number of citations while S_i increases again.

This suggests that Wallace's article that was meant to belong to the field of electronic structure properties (ESP), was later co-opted in the graphene research field. According to the cluster analysis, the ESP field contains approximately 12,000 articles and the much more recent graphene area contains about 5,000 articles. Despite the larger number of articles in ESP, Wallace's paper has been cited mostly by the graphene community (613 times), and much less from the ESP (33 times). The forward normalised entropy of this paper follows the exaptation pattern we assumed. Its IPR pattern (Fig. 3 (right panel)) demonstrates how it switched from the ESP to the graphene community. To visualise the differences between the two ESP and graphene communities, in Fig. 4 we show two word-clouds from the articles citing Wallace's paper: from the graphene community (left) and the ESP one (right).

We found 10 additional articles whose FNE and IPR patterns are similar to those of the graphite/graphene paper. Among those, we mention two notable examples, i.e. *Motion of Electrons and Holes in Perturbed Periodic Fields* Luttinger and Kohn (1955) and *Quantized Hall Conductance in a Two-Dimensional Periodic Potential* Thouless et al. (1982). A third article, that was not in the list of the most 200 cited papers but was highly cited from outside the APS, was chosen on the basis of our personal experience, *Spin Echoes* Hahn (1950). The first Luttinger and Kohn (1955), is mainly cited by articles belonging to two clusters, the "Quantum dots / Quantum wells" cluster (QDQW) and the ESP cluster. These clusters are denoted by id = 8 and id = 1 respectively, and their mutual importance is sketched in the plots on the right panels of Fig. 5. Note how after 1980, the QDQW cluster starts to become more important than ESP, so that Luttinger and Kohn (1955) acquires more importance in that field. A similar situation occurs with reference Thouless et al. (1982) (second row of the panel), where now the graphene cluster (id = 16) competes with the QDQW cluster. Interestingly, from year 2010 on, also the "Bose-Einstein condensate" cluster (id = 12) starts to get some importance.

The third paper on spin echoes was chosen since we expected its importance on Nuclear Magnetic Resonance (NMR) would become prominent in time (third row of the panel). We do not observe a clear NMR cluster in APS, rather we find an exaptation pattern, where the "Entanglement" cluster (id = 7) emerges on the detriment of the QDQW cluster (id = 8), as shown in the bottom right panel. We think that the NMR community cites this paper from outside the APS community, i.e. by papers not published by the APS journals.

Although not directly related to the problem of detecting exaptation in APS articles, it is worthwhile looking at the time evolution of the FNE and the IPR for review articles. We observe the same kind of pattern consistently in all highly cited APS review papers. As an example, we show the Chandrasekhar's review *Stochastic problems in physics and astronomy* Chandrasekhar (1943); the corresponding plots for FNE and IPR are reported in Fig. 6. Both FNE and IPR increase over time, witnessing the number of different scientific fields interested in the review. The manuscript itself Chandrasekhar (1943) features four chapters, the problem of random flights, the theory of the Brownian motion, probability after effects, and probability methods in stellar dynamics. The IPR value reaches the value four soon and oscillates around it in time. On the other hand, the FNE, after reaching its maximum value, starts to

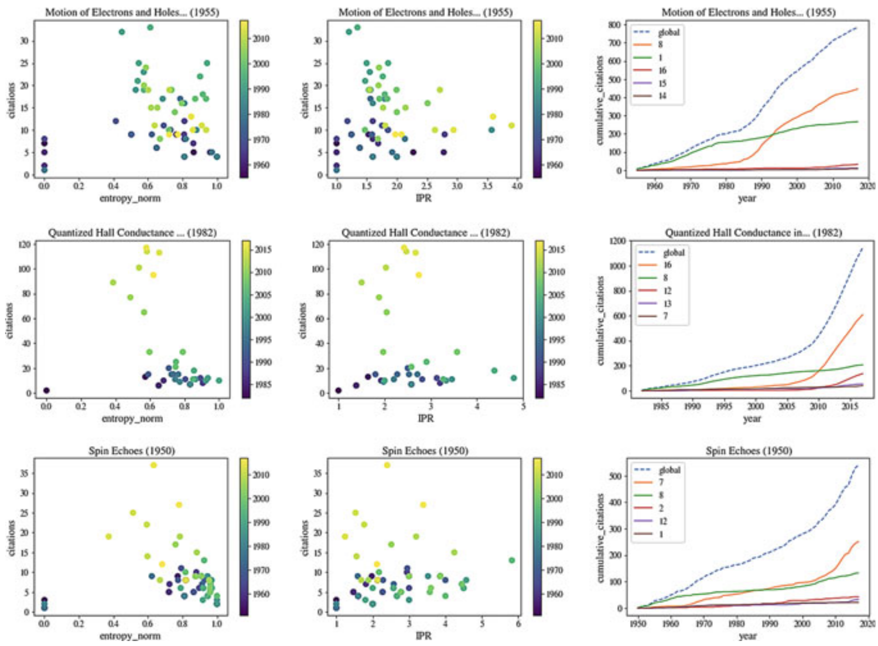


Fig. 5 More examples of exaptation patterns. Three articles are shown: Luttinger and Kohn (1955), Thouless et al. (1982), Hahn (1950), one in each row. In the left and centre panels, we display their citation versus FNE and IPR, respectively. Patterns are similar to what was found in Fig. 3. In panels to the right, we show the time evolution of their cumulative citations in the respective clusters, whose id number is given in the legend. Their vertical order reflects their ranking in 2017, i.e. their relative importance in citing the selected paper

decrease, mainly because one citing field increases its importance over the others. The IPR and FNE behaviour of highly cited reviews is essentially different from the patterns found for co-opted articles presented in Figs. 5 and 3. This finding further reassures us of the robustness of the proposed indicators, as well as of the overall methodology.

4 Discussion

The concept of exaptation has not been appropriately quantified. Only very few systematic quantitative analyses are available in the literature. Here we focused on the exaptation phenomena in the framework of scientific progress as it can be observed in the APS article collection database. Our approach consists of looking for signatures of exaptation in the adoption (as reflected in citation patterns) of specific results by other scientific communities than the original scientific area of belonging. To make the analysis quantitative, we propose a method based on two main components:

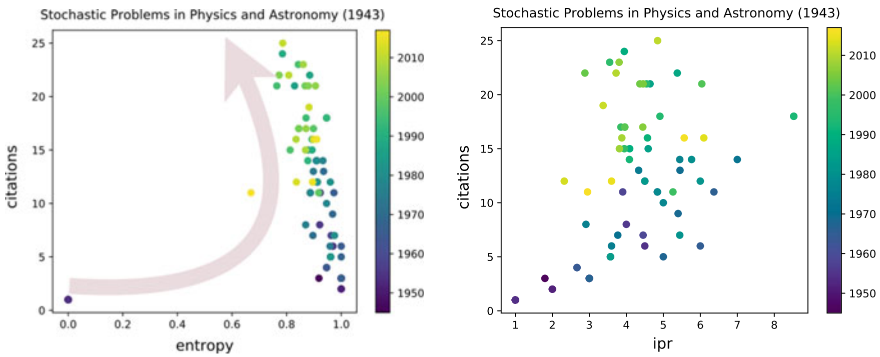


Fig. 6 FNE and IPR pattern for a typical review article in APS. Review articles exhibit a distinctive dynamical behaviour slightly different than the exaptation patterns discussed in Figs. 3. and 5. Left: the forward normalised entropy increases quickly and remains at high values over time, while the number of citations per year grows. Right: the number of clusters citing a review article grows over time showing an increased interest in several sub-disciplines

clustering of publications based on citation relations, and two observables, the Forward Normalised Entropy (FNE) and the Inverse Participation Ratio (IPR). These measures allow to single out patterns that are related to the exaptation phenomena in scientific evolution.

The evolution of feathers is a classical example of exaptation. Feathers were initially adapted to protect against thermal excursions and were later co-opted for flying. As soon as birds learn to fly, their fitness improves since they have higher chances of surviving predators. We extend this reasoning with a thought experiment (*Gedanken-experiment*) to the exaptation of scientific knowledge, where citations represent the fitness and the inverse participation ratio represents the number of functions a publication acquires over time. The example of graphene constitutes a popular instance of exaptation in physics, particularly in contributing to the development of two related sub-fields, electronic structure properties, and graphene. It shows that the 'survival' of a field depends on how pre-existing concepts are re-used or applied by communities in new domains resulting in new functionalities.

These results should be seen as preliminary steps towards a quantitative theory of exaptation; they show that is in principle possible to quantify exaptation, once it becomes possible to get a quantitative handle on the evolving context of a field. A better theory of exaptation is necessary to explain how something emerges and evolves by exploring its *creative potential* Andriani and Cattani (2016). The creative potential has been described as the functional shift of a particular component that could open up an evolutionary path different from its original and perhaps intentional trajectory Andriani and Cattani (2016), Kauffman (1993). We think that this paper could stimulate a new wave of studies in this promising area of scientific research.

Acknowledgments This work was supported by the Austrian Research Promotion Agency FFG under grant 857136.

References

Andriani P, Ali A, Mastrogiorgio M (2017) Measuring exaptation and its impact on innovation, search, and problem solving. Organ Sci 28(2):320–338

Andriani P, Cattani G (2016) Exaptation as source of creativity, innovation, and diversity: introduction to the special section. Ind Corporate Change 25(1):115–131

Andriani P, Cohen J (2013) From exaptation to radical niche construction in biological and technological complex systems. Complexity 18(5):7–14

APS Data Sets for Research. http://journals.aps.org/datasets

Arthur WB (2007) The structure of invention. Res Policy 36(2):274–287

Barve A, Wagner A (2013) A latent capacity for evolutionary innovation through exaptation in metabolic systems. Nature 500(7461):203

Blondel VD, Guillaume J-L, Lambiotte R, Lefebvre E (2008) Fast unfolding of communities in large networks. J Sat Mech Theor Exp 2008(10):P10008

Bock WJ (1959) Preadaptation and multiple evolutionary pathways. Evolution 13(2):194–211

Bonifati G (2010) 'More is different', exaptation and uncertainty: three foundational concepts for a complexity theory of innovation. Econ Innov New Technol 19(8):743–760

Castro Neto AH, Guinea F, Peres NMR, Novoselov KS, Geim AK (2009) The electronic properties of graphene. Rev Mod Phys 81:109–162

Cattani G (2005) Preadaptation, firm heterogeneity, and technological performance: a study on the evolution of fiber optics, 1970–1995. Organ Sci 16(6):563–580

Chandrasekhar S (1943) Stochastic problems in physics and astronomy. Rev Mod Phys 15:1–89

Cohen WM, Levinthal DA (1990) Absorptive capacity: a new perspective on learning and innovation. Administr Sci Q 35(1):128–152

Darwin C (2004) On the origin of species, 1859. Routledge

Dew N, Sarasvathy SD (2016) Exaptation and niche construction: behavioral insights for an evolutionary theory. Ind Corporate Change 25(1):167–179

Dew N, Sarasvathy SD, Venkataraman S (2004) The economic implications of exaptation. J Evol Econ 14(1):69–84

Dewar RD, Dutton JE (1986) The adoption of radical and incremental innovations: an empirical analysis. Manag Sci 32(11):1422–1433

Erwin DH, Krakauer DC (2004) Insights into innovation. Science 304(5674):1117–1119

Fleming L, Sorenson O (2004) Science as a map in technological search. Strateg Manag J 25(8–9):909–928

Gabora L, Scott EO, Kauffman SA (2013) A quantum model of exaptation: incorporating potentiality into evolutionary theory. Progress Biophys Molecul Biol 113(1):108–116

Gould SJ, Vrba ES (1982) Exaptation—a missing term in the science of form. Paleobiology 8(1):4–15

Hahn EL (1950) Spin echoes. Phys Rev 80:580–594

Hidalgo CA, Hausmann R (2009) The building blocks of economic complexity. Proc Natl Acad Sci 106(26):10570–10575

Kauffman SA (1993) The origins of order: self-organization and selection in evolution. OUP USA

Kauffman SA (2000) Investigations. Oxford University Press

Klavans R, Boyack KW, Sorensen AA, Chen C (2013) Towards the development of an indicator of conformity. In 14th international society of scientometrics and informetrics conference. ISSI

Klimek P, Hausmann R, Thurner S (2012) Empirical confirmation of creative destruction from world trade data. PloS ONE 7(6):e38924

Klimek P, Thurner S, Hanel R (2010) Evolutionary dynamics from a variational principle. Phys Rev E 82:011901

Kuhn TS (1962) The structure of scientific revolutions. Chicago and London

Larivière V, Gingras Y (2010) On the relationship between interdisciplinarity and scientific impact. J Am Soc Inf Sci Technol 61(1):126–131

Larivière V, Haustein S, Börner K (2015) Long-distance interdisciplinarity leads to higher scientific impact. Plos One 10(3):e0122565
Levinthal DA (1998) The slow pace of rapid technological change: gradualism and punctuation in technological change. Ind Corporate Change 7(2):217–247
Levitt JM, Thelwall M (2008) Is multidisciplinary research more highly cited? a macrolevel study. J Am Soc Inf Sci Technol 59(12):1973–1984
Lloyd EA, Gould SJ (2017) Exaptation revisited: changes imposed by evolutionary psychologists and behavioral biologists. Biol Theor 12(1):50–65
Loreto V, Servedio VDP, Strogatz SH, Tria F (2016) Dynamics on expanding spaces: modeling the emergence of novelties. In: Creativity and universality in language, pages 59–83. Springer
Luttinger JM, Kohn W (1955) Motion of electrons and holes in perturbed periodic fields. Phys Rev 97:869–883
Mokyr J (1991) Evolutionary biology, technological change and economic history. Bull Econ Res 43(2):127–149
Newman MEJ (2009) The first-mover advantage in scientific publication. EPL (Europhys Lett) 86(6):68001
Rinia EJ, Van Leeuwen TN, Van Raan AFJ (2002) Impact measures of interdisciplinary research in physics. Scientometrics 53(2):241–248
Rogers EM (2010) Diffusion of innovations. Simon and Schuster
Rosenman MF (1988) Serendipity and scientific discovery. J Creative Behav 22(2):132–38
Schumpeter JA (1939) Business cycles, volume 1. McGraw-Hill New York
Servedio VDP, Buttà P, Mazzilli D, Tacchella A, Pietronero L (2018) A new and stable estimation method of country economic fitness and product complexity. Entropy 20(10):783
Stephan P, Veugelers R, Wang J (2017) Reviewers are blinkered by bibliometrics. Nat News 544(7651):411
Sugimoto CR, Larivière V (2018) Measuring research: what everyone needs to know. Oxford University Press
Tacchella A, Cristelli M, Caldarelli G, Gabrielli A, Pietronero L (2012) A new metrics for countries 'fitness and products' complexity. Sci Reports 2:723
Tan SY, Tatsumura Y (2015) Alexander fleming (1881–1955): discoverer of penicillin. Singapore Med J 56(7):366
Thouless DJ, Kohmoto M, Nightingale MP, den Nijs M (1982) Quantized hall conductance in a two-dimensional periodic potential. Phys Rev Lett 49:405–408
Thurner S, Klimek P, Hanel R (2010) Schumpeterian economic dynamics as a quantifiable model of evolution. New J Phys 12(7):075029
Thurner, Liu W, Klimek P, Cheong SA (2019) The role of mainstreamness and interdisciplinarity for the relevance of scientific papers. arXiv:910.03628
Tria F, Loreto V, Servedio VDP, Strogatz SH (2014) The dynamics of correlated novelties. Sci Reports 4:5890
Uzzi B, Mukherjee S, Stringer M, Jones B (2013) Atypical combinations and scientific impact. Science 342(6157):468–472
Van Raan AFJ (2004) Sleeping beauties in science. Scientometrics 59(3):467–472
Wagner CS, Roessner JD, Bobb K, Klein JT, Boyack KW, Keyton J, Rafols I, Börner K (2011) Approaches to understanding and measuring interdisciplinary scientific research (IDR): a review of the literature. J Info 5(1):14–26
Wallace PR (1947) The band theory of graphite. Phys Rev 71:622–634
Watson P (2017) Convergence: the idea at the heart of science. Simon and Schuster
WordClouds.com. Free online word cloud generator and tag cloud creator. http://wordclouds.com. Accessed Jan. 2020

Exaptation and Beyond: Multilevel Function Evolution in Biology and Technology

Pierpaolo Andriani, Christine Brun, Giuseppe Carignani, and Gino Cattani

1 Introduction

Since the publication of Charles Darwin's *On the Origin of Species* (1859), social scientists have attempted to build analogies to extend Darwinian evolution beyond organic evolution and turn it into a more general—in some cases even universal—explanatory framework. Although some abstract principles (e.g. mutation or random variation, selection) from Darwin's model of biological evolution can be used to explain the phenomena of cultural (socio-economic) evolution (Campbell 1975), the conceptual challenges of developing plausible analogies have hindered such attempts. Penrose (1952) was among the first to openly voice her skepticism arguing that the social scientist 'would be well advised to attack his problems directly and in their own terms rather than indirectly by imposing sweeping biological models upon them' (Penrose 1952: 819). Penrose's critique was premised on the belief that, despite some surface similarity between organic and cultural evolution, the underlying structures and processes are substantively different.

A contribution to our chapter of the book 'Understanding innovation through exaptation'.

P. Andriani
Kedge Business School, Rue Antoine Bourdelle, Domaine de Luminy BP 921, 13288 Marseille, France

C. Brun
Aix-Marseille University, TAGC, CNRS, INSERM UMR_S1090, Marseille 13009, France

G. Carignani
Department of Economics and Statistics, University of Udine, Via Tomadini, 30/a, Udine, EU, Italy

G. Cattani (✉)
Department of Management and Organizations, Stern School of Business – NYU, 40 West 4th Street, Tisch Hall, Suite 7–14, New York 10012, NY, USA
e-mail: gcattani@stern.nyu.edu

C. AM. La Porta et al. (eds.), *Understanding Innovation Through Exaptation*,
The Frontiers Collection, https://doi.org/10.1007/978-3-030-45784-6_6

In a similar vein, several evolutionary economists and technology historians (Schumpeter 1911; Usher 1929; Nelson and Winter 1982; Rosenberg 1982; Basalla 1988; Arthur 2009) have emphasized how technological innovation has 'Lamarckian' features which 'are normally considered to be forbidden in biology' (Ziman 2000: 5). The apparent *Lamarckism* of technological change is so evident that in building an evolutionary theory of economic change Nelson and Winter (1982) explicitly acknowledged: 'It is neither difficult nor implausible to develop models of firm behavior that interweave "blind" and "deliberate" processes. Indeed, in human problem solving itself, both elements are involved and difficult to disentangle. Relatedly, our theory is *unabashedly Lamarckian*: it contemplates both the "inheritance" of acquired characteristics and the timely appearance of variation under the stimulus of adversity' (Nelson and Winter 1982: 10–11, emphasis added). Yet the fascination with analogies that extend Darwinian evolution beyond organic evolution remains strong.

One of the main problems with previous attempts to build analogies is that they are rooted in the canonical Darwinian evolutionary model as represented in the universal tree of life. But new development in evolutionary biology, such Woese's horizontal gene transfer (HGT), Niche construction (Odling-Smee et al. 2003) and Endosymbiosis (Margulis and Sagan 2002), have complemented the canonical Darwinian model. In the following, we will focus on Woese's model and highlight the Horizontal Gene Transfer as one of the fundamental forces driving evolution (Woese 2002, 2004). When HGT is a major evolutionary force, the structure of organisms 'is necessarily modular' and 'simple and loosely organized' (Woese 2002: 8746). Embedding specific functions in discrete modules allows 'the core function of a module to be robust to change, but allows for changes in the properties and functions of a cell by altering the connections between different modules' (Hartwell et al. 1999: C48). By unveiling the existence of structures and processes in the evolution of living organisms that exhibit striking resemblance with those observed in the evolution of cultural artifacts, the analogue of functional modules, it is now possible to reconcile critical—and long debated—differences between cultural and organic evolution.

Our goal in this paper is to discuss some of the substantive similarities underneath the surface similarity between biological and cultural evolution. We start with two exemplary cases that reveal the critical role of function and functional shift for understanding organic and cultural evolution. Next, we discuss the centrality of function and, in particular, multifunction in biology and its implication for understanding the role of exaptation in the evolution of complex organismal systems. We then examine how exaptation constitutes a powerful lens through which technological evolution can be studied, and explain how the key mechanisms responsible for the occurrence of exaptive events, within the context of technology, are very similar to those at work in biology. We conclude by emphasizing how a new extended analogy between biological and cultural evolution is now possible.

2 Two Exemplary Cases

2.1 A Biological Revolution: Breathing Animals

Every breathing animal (human or non-human) is the descendent of a fish that evolved a respiratory apparatus, which is itself a complex system. When the theory of evolution was not yet supported by compelling genetic discoveries, the origins of such complex systems constituted a major difficulty on any gradualist evolutionary theory, including Darwin's theory of 'descent with modification'. The objection, raised with great clarity by Catholic biologist St John Mivart, posited that natural selection could hardly explain the early evolutionary stages of complex organs because these organs can improve the fitness of an organism only when they are functional (Mivart 1871).[1] Concerned with this *difficulty on theory*,[2] Charles Darwin cautiously advanced a hypothesis on the origins of lungs, in a paragraph titled '*Organs of extreme complexity and perfection*', as follows:

> The illustration of the swimbladder in fishes is a good one, because it shows us clearly that an organ originally constructed for one purpose, namely flotation, may be converted into one for a wholly different purpose, namely respiration … The swimbladder is homologous, or ideally similar, in position and structure with the lungs of the higher vertebrate animals: hence there seems to me to be no great difficulty in believing that natural selection has actually converted a swimbladder into a lung, an organ used exclusively for respiration (Darwin 1859: 190).

Here Darwin invokes a hypothetical evolutionary phenomenon of '*purpose shift*' in order to provide an answer to Mivart's critique. He 'defined this process '*the wonderful metamorphoses in function*' (see the summary of Chap. 6 of 'Origin of Species, 1859). The concept was later defined 'preadaptation' by French naturalist Lucien Cuénot (1914) to refer to traits whose functional shift increases the fitness of an organism. Gould and Vrba (1982) relabeled the associated process as *exaptation*. According to recent research, *'the air-breathing apparatus of tetrapods has its origin in gill breathing'* rather than in swim bladders (Perry and Sander 2004, in the abstract). Nevertheless, Darwin's intuition was correct as critical phases in the evolution of tetrapods' respiratory apparatuses are indeed explicitly recognized as exaptations.[3]

---

[1] 'Natural Selection, simply and by itself, is potent to explain the maintenance or the further extension and development of favourable variations, which are at once sufficiently considerable to be useful from the first to the individual possessing them. But Natural Selection utterly fails to account for the conservation and development of the minute and rudimentary beginnings, the slight and infinitesimal commencements of structures, however useful those structures may afterwards become' (Mivart 1871: 24).

[2] Difficulties on theory is the title of Chap. VI of Darwin's Origins of Species (1859).

[3] For instance, according to Perry and Sander (2004) the presence of long ribs in early amphibians could suggest the early 'preadaptation' (exaptation) of the amphibian ancestors of amniotes to a fully terrestrial life.

2.2 A Technological Revolution: The Bow-and-Arrow

The successful dispersal of Homo Sapiens out of Africa provoked the extinction of all other competing Homo species, including the Neanderthal, native inhabitants of Europe. The invasion of the Homo Sapiens individuals was supported by a novel revolutionary technology the Homo Sapiens individuals brought with them: the bow-and-arrow. '*If they were armed with the bow and arrow*', paleoanthropologist Sally McBrearthy writes about our Sapiens ancestors, '*they would have been more than a match for anything or anyone they met*' (McBrearthy 2012: 532).

A bow-and-arrow is a composite artifact, made of two main *functional modules*: the *bow*, a flexible rod or stave made of wood or other elastic material, bent and held in tension by a string, and the *arrow*, a thin wooden shaft whose business end, the *arrowhead*, was made of stone in early arrows). The arrow is fitted to the string by a *notch* and drawn back until enough elastic energy is stored in the bow so that when released it will launch the small, light arrow at high speed. Precious little physical evidence of early bow-and-arrows remains: most components of the weapon—made of perishable materials—rarely survive. However, the hard evidence provided by the only surviving components—the arrowheads—document the introduction of bow-and-arrow technology with great confidence and precision. A technological discontinuity is clearly detectable by measuring the engineering attributes of the arrowheads (e.g. angles), a methodology typical of evolutionary archeology (Fig. 1).

The invention of the bow-and-arrow is documented in several different places and ages. However, in the case of the emigration of Homo Sapiens individuals out of Africa it became a critical technology, due to the characteristics of the changing environment both Homo Sapiens individuals and Neanderthal were facing, and in particular climate changes leading to dwindling numbers of big game, the typical

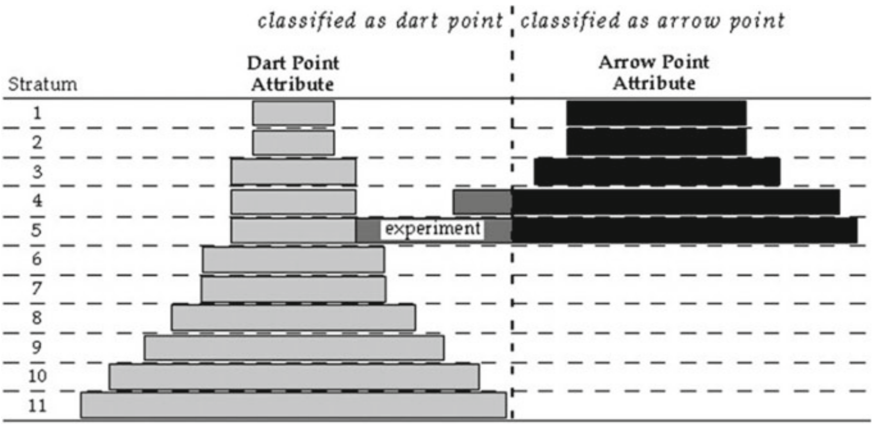


Fig. 1 The invention and successful introduction of bow-and-arrow technology is detectable in stratum 5 where the divergence between dart points engineering attributes and arrow points attributes generates a separate 'design space' (Adapted from Lyman et al. 2008)

preys of Neanderthals. The availability of a lightweight, accurate and powerful alternative to contemporary hand-delivered weaponry gave the humans who invented it as a decisive competitive advantage over other human species. The bow-and-arrow was selected by the harsh environment as a best-fitting hunting weapon not just for the limited increase in range, but more so for giving a single hunter the possibility of shooting many arrows in fast sequence with good accuracy and enough penetrating power to kill or wound small and medium-sized animals, following them over long distances on difficult terrain (Lombard and Phillipson 2010).

Notwithstanding the extraordinary importance of the invention and diffusion of this weapon, only recently have the mechanisms leading to its invention been understood. The origin of the arrow, as we saw, is easier to understand, since it was an adaptation of existing technologies, (e.g. hafting for connecting wooden sticks and stone tips, a technology mastered also by the Neanderthal). A primitive arrow is essentially a scaled-down spear or a modified dart. On the contrary, the origin of the other functional module—the bow—has long been uncertain. Concomitant archeological discovery (Lombard and Phillipson 2010) and novel evolutionary theories of technological change (Carignani 2016; Carignani et al. 2019) have recently shed new light also on the mechanisms leading to the whole composite artifact. According to new research and theory, the invention of the bow-and-arrow can be graphically depicted through the stylized phylogenetic graph shown in Fig. 2. The phylogenetic graph (or network) visualizes the evolutionary relationships between evolving objects, in this case, the bow (left side in figure) and the arrow (right side).

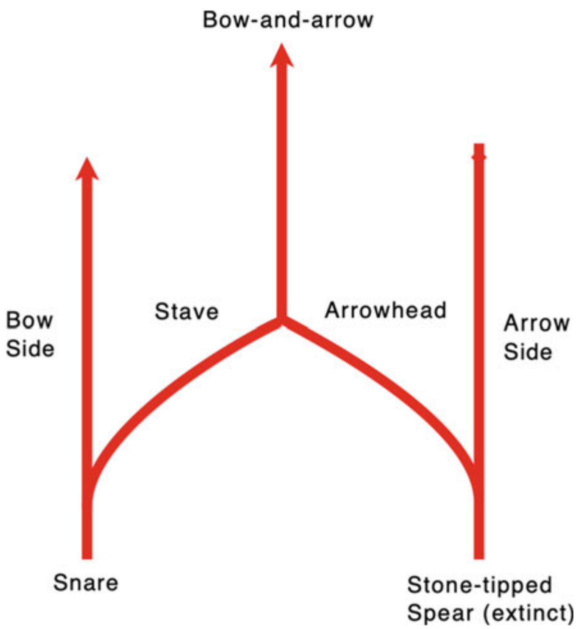


Fig. 2 The bow-and- arrow stylized phylogenetic graph. The recombination takes place at the intersection between the stave (bow) and the arrow directed arcs, from which the 'bow-and-arrow' emerges. The modular exaptation takes place in the left lower arc

Both the bow and the arrow arc represent the horizontal transfer of *preadapted* functional modules (Cattani 2006, 2008), critical for understanding the genesis of modular innovation. Lombard and Phillipson (2010) have demonstrated the presence of two kinds of different artifacts immediately preceding (or concomitant with) the bow-and-arrow invention, which they clearly suggest as possible sources of the bow functional module: they are the *snare*, a spring-trap used for capturing small animals, and the *bow-drill*, used for starting a fire or for piercing soft stone or bone. Both are a candidate to have provided the key functional module whose origin was previously unknown (the bow). Clearly, both were components of artifacts built for a completely different purpose (namely, drilling bone, starting a fire, or capturing small game).

The inception of the bow-and-arrow suggested by Lombard and Philippson seems straightforward: two artifacts already in existence were recombined by a creative early engineer originating a novel artifact. The exosomatic storage and subsequent fast release of elastic energy is the distinctive engineering principle of the bow-and-arrow and other mechanically projected weapons.[4] The inventor did not design (nor he or she really understood) the physics of storage of potential energy in an elastic medium: on the contrary, they found a component already *preadapted.* On the bow side, therefore, we can detect a concomitant phenomenon of *functional shift*: as the preadapted components are integrated into a novel architecture, the unknown Sapiens engineer who invented the bow-and-arrow stretched the performance of the existing components trying to reach the point whereby the minimum level of performance required of a new artifact to function is attained. The storage of elastic energy was the functioning principle of the snare; on the contrary, it was not requested by the bow-drill, in which the bow had the only function of providing an elastic force keeping the string in tension. In both cases, however, elastic energy storage was part of the component's *behaviour*, a key concept in engineering theory of design (Gero 1990).

These two exemplary cases could hardly be more different. Besides belonging to different domains (biology and technology), the case of the respiratory apparatus refers to an existing organism, while the bow-and-arrow involves the transfer of components from other industries. However, we recognize a structural property of different modular systems: *modularity* and the horizontal transfer of *functional modules* from other application domains—a characteristic process of technological transmission that was once considered a critical disanalogy between technological (and cultural) evolution but is now recognized as a full-fledged evolutionary mechanism also in biological evolution (Carignani et al. 2019). The connection between modularity and what Darwin poetically defined *the wonderful metamorphosis of functions* bears the promise of going beyond a local process of functional shift already studied in previous research on exaptation, to which we now turn.

---

[4]The atlatl (Shea and Sisk 2010) and a number of much more recent weapons, including ballistas, catapults and crossbows also belong to this class of artifacts.

3 Multilevel Functions and Their Evolution in Biology

3.1 Multilevel Function, a Vertical Description of Biological Complexity

In biology, the meaning of the word 'function' regularly calls for (re-)definitions. This is generally due to novel discoveries leading to the emergence of new concepts. Recently, the ENCODE debate provided the opportunity to distinguish between the meaning given to 'function' by evolutionary biologists compared to molecular geneticists. Whereas the former consider the 'function' of a genomic element to be the effect for which it has been evolutionarily selected at the organismal level, the latter rather envisage the 'function' as the causal role and activity of this element at a system level, with no regard to evolution (Doolittle et al. 2014; Graur et al. 2015; Keeling et al. 2019).

To sidestep the difficulties to connect, reconcile and eventually merge these conceptual and philosophical considerations (Doolittle et al. 2014), a 'function' interpretation and representation is still needed. The importance of the task lays in the necessity to better grasp the nuances of the term 'function' in order to convey and communicate—novel—biological results and ideas properly. Recently, the measurable properties of a molecular object have been proposed to describe its function through a hierarchy integrating the genetic information flow—Evolutionary implications, Physiological implications, Interactions, Capacities, Expression—(Keeling et al. 2019). To serve the same goal, a hierarchy of functional level descriptions with regard to biological structural and organizational levels, integrating nested biological entities has also been proposed—Populations, Organisms, Tissues-organs, Cells, Molecules (Brun et al. 2004; Jacq 2001; Oltvai and Barabasi 2002). In this hierarchy, the molecular function of a component corresponds to its biochemical activity whereas its cellular function is achieved thanks to its interactions with other molecular entities, generally having different molecular functions. The cellular function thus corresponds to the biological process(es) in which the component is involved (Fig. 3).

The robustness of phenotypes to genetic variations has been largely acknowledged (Henderson et al. 2016; Stelling et al. 2004; Wagner 2012). However, when a functional perturbation, change or shift occurs, the transition and its propagation from an organization level to another—from the molecule to the organism and the population onto which the selection can act—is still poorly understood despite the proposed frameworks. So does its influence at all functional levels that will ultimately impact the organism phenotype. Biological complexity, therefore, blurs our attempts to propose multilevel integrated descriptions of the biological functions.

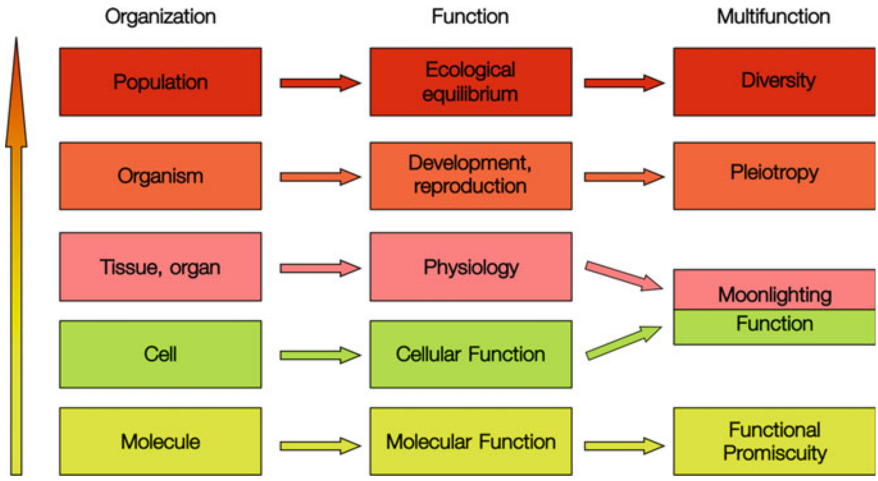


Fig. 3 Different integrative levels of organization, function and multifunction

3.2 Multifunction, an Attempt to Raise Complexity Horizontally

Genome size does not explain organismal complexity. To make more with less, different molecular mechanisms arose, such as alternative splicing that allows a single gene to encode several proteins, and protein multifunctionality that allows a single protein to play several different roles in cells. In both cases, the overall number of effects, activities, and functions performed is increased, therefore contributing to a rise in complexity. Like the notion of function, gene/protein multifunctionality can be defined at each of the organizational levels, ranging from the molecule to the population (Fig. 3).

At the molecular level, the catalytic promiscuity, i.e. the protein ability to catalyze both a primary substrate-specific function and a different secondary one, can account for multifunctionality. At the cellular level, gene products exerting regulatory roles are often termed ‘multifunctional’ since they play a role in multiple biological processes. However, in most cases, these proteins perform *the very same* molecular activity or function in a different spatio-temporal context, leading to different outputs, hence justifying their qualification of ‘multifunctional’. Another type of multifunctional proteins corresponds to a single protein able to perform multiple *unrelated* functions with no change in the polypeptide sequence. These have been named ‘moonlighting’ proteins (Jeffery 1999) by analogy to human individuals holding a second job in addition to a regular one, ‘multitask’ (Franco-Serrano et al. 2018) or ‘extreme multifunctional’ proteins (Chapple and Brun 2015; Chapple et al. 2015; Zanzoni et al. 2019). At the organismal level, when variations in a single locus lead to multiple phenotypes, a pleiotropic effect is detected (Hodgkin 1998). At the population level, the diversity of phenotypes is expressed. The population is indeed made of individuals of different genotypes, that may thereby have diverse phenotypes onto which the selection can act.

At the molecular and cellular levels, the regulation of the multiple activities and functions generally operates in space and time. Hence, the multiple functions of a biological entity either can be performed simultaneously or can switch or be revealed when triggered by cellular localization or environment changes. This tight regulation of the multiple activities and functions is likely to be important for the homeostasis of the biological systems. This leads to the question of the universality of multifunctionality at all organization levels, and its evolutionary history.

3.3 Multifunction at Multilevel, Multilevel Exaptations

How did multifunctionality emerge? Did the multifunctional character persist throughout evolution as a trait? Did multifunctionality evolve from 'monofunctionality' (i.e. from a biological entity having a single function)? Or conversely, does multifunctionality provide the raw material for a functional specialization? In a Darwinian framework, as natural selection operates on the organism and not directly on molecules such as proteins, functional changes in biological entities would be evolutionarily selected when they positively modify the organism's fitness. In this context, attempting to answer the previous questions would require detailing the possible evolutionary processes, a specialized task far beyond the scope of this review. Instead, we here consider 'multifunctionality' in the light of the evolutionary concept of 'exaptation' (Gould and Vrba 1982) that could help to understand the emergence of biological novelties and innovations. Indeed, in 1982, Gould and Vrba proposed that a character, 'evolved for other usages (or for no function at all), and later "coopted" for their current role, be called *exaptations*'. They are fit for their current role, hence *aptus*, but they were not designed for it, and are therefore not *ad aptus*, or pushed towards fitness. They owe their fitness to features present for other reasons, and are, therefore, *fit* (*aptus*) *by reason of* (*ex*) their form, or *ex aptus*' (Gould and Vrba 1982).

What is the relationship between multifunctionality and exaptation? Is multifunctionality generated by exaptation or is multifunctionality a reservoir for further exaptation and neofunctionalization, like gene duplication (Brosius 2019)? We here examine non-exhaustively the multifunctionality of biological entities at each organization level it occurs, with regards to their possible conditions of exaptation. Notably, the three first cases correspond to exaptations occurring within a single species. The following cases happen in different species:

1. **Exaptation by the recruitment of inherent physical properties**: eye lenses are made of proteins transparent when aggregated, therefore enabling the transmission of light. This inherent physical property of these proteins explains their exaptation as 'crystallins', irrespective of their other and evolutionarily selected

molecular functions. Indeed, they are metabolic enzymes in some species and chaperones in others (Piatigorsky and Wistow 1989).

2. **Exaptation of molecular functions**: catalytic promiscuity, that characterizes enzymes able to catalyze several reactions with the same catalytic site and different substrates, can lead to metabolic conflicts when involved in different pathways. However, a catalytic promiscuous (i.e. bi-functional) enzyme can compensate for a gene/activity loss, and therefore contribute to the evolvability of a novel missing function by exaptation, instead of constituting an evolutionary burden (Khersonsky and Tawfik 2010; Plach et al. 2016). Very interestingly, it has been demonstrated experimentally that such multifunctional enzymatic status can perpetuate without selection for very long time-spans (Plach et al. 2016).
3. **Exaptation of cellular functions**: moonlighting proteins performs multiple *unrelated* functions (Henderson et al. 2017; Jeffery 1999) at the cellular level, such as the enolase, a metabolic enzyme in the cytosol that also functions as a receptor involved in cell migration when located at the plasma membrane (Díaz-Ramos et al. 2012). For most of the moonlighting proteins, the manner with which their distinct functions can be performed, coordinated and regulated is largely unknown. In some cases, the capacity of a protein to perform several functions depends on (i) its content in particular small sequence motifs allowing the protein to have diverse interaction partners (Chapple et al. 2015; Zanzoni et al. 2019), and on (ii) its structural or oligomerization status (Jeffery 2014, 2018). Moreover, as moonlighting functions are often revealed and triggered by a modification in subcellular localization or an environmental change (e.g. healthy vs. pathological states), it, therefore, appears that the moonlighting/exapted function contributes to the homeostasis of the systems by responding to the new conditions, rather than indicating an evolution towards a specialization. Of note, the fact that moonlighting proteins (i) are present in all life kingdoms and (ii) have more moonlighting functions when they are evolutionarily ancient (Henderson et al. 2016), leads to propose that multifunctionality and thus, exaptation, is a very ancient mechanism.
4. **Exaptation of functional modules**: Biological processes are modular. In 1999, Hartwell et al. (1999) defined a functional module as 'a discrete entity whose function is separable from those of other modules', generally composed by several interacting molecular entities. Such a modular organization provides the cell both with the insulation and the connectivity necessary to performing cellular reactions. Finding that molecular interactions within functional modules are better conserved across species than those between functional modules, Zinman et al. proposed that a module involved in a cellular process in a species could act in another process in another species through interactions with other modules (Zinman et al. 2011). This possible exaptation at the module level interestingly reminds the urea cycle in mammals and the arginine synthesis in microbes. Both pathways use the same orthologous enzymes (Takiguchi et al. 1989) but performing different combinations of reactions (Wagner and Rosen 2014).
5. **Exaptation of organs**: as described in the introduction of this review, organs have been exapted through evolution, such as the fish swim bladder in respiratory

apparatus described by Darwin or the feathers evolved for temperature regulation in dinosaurs prior to their function in bird flight.

The quantitative estimation of the frequency of the exaptation events called by Gould and Vbra in their original publication is very difficult to obtain experimentally, as explained by (Barve and Wagner 2013). However, our attempt of a qualitative survey, although not exhaustive, highlights that biological systems, at all levels of integration of the biological function, can be exapted for further innovation.

4 The Role of Exaptation in Technological Evolution

The exemplary cases discussed earlier reveal that artifacts or traits designed or selected to play a certain function may, under certain circumstances, evolve or be co-opted for a different one, a process known as exaptation (Gould and Vrba 1982). Indeed, exaptation identifies a new (a third channel)[5] mechanism of novelty generation that is not dependent on the pull from clearly defined needs or on the development of implications of newly discovered phenomena (Andriani and Cattani 2016). In technology, exaptation constitutes a multistage and usually multilevel process (Andriani and Carignani 2014). This reflects the inherently multilevel, modular structure of technological systems.

The degree of modularity of a technological system is important to understand exaptation. Modularity is a systemic concept that describes how a system can be decoupled into subsystems (modules) that perform nearly independent functions. Simon (1962) refers to such systems as nearly decomposable. He further distinguishes between *horizontal* modularity, which refers to the tendency of systems to segregate their multiple components into dense, single-function modules, separated by weakly interdependent ties; and *vertical* modularity, which refers to the combination of lower level modules into more complex systems that become the intermediate forms in the construction of organisms and artifacts. The iteration of this process allows for the emergence of hierarchical complex systems, in which similar rules apply to each level, which limits the combinatorial complexity of highly connected systems.

The multilevel nature of technological systems together with the constraints set by vertical modularity generates the possibility that a functional shift at a modular level may result in selection at a higher level. For example, the 'pure turbojet' architecture required high-speed turbines, a characteristic reached in a different technological lineage (steam turbines) around 1900 when turbines that could 'provide power at the high rotational speed necessary for the turbocompressor's effective operation without requiring speed-multiplying gearboxes' (Constant 1980: 84) first appeared.

[5] Arthur (2009) argues that new functions and corresponding artifacts typically originate from one of the following two channels: the discovery of a new phenomenon in science and technology, which activates the exploration of the possibilities inherent in the new phenomenon and eventually results in the design and development of new artifacts and processes; the expression of a need that drives the formulation of functions that subsequently are translated into new artifacts.

This suggests that the existence of preadapted functional modules during the initial phase of recombinant innovation is 'largely independent of deliberate research efforts aimed at radical innovation, but is instead the result of technological spillovers from prior established and funded research' (Carignani et al. 2019: 520).[6] An exaptation can then occur when such modules are integrated into a novel architecture—i.e. they are co-opted into a new function via horizontal transfer—and inventors stretch their performance trying to reach the point whereby the minimum level of performance required of a new artifact to function is obtained. Like in the case of the pure turbojet, in the initial phases of design and prototyping of the novel artifact, the functional modules may be re-designed in order to attain the requisite performances.

It is then important to distinguish between *multilevel exaptation*—i.e. selection acts on a higher level module compared with the level at which the functional shift takes place; and s*ingle-level exaptation*—i.e. the selection process and functional shift occur at the same level. Hierarchical modularity then leads to a multilevel classification of exaptation (Andriani and Carignani 2014). In light of this distinction, we can identify the following types of exaptation:

- **External exaptation**: The exaptation of the whole artifact. A new function is discovered for an existing artifact, and the exapted artifact shows little or no variation with respect to the architecture of the original artifact or its internal modules. It is usually performed by users. In pharmaceuticals, this type of exaptation is pervasive (Andriani et al. 2017).
- **Internal exaptation**: The exaptation of a module of the artifact, while the artifact does not change its current function. It is usually performed by a designer or manufacturer to improve the performance of the artifact without changing its purpose. Users may not be aware of internal exaptations, especially if they happen at lower modular levels (e.g. tractor).
- **Radical exaptation**: An exaptation of an internal module of a system, leading through horizontal transfer to the emergence of a completely new system built around the exapted module (Carignani et al. 2019). The exaptation of an internal module thus leads to the emergence of a novel artifact with a new purpose. In a radical exaptation, the new function characterizes the core module and its system, leading to the emergence of a new market. There is no technological continuity between the two systems, apart from the exapted module (e.g. microwave oven).

A related question concerns the overall contribution of exaptation to technological change. We will briefly mention two aspects. First, does exaptation constitute a new type of discovery mechanism? The examples in the introduction show that exaptation may trigger the emergence of new evolutionary trajectories. The emergence of these new technological behaviours raises scientific and technological questions that forces science to catch up with exaptive discoveries (see, for example, the discoveries

[6] 'In the turbojet case the historical records show how initially the necessary 'preadapted' functional modules came both from the aero-engines industry and from diverse and hardly related technological lineages. For instance, in 1936 Power Jets' industrial partners were British Thompson-Houston, a manufacturer of heavy steam turbines for the electric industry, and Laidlaw, Drew and Company, a Scottish manufacturer of industrial burners' (Carignani et al. 2019: 523).

of antipsychotic and antidepressant drugs). In exaptive discovery, theory-follows-practice rather than the other way around. Second, what percentage of technological change can be ascribed to exaptation? If we restrict the analysis to the emergence of novel functions rather than new technologies per se, then an estimate exists that applies to the pharma sector: about a third of used functions exhibit an exaptive origin (Andriani et al. 2017). This estimate indicates that exaptation is a central mechanism in technological evolution.

5 Conclusion

The question of whether the structures and processes in living organisms are truly analogous to the structure and processes observed in the evolution of cultural artifacts has been contested. Historically, attempts to address this question have tried to establish to what extent technological—and, in general, cultural—evolution is inherently Darwinian and, therefore, the underlying evolutionary mechanisms are analogous. The analogy between biological and technological evolution is fascinating, but historically it has been challenged by critical disanalogies that ultimately have called into question both the validity of biological analogies and the insight we can derive from them. One of the main challenges of using analogies from evolutionary biology is to justify their significance in other fields. Recent developments in molecular biology suggest how most disanalogies haunting extant biological analogies of technological change may, in fact, disappear. By unveiling the similarity between the critical structures and processes in both the biological and cultural spheres these developments allow to overcome some of the conceptual limitations of previous organic-mechanical analogies.

Previous attempts to build analogies refer solely to the canonical Darwinian evolutionary model as represented in the universal tree of life. This model, however, only partly explains the initial phase of biological evolution—i.e. the evolution of cells—when the organic world was dominated by unicellular bacterial organisms. Recently, the 'Woesian' model has complemented the canonical Darwinian model by proposing pre-Darwinian Horizontal Gene Transfer (HGT) as the fundamental force driving cellular evolution (Woese 2002, 2004). This model identifies *horizontal gene transfer* (HGT) as a critical force that drives evolution and complements the Darwinian theory of vertical inheritance. The model describes the evolutionary phase preceding the so-called Darwinian Threshold, a critical discontinuity where the origin of species is located. Before the Darwinian Threshold, a modern type of genome replication mechanism did not yet exist, species had not yet emerged and HGT was the main force driving evolution—i.e. organisms exchanged their genes in a common gene pool freely via HGT instead of intra-lineage variation. Recent findings in microbiology further suggest that HGT operates even after the Darwinian Threshold (e.g. Kreimer et al. 2008; Woese and Goldenfeld 2009).

In their re-examination of the turbojet revolution, Carignani et al. (2019) have shown how two modules needed to make functioning turbojets—i.e. high-compression-rate centrifugal compressors and special high-temperature-resistant turbines—were external to the turbojet development efforts: unlike the internal combustion engine, the turbojet did not justify any investments in metallurgy or high-pressure compressors. This suggests that the horizontal transfer of *preadapted* functional modules (Cattani 2006, 2008) is critical for understanding the genesis of modular innovation.[7] A concomitant phenomenon of *modular exaptation* (Andriani and Carignani 2014) then takes place: as the preadapted components are integrated into a novel architecture, inventors then stretch their performance trying to reach the point whereby the minimum level of performance required of a new artifact to function is attained.

What emerges from the previous discussion is that exaptation is not an isolated evolutionary phenomenon, but instead an integral and important part of a generalized evolutionary process clearly emerging from the commonalities between the biological and in the technological domain. By uncovering multilevel and multifunctional features of exaptation in both organic and cultural (technological) evolution, it then becomes possible to overcome some of the conceptual limitations of previous organic-mechanical analogies that can be overcome. Interestingly, this implies that the flow of analogies, which early on moved from technology to biology and then from biology to technology—especially after the diffusion of Darwin's evolutionary theory (Basalla 1988)—might actually start to move in both directions at the same time.

References

Andriani P, Carignani G (2014) Modular exaptation: a missing link in the synthesis of artificial forms. Res Policy 43(8):1608–1620

Andriani P, Cattani G (2016) Exaptation as source of creativity, innovation, and diversity: introduction to the special section. Ind Corp Change 25(1):115–131

Andriani P, Ali A, Mastrogiorgio M (2017) Measuring exaptation and its impact on innovation, search, and problem solving. Organ Sci 28(2):320–338

Arthur WB (2009) The nature of technology. Free Press, New York

[7]The nature of 'preadaptation' is evident in the following technical report that explains how and why the battery was the critical functional module for the electric car that originated from the cell phone industry: 'Designed to use commodity, 18650 form-factor, Li-ion cells, the Tesla Roadster battery draws on the progress made in Li-ion batteries over the past 15 years. Under the market pull of consumer electronics products, energy and power densities have increased while cost has dropped making Li-ion the choice for an electric vehicle. In the past, to achieve such a tremendous range for an electric vehicle it would need to carry more than a thousand kilograms of nickel metal hydride batteries. Physically large and heavy, such a car could never achieve the acceleration and handling performance that the Tesla Roadster has achieved. Due to their high energy density, Li-ion batteries have become the technology of choice for laptops, cell phones, and many other portable applications' (Berdichevsky et al. 2006: 1).

Barve A, Wagner A (2013) A latent capacity for evolutionary innovation through exaptation in metabolic systems. Nature 500:203–206

Basalla G (1988) The evolution of technology. Cambridge University Press, Cambridge

Berdichevsky G, Kelty K, Straubel JB, Toomre E (2006) The tesla roadster battery system. Tesla motors report, August 16

Brosius J (2019) Exaptation at the molecular genetic level. Sci China Life Sci 62:437–452

Brun C, Baudot A, Guénoche A, Jacq B (2004) The use of protein-protein interaction networks for genome wide protein function comparisons and predictions. In: Methods in proteome and protein analysis. Springer, Berlin Heidelberg, pp 103–124

Campbell DT (1975) On the conflicts between biological and social evolution and between psychology and moral tradition. Am Psychol 30:1103–1126

Carignani G (2016) On the origin of technology: the invention and evolution of the bow and arrow. In: Panebianco F, Serrelli E (eds) Understanding cultural traits, a multidisciplinary perspective on cultural diversity. Springer, Berlin, pp 315–340

Carignani G, Cattani G, Zaina G (2019) Evolutionary chimeras: a Woesian perspective of radical innovation. Ind Corp Change 28(3):511–528

Cattani G (2006) Technological pre-adaptation, speciation and emergence of new technologies: how corning invented and developed fiber optics. Ind Corp Change 15(2):285–318

Cattani G (2008) Reply to Dew's (2007) commentary: pre-adaptation, exaptation and technology speciation: a comment on Cattani (2006). Ind Corp Change 17(3):585–596

Chapple CE, Brun C (2015) Redefining protein moonlighting. Oncotarget 6:16812–16813

Chapple CE, Robisson B, Spinelli L, Guien C, Becker E, Brun C (2015) Extreme multifunctional proteins identified from a human protein interaction network. Nat Commun 6:7412

Constant EW (1980) The origins of Turbojet revolution. Johns Hopkins University Press, Baltimore, MD

Cuénot L (1914) Théorie de la préadaptation. Scientia 16:60–73

Darwin C (1859) On the origin of species, 1st edn. John Murray, London

Díaz-Ramos A, Roig-Borrellas A, García-Melero A, López-Alemany R (2012) α-Enolase, a multifunctional protein: its role on pathophysiological situations. J Biomed Biotechnol 2012:156795

Doolittle WF, Brunet TDP, Linquist S, Gregory TR (2014) Distinguishing between "function" and "effect" in genome biology. Genome Biol Evol 6:1234–1237

Franco-Serrano L, Hernández S, Calvo A, Severi MA, Ferragut G, Pérez-Pons J, Piñol J, Pich Ò, Mozo-Villarias Á, Amela I et al (2018) MultitaskProtDB-II: an update of a database of multitasking/moonlighting proteins. Nucleic Acids Res 46:D645–D648

Gero JS (1990) Design prototypes: a knowledge representation schema for design. AI Mag 11(4):26–36

Gould S, Vrba E (1982) Exaptation—a missing term in the science of form. Paleobiology 8:4–15

Graur D, Zheng Y, Azevedo RBR (2015) An evolutionary classification of genomic function. Genome Biol Evol 7:642–645

Hartwell LH, Hopfield JJ, Leibler S, Murray AW (1999) From molecular to modular cell biology. Nature 402(6761 Suppl):C47–C52

Henderson B, Fares MA, Martin, AC (2016) Protein moonlighting and new thoughts about protein evolution. In: Protein moonlighting in biology and medicine. Wiley, pp 63–80

Henderson B, Fares MA, Martin ACR (2017) Protein moonlighting in biology and medicine. Wiley, Hoboken, NJ

Hodgkin J (1998) Seven types of pleiotropy. Int J Dev Biol 42:501–505

Jacq B (2001) Protein function from the perspective of molecular interactions and genetic networks. Brief Bioinform 2:38–50

Jeffery CJ (1999) Moonlighting proteins. Trends Biochem Sci 24:8–11

Jeffery CJ (2014) An introduction to protein moonlighting. Biochem Soc Trans 42:1679–1683

Jeffery CJ (2018) Protein moonlighting: what is it, and why is it important? Philos Trans R Soc Lond B Biol Sci 373

Keeling DM, Garza P, Nartey CM, Carvunis A-R (2019) The meanings of “function” in biology and the problematic case of de novo gene emergence. Elife 8

Khersonsky O, Tawfik DS (2010) Enzyme promiscuity: a mechanistic and evolutionary perspective. Annu Rev Biochem 79:471–505

Kreimer A, Borenstein E, Gophna U, Ruppin E (2008) The evolution of modularity in bacterial metabolic networks. Proc Natl Acad Sci USA 105(19):6976–6981

Lombard LM, Phillipson L (2010) Indications of bow and stone-tipped arrow use 64 000 years ago in KwaZulu-Natal, South Africa. Antiquity 84(325):635–648

Lyman RL, Van Pool TL, O’Brien MJ (2008) The diversity of North American projectile-point types, before and after the bow and arrow. J Anthropol Archaeol 28(1):1–13

Margulis L, Sagan D (2002) Acquiring genomes: a theory of the origins of species. Basic Books

McBrearthy S (2012) Sharpening the mind. Nature 491:531–532

Mivart G (1871) On the genesis of species. MacMillian, London and New York

Nelson RR, Winter SG (1982) An evolutionary theory of economic change. Belknap Press, Cambridge

Odling-Smee FJ, Laland KN, Feldman MW (2003) Niche construction: the neglected process in evolution. Princeton University Press, Princeton, NJ

Oltvai ZN, Barabasi AL (2002) Systems biology. Life’s complexity pyramid. Science 298:763–764

Penrose ET (1952) Biological analogies in the theory of the firm. Am Econ Rev 42(5):804–819

Perry SF, Sander M (2004) Reconstructing the evolution of the respiratory apparatus in tetrapods. Respir Physiol Neurobiol 144:125–139

Piatigorsky J, Wistow GJ (1989) Enzyme/crystallins: gene sharing as an evolutionary strategy. Cell 57:197–199

Plach MG, Reisinger B, Sterner R, Merkl R (2016) Long-term persistence of bi-functionality contributes to the robustness of microbial life through exaptation. PLoS Genet 12:e1005836

Rosenberg N (1982) Inside the black box: technology and economics. Cambridge University Press, New York

Schumpeter JA (1911) The theory of economic development. Harvard University Press, Cambridge

Shea JJ, Sisk ML (2010) Complex projectile technology and Homo Sapiens dispersal into western Eurasia. Paleo-anthropology, 100–122

Simon H (1962) The architecture of complexity. Proc Am Philos Soc 106:467–482

Stelling J, Sauer U, Szallasi Z, Doyle FJ, Doyle J (2004) Robustness of cellular functions. Cell 118:675–685

Takiguchi M, Matsubasa T, Amaya Y, Mori M (1989) Evolutionary aspects of urea cycle enzyme genes. BioEssays 10:163–166

Usher AP (1929) A history of mechanical inventions. McGraw-Hill, New York

Wagner A (2012) The role of robustness in phenotypic adaptation and innovation. Proc Biol Sci 279:1249–1258

Wagner A, Rosen W (2014) Spaces of the possible: universal Darwinism and the wall between technological and biological innovation. J R Soc Interface 11:20131190

Woese CR (2002) On the evolution of cells. Proc Natl Acad Sci 99(13):8742–8747

Woese CR (2004) A new biology for a new century. Microbiol Mol Biol Rev 68:173–186

Woese CR, Goldenfeld N (2009) How the microbial world saved evolution from the Scylla of molecular biology and the Charybdis of the modern synthesis. Microbiol Mol Biol Rev 73(1):14–21

Zanzoni A, Ribeiro DM, Brun C (2019) Understanding protein multifunctionality: from short linear motifs to cellular functions. Cell Mol Life Sci 76:4407–4412

Ziman J (2000) Technological innovation as an evolutionary process. Cambridge University Press, Cambridge

Zinman GE, Zhong S, Bar-Joseph Z (2011) Biological interaction networks are conserved at the module level. BMC Syst Biol 5:134

The Role of Affordance Landscapes in Exaptive Innovations

Antonio Mastrogiorgio and Mariano Mastrogiorgio

1 Introduction

Understanding how decision-makers make strategic decisions related to innovation is a central issue in contemporary research. In the past decades, part of the research has focused on the cognitive dimensions underlying strategic decision-making. That is, how organizational actors represent the environment in which they make decisions. The representational framework is mainly linked to the debate that sees strategic and innovation decisions as the ability to represent the environment in a way that is comparatively better with respect to other actors (e.g., Csaszar 2018). In this view, the ability of representation and foresight is the factor that connotes the quality of strategic decisions. As suggested by Gavetti (2007, p. 530): "actors' representations or mental models of their problem environments significantly influence both their sampling and evaluation of alternatives".

However, if we analyze the representationalist approach in light of the last developments in cognitive, behavioral and neuro-science, we easily realize that the theoretical assumptions for the existence of a veridical representation of the environment are critical. In fact, during the past two decades, cognitive, behavioral and neuro-science have highlighted the inadequacy of the representationalist approach: cognition cannot be simply conceived as a problem of abstract representations of the environment, to the extent that cognitive processes are rather embodied (see Wilson 2002 for an overview). In other words, cognitive processes are strictly dependent on the sensory-motor system, which defines what can be represented and how.

A. Mastrogiorgio (✉)
AXES, IMT School for Advanced Studies Lucca, Lucca, Italy
e-mail: a.mastrogiorgio@imtlucca.it

M. Mastrogiorgio
Department of Strategy, IE University, Segovia, Spain
e-mail: mmastrogiorgio@faculty.ie.edu

C. AM. La Porta et al. (eds.), *Understanding Innovation Through Exaptation*,
The Frontiers Collection, https://doi.org/10.1007/978-3-030-45784-6_7

In this regard, a prominent notion in embodied cognition research—and part of the ecological school too—is the notion of *affordance*, defined as the physical properties of an artifact that invite a specific action (see Gibson 1979; see also Rietveld and Kiverstein 2014). For the purpose of our arguments, affordances are central because a growing number of studies (also recent, like Felin et al. 2016) are highlighting the importance of conceptualizing exaptive innovation in the light of the theory of affordances. Indeed, exaptive innovation can be conceived as the discovery and emergence of new affordances of an artifact and, broadly speaking, of new uses. What is interesting about this perspective is the emphasis it places on the non-representational and tacit dimension underlying the processes of innovation and change (Nayak et al. 2019).

Recent research on affordances—and, in particular, on the concept of *affordance landscape* and related "affordance competition hypothesis"—could provide new insights on exaptive innovations. In this chapter, we thus elaborate on the ability of actors to discover new potential uses in a landscape of potential affordances, suggesting that actors do not simply experience preexisting affordances but they are able to attribute novel ones to artifacts they habitually use.

This chapter is organized as follows. In Sect. 2, we develop the theoretical background, focusing on the notion of "affordance landscape" and on the related "affordance competition hypothesis". In Sect. 3, we explore the possibility of conceiving the affordance landscape as a source of discovery and emergence of new uses. In Sect. 4, we highlight the importance of the tacit dimension in managerial practice and conclude.

2 Theoretical Background

The notion of "representation" is a fundamental element of the so-called Cognitivist paradigm, according to which cognition is mainly a matter of symbolic manipulation of a representation of reality. Among its foundational assumptions, we find the so-called "physical symbol system hypothesis" (Newell and Simon 1976), which looks at cognition as information processing, where cognitive processes can be artificially simulated through the use of computational devices. The representational primacy of high-level cognitive phenomena is a defining characteristic of the cognitive and behavioral sciences during the past four decades. As suggested by Thagard (2014): "thinking can be understood in terms of the representational structures in the mind and computational procedures that operate on those structures". In general terms, this view assumes the existence of three sequential processes: perception, cognition, action. Sensing, thinking, and acting are the three "sacred cows". According to this general model, individuals first build representations based on their sensory devices, then they manipulate such representations (along with the use of memory) to make decisions and, finally, they implement and execute according to an action plan. This framework is consistent with the idea that cognition works as a computer: while perception and action represent, respectively, the input and output of the system, cognition is seen as information processing enabled by "veridical" representations of the environment.

This approach to cognition has been subject to significant criticism, mainly related to the idea that cognition is rather embodied (for an overview, see Gomila and Calvo 2008), as it is based on the specificity of the sensory-motor system. Among the various debates on the subject, one of them (published on a special issue of *Cognitive Science* in 1993) concerns the computational implementability of situated cognition (situated cognition is based on the hypothesis that cognitive processes cannot be separated from the context as individuals think on the fly, instead of recalling knowledge stored in memory, e.g., see Clancey 1997). Relying on the distinction between first- and third-person cognitive representations, Clancey (1993) argues that we can build a formal third-person representation of the situation, implemented on artificial devices through the use of symbolic systems. However, this type of representation is not able to account for—explain and/or predict—the first-person, situated action, which involves considerations about the role of the sensory-motor system in its ongoing interaction with the environment.

In more general terms we oppose, to the idea that the representation of the environment is universal and veridical, the idea—traditionally related to the "umwelt" notion (von Uexküll 1934)—that representations are organism-specific, since different types of organisms construct different types of representations of the same environment. According to this perspective of subjectivity—instead of objectivity—the environment must be thus reconsidered and seen as not neutral with respect to a specific observer. Indeed, as Felin et al. (2017) recently argue: "No true representation—more specifically, no single objective representation—is possible as there are many possibilities for representing reality" (p. 1051).

2.1 *Affordance Landscape*

The representationalist approach has been strongly criticized during the past two decades, on the basis of a significant number of arguments supported by the evidence that cognition is embodied (e.g., Wilson 2002), meaning that it cannot be considered as a simple, computer-like, information type of processing. The idea that cognition is embodied is indeed supported by evidence on the neural activity as somehow inconsistent with sequential processes, since perception, cognition, and action do not occur in a sequential fashion. In order to shed light on such inconsistencies, an alternative model has been proposed by Cisek (2007), known as the "affordance competition hypothesis". This model makes a critical distinction between "action specification" and "action selection": action specification uses "sensory information to define potential actions and guide their execution online", while action selection helps to "select which potential action will be performed at a given moment" (p. 1595). According to the "affordance competition hypothesis", action specification and action selection are simultaneous. In other words, "what we decide to do" and "how to do" are processes that occur in parallel. This model, which is gaining significant credit, represents a significant alternative with respect to traditional theories because it directly challenges (based on sound evidence) the foundational assumptions about the tripartite and sequential nature of brain functioning, thus endorsing an embodied view of cognition. Cisek (2007) illustrates neural results for a reach-decision type of task. During a spatial-cue period, two targets were presented. During a color-cue period, one of the two was indicated as the correct one. After the GO signal, the movement started. Simplifying, the evidence based on the task suggests that action specification is present before action selection: in other words, different actions compete before a choice is specified.

The general idea underlying the "affordance competition hypothesis" is that the role of the brain is to guide the interaction with the environment and not just to represent it. Such interaction, as it was proposed by Pezzulo and Cisek (2016), relies on feedback control mechanisms, which represent an alternative model with respect to the traditional framework of serial information processing. As put by Pezzulo and Cisek (2016, p. 414): "A feedback control system is one in which outputs are generated so as to control some variable whose value is measured via input. In the case of behavior, actions are performed to keep the animal in a desirable state (satiated, safe, etc.) and perceptions are used to evaluate that state". Put differently, behavior is based on feedback control, that is, in the words of Pezzulo and Cisek (2016, p. 414) "it relies on predictable causal relationships between actions and outcomes (approach food → make food obtainable) and is self-regulating (eat food → satiate hunger/deplete food)". *Mutatis mutandis*, this model is the one of a thermostat that turns on or off in order to maintain the room temperature constant.

While feedback control is traditionally used to understand the low-level physiological mechanism, according to Pezzulo and Cisek (2016) it can be extended to higher cognitive processes. This represents a significant theoretical novelty, as it allows understanding higher cognitive skills and intentional action without claiming an underlying representational framework, but only through the recognition of the relationship between perception and action. Such approach to higher cognitive skills is enabled by the idea, discussed by Pezzullo and Cisek (2016), that affordance competition works through a hierarchical model as "brain's ability to predict the consequences of actions enables it to link across levels of abstraction, and to bias immediate actions by the predicted long-term opportunities they make possible" (p. 415). This mechanism allows to model intentional action as a goal-oriented navigation in the *affordance landscape*, considered as "a temporally extended space of possible affordances, which changes over time due to events in the environment but also—importantly—due to the agent's own actions" (p. 415). In this regard, in order to better understand how affordance competition enables different levels of abstraction, let us consider the simple case of a monkey, as discussed by Pezzulo and Cisek (2016).

Let us imagine a monkey on a tree branch, at the end of which there is a reachable berry, so that the monkey can directly pick it up and eat it. In the alternative, there is a larger apple a few branches away, meaning that the apple is unreachable, unless the monkey decides to walk on the branches and reach it. The bottom line is that the monkey must choose between a small but reachable berry and a larger but less reachable apple. According to Pezzulo and Cisek (2016, p 516): “the monkey can predict that walking out on the tree branch will result in putting an apple within reach—a prediction from available affordances (a ‘walkable’ tree branch) to the expected affordances that those actions make available (a ‘reachable’ apple)”. The case is exemplary in showing that a top-down process is able to favor non-immediate results, as the monkey is able to navigate an affordance landscape, in potential. In particular, there is a high-level competition between different expected results (berry vs. apple) that affect the competition among proximal actions at a lower level (picking the berry versus walking on the branch). This logic can be extended to a hierarchy of control loops to explain the presence of an intentional—and not just a reactive—use of affordances. In other words, as put by Pezzulo and Cisek (2016, 416, emphasis added): “an intentional agent is not limited to (*reactively*) pick up one of the currently available affordances, but can also (*intentionally*) create or destroy affordances, which can then be exploited to execute successive actions that ultimately achieve long-term goals”.

3 Discussion

In this chapter, we argue that the theory of affordance landscapes could be useful to understand the cognitive origins of exaptive innovations. In fact, exaptive phenomena are largely contingent, as the cognitive processes of innovators rely on embodied and situated interaction with technologies, artifact, and economic resources—and, broadly speaking, on the specific affordance landscape experienced by the actor. In particular, the idea of affordance landscapes could shed light on the high-level processes related to the discovery of new uses of existing technologies, artifacts, and economic resources. In order to better understand this point, let us consider the perception of a cliff as described by Gibson (1979, p. 157): “To perceive a cliff is to detect a layout but, more than that, it is to detect an *affordance*, a negative affordance for locomotion, a place where the surface of support ends”. The point to emphasize is that there is a multiplicity of affordances that can be detected, but their salience depends on their relevance for an individual (e.g., the cliff edge is dangerous). As discussed by Rietveld and Kiverstein (2014, p. 344) with reference to a cliff: “the environment affords a multiplicity of possibilities for action: it affords being perceived, it affords calling it correctly a cliff, it affords looking down safely by lying flat on the ground and looking over the edge, it affords asserting or judging that this cliff is a dangerous place for a children’s soccer game, it affords taking a piece of substance from the cliff’s wall and analyzing it chemically in one’s lab, and so on”. And, to be noticed, there are a number of possibilities that the environment (the cliff in our case) does not afford. In the words of Gibson (1979, p 157–158) “What animals need to perceive is not the layout as such but the affordances of the layout”. Such kind of considerations can be useful to shed new light on the role of affordance landscape for the discovery of new uses of existing artifacts.

3.1 The Discovery of New Uses

While the traditional notion of affordance refers to the immediate interaction between an individual and an artifact, the concept of affordance landscape offers new insights to understand the relationship, mediated by top-down processes, between a subject and its non-immediate, environmental resources. In other words, it helps us to shed light on an individual's ability to construct causal relations capable of biasing the use of sensory-motor devices. The intentionality underlying the use of such devices is crucial. A trivial aspect related to the existence of an affordance landscape (but important in our discussion) is that the landscape is by definition made up of several steps. And, as such, it can be conceptualized as the *locus* of discovery. Indeed, as an individual perceives a landscape of potential affordances (a potential sequence of feasible actions to reach a specific desired state), the actor is also creating the conditions for unexpected things to be perceived. Navigating the landscape can be a fundamental requirement for discovery. Continuing with the case of the monkey, its progression toward a distant apple (instead of the reachable berry) can be a condition for discovery: during the journey the monkey, step by step, will see new things—for instance, a predator hidden behind the leaves—that were invisible at the starting point. Therefore, every step on the landscape opens up new horizons that were invisible at the previous stage, meaning that the presence of several steps in the landscape is a substantial requirement for discovery. To be noticed that, in the direct interaction between an organism and its environment—one step on the landscape—there is no real space for the unexpected.

However, the presence of more steps in the landscape presents a further implication, which is central in our discussion. In fact, the matter here is not the discovery *tout court*, but the discovery of new uses of existing resources. Here we hypothesize that the existence of an affordance landscape is a requirement for the creation of new uses. In order to understand this point, let us continue with the case of the monkey. In its progression on the landscape, from branch to branch, the monkey is able to conceive new uses of the branches. For example, a branch could be reused as a weapon against a predator. The significant point here is that the monkey perceives the branch as an enabling constraint to the extent that the branch represents a stationary body allowing the monkey to anchor and to produce the actions necessary for movement. The branch is, therefore, the constraint that specifies, through the affordances, the degrees of freedom of the monkey's movement. In simple words, the monkey is able to move from branch to branch to the extent that the branch is fixed and the monkey moves, exploiting the specificities of its sensory-motor apparatus.

So, what about the new uses? Let us imagine at this point to invert the order: the monkey remains fixed and the branch has degrees of freedom of movement. The monkey "invented" the stick, as the branch is moving and the monkey is stationary. It should be noted that what changes is not the affordance per se. The sensory-motor apparatus shares specific devices, both in the case in which the branch is used for walking and in the case in which the branch is reinvented as a stick. In both cases, the branch is manipulated by exploiting the same sensory-motor devices, which rely on the use of opposable thumbs. What changes is the intentionality toward the branch, which is possible through the habits of the monkey with the branch. Indeed the knowledge of the branch (perceived as an affordance) allows the monkey to reuse it as a stick. Therefore, top-down processes bias the “practice of branches” identifying new original possibilities of use. In this perspective, an artifact—which is perceived in the light of the affordances it offers—can be exapted to the extent that new uses emerge precisely from its habitual use. Speculatively, what causes the monkey to be able to reconceive the use of a branch as a stick is based precisely on a top-down shift in the attribution of functionality, happening within the sensory-motor experience of jumping from one branch to another (in order to reach a fruit). Notice that, while the reaching of a fruit is a basic skill, the use of a branch as a stick is a later development in the evolutionary history.

4 Conclusions

A relevant part of the literature in innovation and strategy highlights that veridical representations of the environment are able to produce superior decisions (e.g., Csaszar 2018). Here we explore the opposite hypothesis: the origin of new uses is compatible with the existence of tacit habits. That is, it is the physical manipulation of artifacts—like technological artifacts—that represents a substantial requirement for the discovery of new uses. An anti-cognitivist stance on strategy and innovation is relatively new in management and organization studies. According to Nayak et al. (2019): “a firm’s dynamic capabilities rest upon a tacitly-shared substrate of sensitivities and predispositions that precede cognitive representation. [...] Such sensitivities and predispositions provide an organizational modus operandi for members to reconfigure capabilities and resources and capitalize on the opportunities arising therefrom” (p. 280). The bottom line is that the possibility of exploiting specific behavioral practices, associated with a procedural type of knowledge, is in our view what allows some technologies, artifacts, and economic resources to be exapted for new uses. With reference to the traditional distinction between exploration and exploitation (March 1991), for instance, we are thus somehow hypothesizing that exploitation generates a number of enabling constraints for exploration processes, and not the other way around. Hence, the sequential link from discovery to use is somehow overturned: it is exploitation, in the form of practical embodied use, that represents the locus within which it is possible to identify new uses of existing resources. One of the normative implications is to consider exaptive processes as resulting not from the intentional search for opportunities within a propositional knowledge base but, on the contrary, as the ability to recognize new uses within extant organizational practices, often inert and blind. Therefore, in this contribution, we highlight how recent trends in cognitive, behavioral and neuroscience can provide novel insight on the nature of exaptive innovations. In particular, the notion of “affordance landscapes” (along with the “affordance competition hypothesis”) can help us to shed light on how individuals are able to identify new uses of existing artifacts. The fundamental idea is that top-down process is able to bias the sensory-motor, reactive system, so to attribute "novel intentionality" to existing habits, and their underlying affordances.

References

Cisek P (2007) Cortical mechanisms of action selection: the affordance competition hypothesis. Philos Trans Royal Soc B: Biol Sci 362(1485):1585–1599

Clancey WJ (1993) Situated action: a neuropsychological interpretation (response to Vera and Simon). Cognit Sci

Clancey WJ (1997) Situated cognition: on human knowledge and computer representations. Cambridge University press, Cambridge, MA

Csaszar FA (2018) What makes a decision strategic? Strategic representations. Strateg Sci 3(4):609–619

Felin T, Kauffman S, Mastrogiorgio A, Mastrogiorgio M (2016) Factor markets, actors and affordances. Ind Corp Change 25(1):133–147

Felin T, Koenderink J, Krueger JI (2017) Rationality, perception, and the all-seeing eye. Psychon Bull Rev 24(4):1040–1059

Gavetti G, Levinthal D, Ocasio W (2007) Perspective—Neo-Carnegie: the Carnegie school's past, present, and reconstructing for the future. Organ Sci 18(3):523–536

Gibson JJ (1986) The ecological approach to visual perception. Lawrence Erlbaum. (Original work published in 1979)

Gomila T, Calvo P (2008) Directions for an embodied cognitive science: toward an integrated approach. In Calvo P. Gomila T. *Handbook of cognitive science*. Elsevier, pp 1–25

March JG (1991) Exploration and exploitation in organizational learning. Organ Sci 2(1):71–87

Nayak A, Chia R, Canales JI (2019) Non-cognitive microfoundations: understanding dynamic capabilities as idiosyncratically refined sensitivities and predispositions. Acad Manage Rev 45(2):280–303

Newell A, Simon HA (1976) Computer science as empirical inquiry: symbols and search. Commun ACM 19:113–126

Pezzulo G, Cisek P (2016) Navigating the affordance landscape: feedback control as a process model of behavior and cognition. Trends Cognitive Sci 20(6):414–424

Rietveld E, Kiverstein J (2014) A rich landscape of affordances. Ecol Psychol 26(4):325–352

Thagard P (2014) Cognitive science. In Zalta EN (ed) The Stanford encyclopedia of philosophy, Fall 2014 edn. Stanford University

von Uexküll J (1934) A stroll through the worlds of animals and men. In: Schiller CH (ed) Instinctive behavior: the development of modern concept. International Universities Press, New York, NY

Wilson M (2002) Six views of embodied cognition. Psychon Bull Rev 9(4):625–636

Mapping Exaptation as Source of Smart Specialization in European Regional Policy Between Tacitness and Codification

Ivan De Noni, Andrea Ganzaroli, and Luciano Pilotti

1 Introduction

The year 2020 is the last of the current European Framework Program. From 2021, a new set of policies will guide the development of European regions. The concept of smart specialization has been a cornerstone in this last European framework program (McCann and Ortega-Argilés 2015). Through the smart specialization strategy, the European Commission attempted to combine the advantages of both horizontal and vertical policies and, at the same time, minimize their respective disadvantages (Foray 2016, 2018). Horizontal policies are intended to create the framework conditions to lever the competitiveness of single countries and regions independently form their specific specializations. These policies are designed to stimulate long-term investment in general-purpose and high impact technologies, such as biotech and digital technologies, which can be applied to several different industries. However, not all industries and regions are equally prepared to exploit the potential enabled by investments in the development of those technologies. Exploiting the potential generated by those investments requires the availability of complementary sources to contextualize/translate that potential into a value that can be easily appropriated by firms embedded in a specific industry/specific region. Thus, the smart specialization strategy has been implemented to stimulate the local and endogenous production of those complementary resources.

The time has not yet come to take the stock on smart specialization strategy as policy framework mechanism that has guided the development of EU regions in the past 7 years. However, what is certain is that the smart specialization strategy has completely ignored exaptation as a tool for strengthening smart specialization.

I. De Noni
Department of Economics and Management, University of Padua, Padua, Italy

A. Ganzaroli · L. Pilotti (✉)
ESP – Department of Environmental Science and Policy, University Of Milan, Milan, Italy
e-mail: luciano.pilotti@unimi.it

C. AM. La Porta et al. (eds.), *Understanding Innovation Through Exaptation*,
The Frontiers Collection, https://doi.org/10.1007/978-3-030-45784-6_8

Exaptation is the cooption of an existing technologies to new and unanticipated domain of application (Andriani and Cattani, 2016, 2017; Mastrogiorgio and Gilsing 2016). It evolves in two phases (Cattani 2005, 2006). In the first phase, the know-how related to a technology is accumulated to serve a specific function without anticipation of its future usage. In the second phase, this know-how is co-opted and exploited to serve another and unanticipated function. This implies that expiation does not involve any significant technological advancement. Differently, the novelty stays in where this technology is (re-)applied and evolve. Exaptation also implies a discontinuity in the technological lineage as it is driven by functional shift in the domain of application. For this reason, exaptation is often a trigger for radical innovation and technological breakthroughs.

Exaptation is a source of smart specialization because it implies the exploitation of an existing specialization into a new field of knowledge development (Boschma et al. 2017; De Noni et al. 2018). In this perspective, exaptation is very different from traditional forms of innovation, which relies on the recombination of knowledge across technologically distant but lightly related fields. Differently, exaptation is incremental on the technological side, but drive radical and significant impacts on the applications' sides. In this sense, exaptation represents an opportunity even for lagging-behind regions, which often do not hold the capacity to hook into high-tech innovation trajectories, to enter those trajectories by exploiting their unique specificities and specializations.

However, exaptation requires specific competencies and abilities. First, exaptation is an analogical innovation. It is driven by a chain of analogies linking one domain of application to another (Andriani and Cattani, 2016). Therefore, it relies more on tacit knowledge and embedding rather than on codified knowledge and calculation. Second, it requires the capacity to scan for alternative contexts where a given technology can be applied (Dew et al. 2004). Both those competencies are peculiar and, therefore, should be objective of specific policymaking in order to stimulate their development and consolidation in regions. The objective of this paper is indeed to show the potential embedded in exaptation as a specific tool for enhancing smart specialization and to provide policymakers with some initial advice on how to design a smart specialization policy that supports also exaptation.

The paper is structured as follows. In the first part of the paper, we address the concept of exaptation. We highlight the origin of this concept and explain how this concept has been recontextualized in the field of management. We also highlight the debate its re-contextualization in the field of management has triggered off. Then, in the second part of the paper, we review the metrics that have been applied in the field of management to measure exaptation and we discuss the main advantages and disadvantages associated with each of those metrics. Then, we apply the metric by De Noni et al. (2018) to assess the distribution of exaptive patent across EU regions in two subsequent 10-year windows. Our analysis highlights that exaptive patents are endogenously generated into innovation-intensive regions while this is not the case into lagging-behind regions, which could benefit more from the exploitation of this innovation mechanisms. Finally, in the last part, we provide some initial advice on how to draft smart specialization policy that includes exaptation as a smart tool.

2 Exaptation: Genesis of the Concept

The term exaptation has been originally coined by Gould and Vrba (1982). They introduce this term to name characters that are co-opted to a new use from a previous function or no apparent function at all. In the first case, from a previous function, characters have been shaped by natural selection. Differently, in the second case, from no apparent function, natural selection did not play any role in shaping the co-opted characters. An example of exaptation are the feathers of birds, which were selected for a thermoregulating function and later co-opted to the flying function. In the second case, the relevance of exaptation is associated with phenomena like genetic drifts, which implies the accumulation of genetic code that does not play any apparent function. In both cases, anyway, exaptation implies a discontinuity in the biological lineage of species.

The introduction of the term exaptation in the vocabulary of evolution has been long opposed (Dew 2007). This is for two reasons. First, its acceptance implies questioning the primacy of selection in the theory of evolution. In fact, in exaptation of the second type, selection does not play any role in the initial evolution of a character. However, also in the first case, the cooption from a precedent function implies a discontinuity in the selection function. This leads us to introduce the second reason why the introduction of the term exaptation has been fiercely opposed, which is the fact that implies a discontinuity in the evolution process. In fact, differently from what is claimed by the Darwinian theory of evolution, evolution is not always the result of small variations positively selected by the environment, but maybe a consequence of the shift in the functioning of certain characters. However, what is even more important is that, according to Gould and Vrba, exaptation may be the reason for short periods of radical changes punctuating evolution. Therefore, according to Gould and Vrba, periods of creative destruction are not only the result of exogenous factors, but endogenous.

In the managerial literature, the term exaptation has been originally introduced by the historian economist Mokyr (1990) to describe the existence of discontinuity in the evolution of technological lineages and explain the rise of new and emergent punctuated equilibria. However, Mokyr limits himself to a metaphoric use of this term, but never attempted to develop a comprehensive theory of technological exaptation. There are, however, two contributions that have signed a change of pace in the conceptualization of exaptation in the managerial literature. Those are Dew et al. (2004) and Cattani (2006). Dew et al. (2004) contribute to the literature offering a comprehensive classification of technological exaptation and showing how exaptation is associated with true Knightian uncertainty, the rise of new markets and the role of entrepreneurship. In truth, Cattani (2006) does not use the term exaptation, but preadaptation. In so doing, Cattani emphasizes the phase in which knowledge is accumulated without anticipation of its future use. His goal, in fact, is to highlight the distinction between luck and foresight. That is, the distinction between the phase in which knowledge is accumulated without anticipation of its future usage and, therefore, luck plays a dominant role, and the phase in which the opportunity to reuse an existing artifact/know-how into a new and distant domain is perceived and is consciously actively exploited and levered (foresight). Therefore, between a phase in which entrepreneurship is not involved and a phase in which Knightian entrepreneurship is levered in the rising of a new market.

Those two contributions are not only relevant for their content, but because have fed a debate, which has been hosted in the pages of Industrial and Corporate Change, between Dew and Cattani on the opportunity to use exaptation rather than preadaptation. A similar debate took place between evolutionary biologists. On the one hand, Darwinian evolutionary biologists argued that there was no need for a new term such as exaptation since Darwin already introduced the term preadaptation to name characters that were shaped by natural selection for other purposes and then were co-opted to their present function. On the other hand, scholars supporting the use of the term exaptation, contended that the use of the term preadaptation hides the attempt to support the primacy of adaptation over other forms of evolution. That is, a view of evolution as gradual and based on natural selection of small inherited variations that increase the individual's ability to compete, survive and reproduce. Therefore, a view of evolution that relegates discontinuity and punctuation to minor factors in the history of evolution.

The terms of this debate, recontextualized within the boundaries of the evolutionary theory of technological change, lead contenders to discuss one of the key assumptions on which this theory is grounded. That is, the role of intentionality compares to selection in the evolution of technologies or said differently the extent to which designers foresee and control the success of their variations. In fact, as Cattani argues in the reply to Dew's commentary, a key difference between biology and technology is that foresightful evolutions occur in the context of technology. Technological change is driven by variation and selection, but those are neither blind nor natural. In their original paper, Dew et al. (2004) define three possible sources of exaptation. Two of them are defined as nonadaptive. That is, technological features that were not originally selected for their function. In both cases, those features are selected as part of a bundle. However, in the first case, those features are neutral to the selection environment and indeed do not make any contribution to the performance of the technology. Differently, in the second case, those features are selected even if are negatively draining on the performance of the whole. However, according to our point of view, even if those features were not selected for their contribution to the performance of the whole, it is still difficult to imagine that designers, especially in the case of features with a negative impact on the overall performance, did not spend any time in trying to optimize the costs of those components. Therefore, even if those features may seem nonadaptive, they were selected as part of a bundle carrying on a specific purpose, which has played a significant role in shaping the designers' intentionality in the development of those features. Therefore, even in those cases, we believe it is more appropriate to say that the origin of those features is adaptive.

However, differently from Cattani (2008), we do not believe that preadaptation is a better term. The main reason is that it is a term that preserves an adaptive view of technological change, which is mainly grounded on knowledge recombination and see radical innovation as the result of the recombination of knowledge across a large variety and cognitively distant technological fields. Differently, the term exaptation marks a discontinuity with this perspective and highlights the cooption of already existing artifacts and indeed know-how to a new function as an alternative and complementary trigger of the process of radical innovation. In this perspective, we believe exaptation is a better term than pre-adaptation as it stimulates scholars to focus on the functional shift rather than only on the origin of the knowledge. Therefore, on the specific factors facilitating enterprises and entrepreneurs in seeing the value in the reapplication of an existing artifact to a new domain (Dew et al. 2004).

3 Drivers of Exaptation

There are four main drivers of exaptation highlighted in the literature.

The first is complexity and near decomposability. Near decomposability is a characteristic of the architecture of the complex system. It can be thought of as boxes-within-boxes hierarchy with an arbitrary number of levels. Its special characteristic is that the intensity of the equilibrating interaction is stronger within boxes than between boxes at the same level than between boxes located at different levels all the way to the top of the hierarchy (Simon 1995). This implies that the behavior of the single boxes can be taken as independent from that of others in the short run, but the consequence of changes taking place within a box is going to get reflected on the behaviors of the others in the long run. This organizational architecture has been proven to carry significant evolutionary advantages. It is, given the level of complexity, more resilient than non-decomposable architecture because less sensible to the effect of external shocks. Second, it is, given the level of complexity, more adaptable than a non-decomposable system. This is because each component, at least in the short run, maybe optimized independently from others. Third, it saves on coordination costs as it is based on feedbacks and self-coordination between subparts (local processes). However, this peculiar architecture is responsible for the endogenous and punctuated character of evolution. In fact, the near independence between subparts implies that evolution may take place independently within subparts at different levels of the hierarchical architecture without any significant change in the overall system. However, when the cumulative effect of those changes reach a certain threshold, even apparently insignificant changes may trigger off cascading effects and network externalities with radical consequences on the functionality and structure of the overall system.

The concept of near decomposability is tied intertwined with one of the modularity and functional modules. Modularity, in fact, is a systematic concept that describes how complex systems can be decoupled into subsystems that perform nearly independently of each other (Andriani and Carignani 2014; Simon 1962). In this context, a functional module is defined as a physical subpart that performs a well-defined and single function, where the function is an emergent property resulting from the interaction between designers' intentional function (what the object is designed for) and what the object is selected for, which is the result of the aggregated actions of people and organizations that select and modify artifacts according to the intended or emergent usage. Exaptation entails a functional shift. Therefore, exaptation reflects a change of function that may take place at different levels of the hierarchy and resonate at different levels of the hierarchy as well. Based on this observation, Andriani and Carignani (2014) define three types of exaptation: internal, external, and radical. Internal exaptation is functional shift at the level of the internal module without any significant change in the domain of application of the entire system (the artifact). External exaptation, differently, is a change in the domain of application of an existing artifact that does not resonate/induce any change of the internal structure and indeed on the function of the internal modules. Finally, radical exaptation is the result of an internal module changing its function and leading to the generation of a completely new system built around the exapted module.

Furthermore, Mastrogiorgio and Gilsing (2016) highlight the existence of an inverted U-shaped relationship between technological complexity and exaptation. Modularity, on the one hand, implies the hiding of information within modules. On the other hand, it highlights the role of a specific subset of information that ensures coordination between modules. Therefore, on the one hand, a high level of complexity as a result of the decomposition into many subparts strongly bounded together reduce inventors' capacity to reuse modules into a different context. This is because the interface is too specific to the functionalities of the two modules. On the other hand, reducing the complexity into a small number of modules implies that large part of the information is hidden within each module. Therefore, also, in this case, designers find difficult to see opportunities in exapting the functionality incorporated within modules.

Near decomposability and complexity are only two conditions for knowledge accumulating without anticipation of its additional potential uses. There are other drivers contributing to the rise of exaptive innovation. Dew et al. (2004) highlight the impossibility to state ex-ante all the possible applications of a technology, which is mainly a consequence of bounded rationality. Another driver is entrepreneurship. According to Shane and Venkataraman (2000), entrepreneurship is the capacity to discover, evaluate and exploit opportunities to create future goods and services. In this perspective, exaptation represents a specific type of entrepreneurial opportunity, which is related to the opportunity to reapply the functionality of an existing artifact into a new domain of application. According to Dew et al. (2004), exaptive innovation is associated with true Knightian uncertainty and entrepreneurship, which is amenable to probabilistic calculation. Even if Cattani (2005, 2006) does not make any explicit reference, entrepreneurship is a key driver in the transition from the state of "pre-adaptation", when knowledge is accumulated without anticipation of its future usage, and exaptation, when that knowledge is levered to the new domain of application with intention and foresight. The lack of entrepreneurship precludes the capacity to see opportunities in exploiting an existing artifact into a new domain. Finally, Mastrogiorgio and Gilsing (2016) add the capacity to draw analogy across fields as a specific driver of the exaptive capacity of both inventors and entrepreneurs and users.

4 Measuring Exaptation

One of the main problems in developing a comprehensive and grounded theory of exaptation is to measure exaptation. This is especially important if the goal is to assess quantitatively the effects of different factors on the likelihood of exaptation. This is because one of the requirements in the definition of exaptation is that exapted knowledge is accumulated without anticipation of its future use. In the literature, to our knowledge, there are three methods to measure exaptation. Those methods refer to two different types of artifacts: patents and off-label uses.

The first method has been proposed by Mastrogiorgio and Gilsing (2016). This is specific to U.S. Patents because based on the distinction between OR class and XR classes, which is available only in the USPTO-NBER patents database. The OR class is mandatory and reflects the most comprehensive claim or main function of the invention. XR classes can be more than one and reflect alternative applications envisioned by the inventor(s) at the time when the patent is granted. According to Mastrogiorgio and Gilsing (2016), exapted patents are those cited by patents registered into a different OR class compared to the OR class and XR classes of the focal one. Therefore, the focal patent is exapted because, at the time when it was granted, inventors could not envisage the OR class of citing patents as the possible domain of application. In this perspective, exaptation is defined as a fraction of the number of forward citations received from OR classes different from the OR class and XR classes of the focal patents. Thus, the higher the number the more the knowledge embodied in the focal patent have been exapted in unanticipated domains of application.

The second method, which has been proposed by Andriani et al. (2017), is specific to the pharmaceutical industry. It exploits the fact that new molecular entities (NMEs) are approved for specific uses from a formal institution. However, experimentation through exposure to different contexts reveals new uses for drugs based on positive side effects. This is called off-label uses, which are not approved but registered in the commercial database DrugDex. Therefore, crossing data from those two sources, Andriani at el. (2017) identify NMEs that have been approved for use, but then are later exploited for alternative uses, such as in the case of Viagra. In their metric, Andriani et al. (2017) introduce also the notion of distance. That is, the distance between entry and emergent use, where distance is measured as a function of the length of the pathway between the two uses (diseases) in the tree-like structure of the International Classification of Diseases. Long-distance exaptations refer to molecules that are applied into a different general class (first-level bifurcation) compare to the one of entry. Intermediate distance refers to exaptations between two subclasses within the same general class (second-level bifurcation). Finally, short distance exaptations are those between functions within the same subclass (third or lower bifurcation level).

Finally, the third method has been proposed by De Noni et al. (2018). Like Mastrogiorgio and Gilsing (2016), it refers to patents. However, it is more generic as it is based on data available on OECD RegPat and Patent Quality Indicators database.

Exaptation is assessed based on the combination of two patent quality indicators: originality and radicalness. Originality refers to the breadth of the technological fields on which a patent relies. The larger the number of diverse knowledge sources embodied in a patent the larger the originality of the patent. Differently, radicalness is defined as the extent to which a focal patent relies on knowledge sources classified into different technological domains compare to those in which that focal patent is applied/granted. According to De Noni et al. (2018), the patent is exaptive if it is, at the same time, incremental (low originality) and radical (high radicalness). Therefore, it does not include significant technological changes, but it is applied to different technological domains.

All these three indicators have pros and cons. They are specific. On the one hand, both Mastrogiorgio and Gilsing (2016) and De Noni et al. (2018) refer to technological patents. Therefore, their indicators can be applied only in the case of patented technological inventions. However, there are evidence showing that tacit knowledge plays a significant role in exaptation. This is also supported by the positive relationship holding between complexity and exaptation. Furthermore, those indicators refer to invention and not to innovation. Regarding the pros and cons of each indicator, Mastrogiorgio and Gilsing (2016) have designed an indicator that well suited to capture non-anticipation as a requirement for exaptation. However, in doing so, they had to restrict their sample only to USA-patents. Furthermore, their indicator captures only one dimension of the exaptive process. That is, the technological shift. But does not assess the extent to which the exapted knowledge is cumulative and incremental. Differently, the indicator proposed by De Noni et al. (2018) does not specifically capture non-anticipation, but it does not restrict the sample only to USA-patents and assesses the incremental and cumulative nature of the exapted knowledge.

Finally, the indicator proposed by Andriani et al. (2017) is probably better designed to capture exaptation. First, it refers to innovation and not only to invention. In fact, it assesses exaptation between entry use and off-label uses. That is, between the use defined at the end of the trial process and emerging uses resulting from the market exploitation of side effects observed in daily practices. Second, it also captures non-anticipation as the inventors of the molecule did not envision off-label uses. Third, it also assesses the length of the exaptation path. However, as the other indicators, this also has limitations. First, as Mastrogirgio and Gilsing (2016), this indicator captures only the functional shift, but not the incremental nature of knowledge embodied in the molecules. Second, its application is limited only to the pharmaceutical industry.

5 Exaptation as Driver of Smart Specialization in Regions

The smart specialization concept is a driving force both behind both the new 'Innovation Union' flagship program of the European Commission and the EU cohesion policy reforms. It originated in the literature analyzing the productivity gap between the United States and Europe (McCann and Ortega-Argilés 2015). This literature has highlighted the key role played by technological linkages and spillovers between industries and regions in explaining this productivity gap. However, it has also stimulated further reflection within the so-called K4G group, which originally conceptualized the idea of smart specialization and drew the initial guidelines for its development and implementation.

The smart specialization strategy aims at solving two problems related to past innovation policies implemented in Europe (Foray 2016, 2018). The first is the partial failure of horizontal policies, in which resources are allocated in a horizontal manner avoiding any preferential interventions and acting on general framework conditions. Even if these policies are required for a region being competitive, do not stimulate the production of those complementary resources and competencies that are required for the existing industrial system being capable to exploit the transformative potential and dynamism generated by the improvements in general framework conditions. For instance, investing in the development of the 5G infrastructure does not necessarily trigger off the starting up of new entrepreneurial initiatives capable to exploit the innovative potential made available by the large availability of this infrastructure within a region. This is even more true in lagging-behind regions, which lack the organization thickness required to self-produce those complementary resources and competencies. The second is the failure of the so-called MOPs (Mission Oriented Policies), which are grounded on the role of the omniscient planner.

The solution proposed by the smart specialization strategy relies on the definition of priorities between transformative activities and on the role of entrepreneurial discovery. Transformative activities are "collection of innovation capacities and actions, that have been extracted as it were from an existing structure or several structures, to which can be added extra-regional capacities and that is oriented toward a certain structural change" (Foray 2018, p. 818). The objective, therefore, is not finance neither a single project nor a sector as whole, but rather the local process of entrepreneurial discovery to integrate and combine dispersed, fragmented, and hidden local knowledge to open and explore a new domain of market and technology opportunities. Thus, entrepreneurship plays a dual function. On the one hand, it does the actual work of discovering information that is otherwise extremely costly, if not impossible, to collect. On the other hand, it produces information about the value of the prospected new area of specialization for the region.

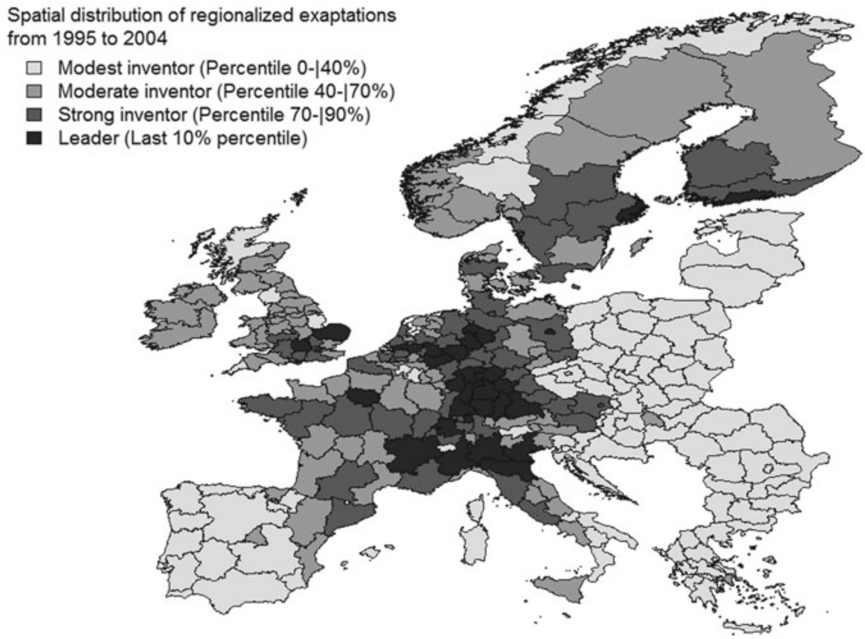
Even if the smart specialization strategy points out the importance of levering on existing specialization to stimulate the generation of new areas of opportunities on which to construct the future competitiveness of a region, it remains rather unspecific on how policymakers should select transformative activities. In this perspective, a rather accredited solution is the one grounded on the trade-off between technological relatedness and technological complexity Balland et al. (2019).

According to this view, valuable innovations are the result of the recombination of knowledge available into different industries/technological fields. Therefore, regional competitiveness and growth depend on the variety of knowledge sources available. However, given the breadth and depth of the variety, not all combinations work the same. There are combinations that are more efficient than others because, on the one hand, reduce the cost of recombination across specializations, but, on the other hand, stimulate creativity. Those are the combinations maximizing the level of technological relatedness between regional specializations. That is, combinations adding up areas of knowledge specialization strongly interconnected and often combined in the production of new knowledge. Therefore, according to this view, regions hold a competitive advantage compared to others when, for some historical reason, have combined, within their geographical boundaries, a large set of specific resources and skills complementing each other in the process of innovation. Balland et al. (2019) transpose the concept of technological relatedness and connect it to the one of smart specializations. Therefore, according to their view, regions should invest in transformative activities connecting local bundle of specializations to related global trajectories of innovation. However, in their view, technological relatedness is also constraint as it prevents regions to enter more complex technological developmental paths, which lead to stronger economic growth.

However, there are already scholars voicing their concern about the possible risks associated with smart specialization strategy focusing only on technologically related innovation paths (Castaldi et al. 2015; De Noni et al. 2018). As suggested by Castaldi et al. (2015), one may expect that the related variety hypothesis to hold for innovation in general. However, it should be recognized that innovation based on the recombination between previously unrelated pieces of knowledge implies that new relations are established in the form of artifacts that paves the way for future innovation to follow suit. Even if Castaldi et al. (2015) remain tied to a combinatorial and adaptive view of innovation, they highlight the importance of unrelatedness, which settle the opportunity to establish new connections between previously unrelated sources of knowledge, as a significant driver of path-breaking innovation and economic growth. This opportunity has been so far overlooked for the high costs and risks associated to combine cognitively distant sources of knowledge. Differently, exaptation is also a driver of radical and path-breaking innovation. However, it does not require covering the cognitive distance between many highly diversified knowledge sources, but levers on an existing artifact to enter a new and emerging innovative trajectory. Therefore, it enables the opportunity to lever of existing specialization to enter emerging and path-breaking innovation trajectories. Therefore, exaptation is an opportunity, still overlooked, for smart specialization in regions.

6 The Map of Exaptive Patenting in European Regions

In the previous section, we highlight exaptive patent as a potential source of smart specialization in regions. In this section, we map the occurrence of exaptive invention in European regions as a way to highlight the opportunities associated with lever of exaptation as a source of smart specialization. The results of our analysis are summarized in Fig. 1a, b, which refers to 284 European regions (defined at NUTS2 level). Exaptive patents are assigned to each region according to a regionalization process based on the addresses of inventors and accounting for inventors share. In



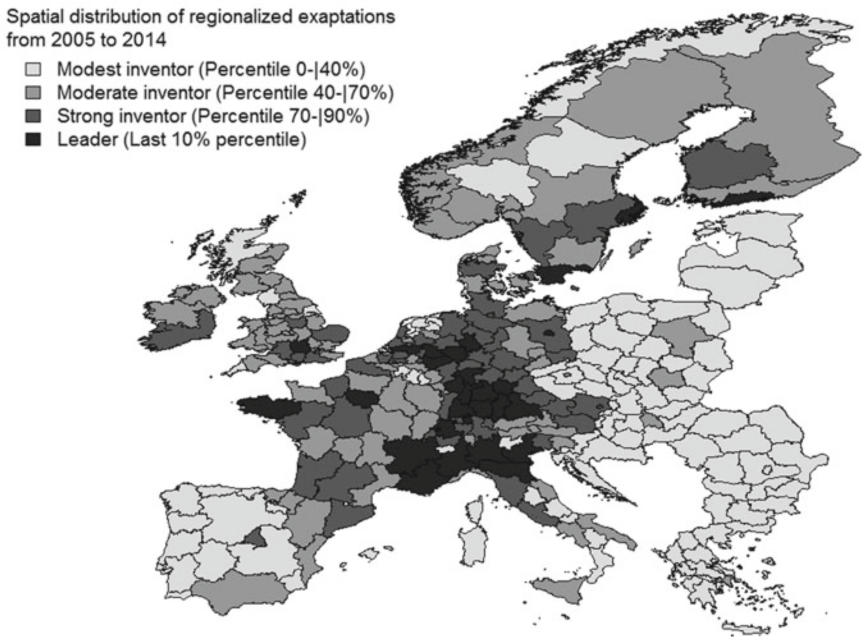


Fig. 1 Spatial distribution of exaptive patents across European regions. *Note* Our elaboration from OECD-RegPat database (version release July-2019). Data refers to the number of exaptive EPO patents involving at least a European inventor. Patents are regionalized based on inventors' addresses. Thus, a fractional counting is carried out in case of interregional co-patents

other words, collaborative patents, involving more than one inventor not coming from the same region, are fractionalized. Two 10-year windows are represented by referring to the priority year of patents. While Fig. 1a refers to exaptive patents registered from 1995 to 2004, Fig. 1b illustrates the most recent period from 2005 to 2014. In the figures, regions are classified, based on the percentile distribution, in modest inventors (less than 40th percentile), moderate inventors (between 40th and 70th percentile), strong inventors (between 70th and 90th percentile) and inventor leaders (more than 90th percentile). The four groups are colored through a grayscale, where the darker regions correspond to the more exaptive ones.

The spatial distribution in Fig. 1a reveals that the most performing regions in terms of exaptive patents are localized in central Europe, and specifically in West Germany (plus Berlin), North Italy, South England, South Scandinavia, and France. Referring to the spatial distribution of EPO (European Patent Office) patent across European regions in De Noni et al. (2018), exaptive patents result to be embedded within the most inventive regions. This suggests that high-intensive regions with extended and complex knowledge domains are more inclined to support exaptation than lagging-behind regions. It might be linked to a more developed institutional thickness, which better supports a creative disruption process by moving knowledge from one technological field to another one.

Figure 1b does not suggest a large change in the distribution of exaptation performance across regions moving to the most recent 10-year time window. Better performance is registered in France and Spain while worst performance is registered in some regions in Germany and the UK. Stable are, among others, Italy and Scandinavian. High exaptation performances are mainly carried out in metropolitan areas like Milan, Paris, Berlin, and London, too. The higher potential of large cities in boosting exaptation might suggest the role played by universities and R&D services which are frequently bounded in urban areas and are able to better support firms in experimentation and radical innovation processing. Smart cities also attract a large number of R&D resources in terms of human and financial capital, public and private funds as well as foreign investments. Finally, urban density rises the spatial proximity effects and increases the opportunities for collaboration, knowledge diffusion, and cross-fertilization processes. All these elements likely make cities the best loci for exaptation.

If an evident gap exists between high-intensive and lagging-behind regions, Fig. 2 specifically explores the relative exaptation performance of strong inventors and leader regions[1] in order to better control for different potentials across regions. An exaptation rate is implemented by measuring the relative accounting of exaptive papers as referred to the total numbers of patents filed in the region. The percentile distribution of exaptation rate highlights the relevant role of some German, French, and Italian regions (Fig. 2a) as well as the growing relative performance of Paris and Provence regions (Fig. 2b). Exceptionally, the map suggests the increasing relative performance of Ireland and the Netherlands.

[1]Modest and moderate inventor regions are not included because of the low number of patents which make relative indicators lowly performing.

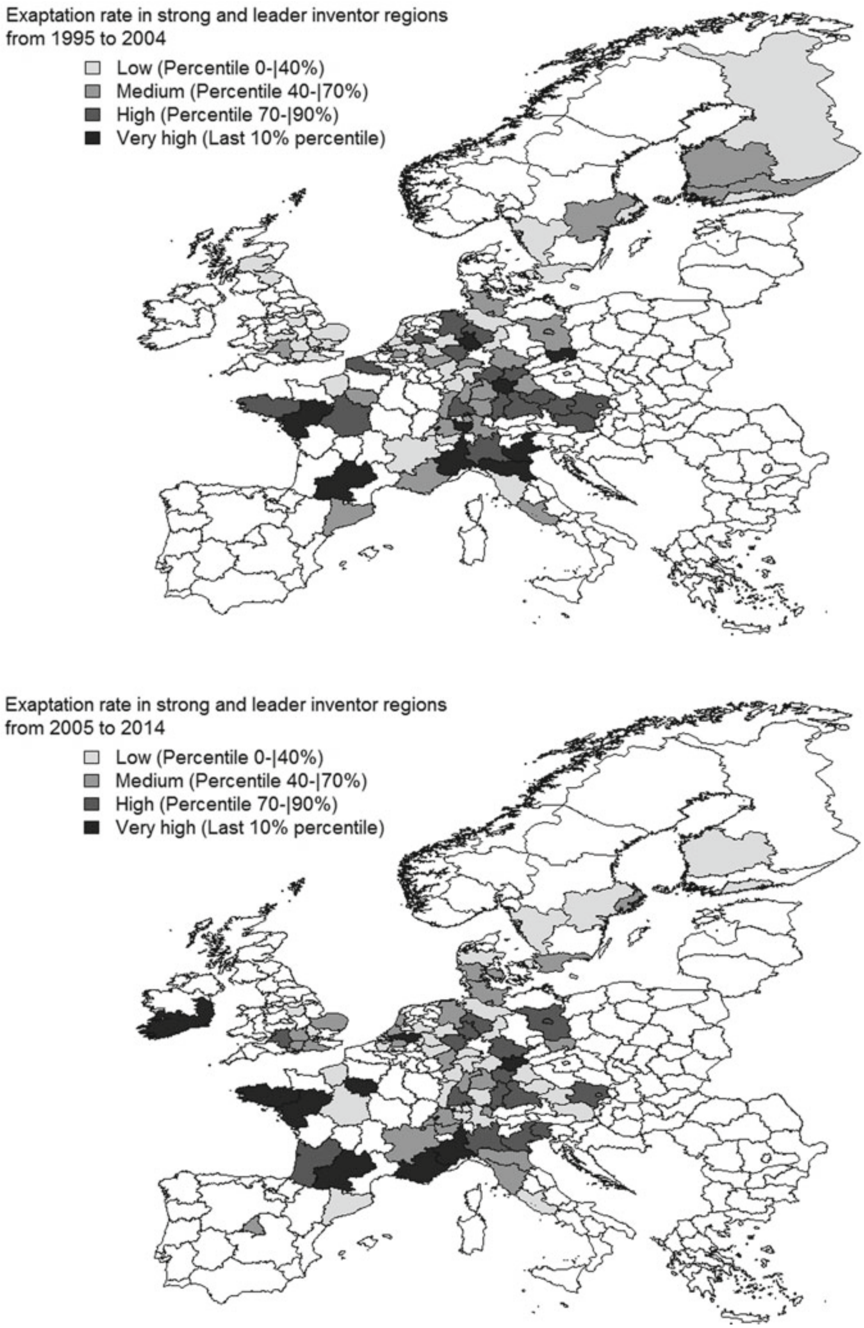


Fig. 2 Exaptation rate across European strong and leader inventor regions. *Note* Our elaboration from OECD-RegPat database (version release July-2019). Data refers to the number of exaptive EPO patents involving at least a European inventor. Exaptation rate is computed as the share of regionalized exaptive patents on the total number of patents

To sum up, the large number (in absolute terms) of exaptive patents within German regions is likely fostered by a very performing regional innovation system able to support collaboration, cross-fertilization, and knowledge spillovers and to produce incremental, radical as well as exaptative inventions. The exaptation propensity, however, is lower than other regions and is inclined to decrease in the last period. The same for the most inventive Italian regions like Lombardy, Emilia Romagna, and Veneto. Only Piedmont in Italy appears to be highly performing in both absolute and relative terms. In Spain, only Madrid and Catalonia attempt to catch up with the most innovative regions in terms of exaptation performance.

The best practices concerns some French regions like Ile de Framce (Paris), Bretagne, Pays de La Loire, Midi-Pyrenees (Tolouse) and Provence which disclosed a higher propensity to produce exaptation in spite of a slighter patent portfolio (compared to some knowledge-intensive German regions) and further reveal an increasing exaptation potential.

7 Enhancing the Competitiveness of EU Regions Through Smart Specialization and Exaptation Toward Local Industrial Policy Able to Sustain Innovation Ecosystems Trajectories

Now we can translate an exaptation trajectory in a path for policy in the European Union. For all reasons described upon in Europe is urgent a shift from vertical policy to horizontal policy and necessary to unify industrial policy oriented to the promotion of ecosystems crossing metropolitan area, clusters and multi-district, traditional sectors and territories able to enlarge and extent building platform to recoupling division of labor (in Smithian meaning) and division of knowledge (in Nonaka meaning) also as reconnecting tacitness and codified resources. In particular with more attention to tacitness as a frontier of power on a matching between serendipity and exaptation extending variety. Primarily, because competitiveness is no longer between companies but between regions as the self-contained frame of triangulation: manufacturing-services-intelligence in public and private alliances. Secondarily, because we need of more large division of labor at multilevel trajectories (people, companies, and territories) in a cognitive sense toward growing servitization able to increase both radical variety and customization moving quality of context (product, services, intelligence, and territories) increasing externalities and appropriability. Thirdly, because we need to push smart specialization in connection with quadruple innovation helix in a hard interaction between regional-local level and national-global level reducing duplication of industrial policy.

We can do this along four main trajectories of specialization action, inside the transition between a century of conflict to a century of negotiation and now toward intelligent collaboration with Fourth Industrial Revolution (digital world, AI, Cloud computing, simulation, Big Data) overcome the multilevel division of labor realized by Fordism in twentieth century between: rationality and creativity, technology and nature, individuality and community, science and arts, decision and culture.

1. Function of interaction between multiple public-private actors of cohesive communities
2. Agglomeration of common interests via local and transnational networks
3. Sectoral/intersectoral shared innovation with strong local roots
4. Knowledge Economy: networking, TLC, Internet, sharing activity.

We start by a focalization on knowledge-based society about for main points reinforcing horizontal industrial policies:

a. Central pre-and post-manufacturing phases for product and process innovation;
b. Centrality of intangible assets (knowledge, innovation, HR, organizational and social capital, human and semantic);
c. New actions and framework programs for innovation and knowledge;
d. Diffuse trajectory on sustainability and responsibility unifying actions on product, services, and intelligence with intermediate and final users.

Points developed by 6th European Framework Program (2002–2006) as a hard integration as reinforcing cross-industry trajectories of next UE Commission Program (2020–27):

(i) University-industry relations; (ii) Public research centers; (iii) Industrial technology development

(iv) Promotion of competition to encourage innovation; (v) European Aria Research Training (AER): coordination of national and regional programs.

A European Program able to sustain variety of industrial context in the different local regions in a multinational perspective for extended inter-industry technology and competences portfolios (Cappellin et al. 2019).

To create an environment conducive to innovation coherent with Lisbon's Strategy able to develop the absorptive capacity of regions and smart cities:

- integration of both sectoral and intersectoral platform projects;
- creation of networks of excellence: research, production and sales;
- joining programs between the Commission and member states;
- promoting technology transfer;
- making risk capital available;
- intellectual property protection;
- human resources development;
- social capital consolidation;
- increasing global spending on R&D at 3%;
- mobilizing actors in a triangulation between three main integrated levels—regional, national, European.

These are translated in the European policy of innovation in 7th Framework Program 2007–2013 described in five main integrated elements:

I. Cooperation: 2/3 resources 7th Framework Program in collaborative research in 10 areas (health, food, telecommunications, nanoscience/nanotechnologies, energy, climate change, transport, human sciences, space, security),
II. Ideas: scientific research of excellence,
III. People: internal researcher mobility Union,
IV. Capacity: research and knowledge society,
V. Nuclear research: nuclear fusion. Joint research center.

A set of incentives, therefore, that allow us those eco-systemic alignments (network, supply chain, platform, and multi-district) in the diffusion/acquisition of innovations, codifying in a more systematic way the relations between products, services, and knowledge, between material and immaterial, between concrete and digital. Mechanisms that can allow us to raise the quality of our platforms by extending the intersectoral boundaries through new materials, reengineering, innovative design, hybridization of emerging needs under the banner of radical customization modeled by digitalization. In particular, applying medium-tech research in the biomedical, packaging, agro-industry, wood-furniture (from the house to the boats), software, recreational boating, sportswear and technical clothing, mechatronics, domotics, pharmaceuticals, of which we report some emerging cases not representative but significant for the hybridization processes in Italy and Europe (Pilotti 2017). In short, we can raise the level of quality to make our products inimitable if the corporate culture and the intertwining of intersectoral relations toward new thickening and densifications due to hybridization and generative contamination of superior variety and creativity change supporting exaptation trajectories. Transferring between medium-large companies and SME systems, between multisectoral platforms and between territories, skills, and know-how toward a new socioeconomic, competitive, and technological order, cumulatively reorienting information-knowledge toward new diversity and virtuous asymmetries (in exaptation meaning as described before), between: large and small, invention and application ideas, territories and needs. Toward a recombined new multilevel and multicentered integrations. Levers to raise our eco-systemic productivity through an increase in the rate of innovation and quality, but also with their diffusion in a cross-industry sense and that Industry 4.0 can facilitate and strengthen the intersectoral networking with extended exaptated conditions of contexts. Roads that lead precisely to the servitization of products, as in the car industry, where customers will pay ever more for the cost to get access to the services offered by a product rather than for the ownership of the product itself is codifying the transfer channels of the information toward a new diffusive order: product born with a function and now transformed in other function by digitalization.

In fact, according to the scheme of Hidalgo, proposed in *The Evolution of the Order*, we should be able to find a new order to the wealth of information and know-how that over the centuries have allowed us to become a creative, albeit messy and unequal as it is weak in the transfer of knowledge due to an excess of informality and individualism. Such as crossing the existing information assets channeling them to new knowledge platforms with actions of contamination and formal and codified hybridization to renew our creativity bases and continue to make good products even if more complex via servitization.

Today we are condemned to higher levels of complexity for "long" chains of progress that cannot be achieved in solitude and/or through hyper-local channels but exploring inter-industry division of labor as matching between physical and cognitive ones. We will be able to achieve this by injecting superior confidence and empowering intercompany and interpersonal relations, overcoming selfishness, individualism, and familisms that often slow down the transmission of information and knowledge useful for creating value, as decreasing exaptation conditions of growth or serendipity results. The family that has represented a nucleus of development—entrepreneurial and educational—fundamental of this country for a century until the first two decades of the second post-war period, now risks representing a heavy constraint especially in the transfer of information and knowledge, reducing variety and tacitness. For this reason, family networks should be open to "external" contributions and to the variety (of members, managerial skills and ideas) injecting confidence to renew knowledge bases to transfer useful information to innovation, increasing exaptation conditions to growth (also with *emotional organization—creative and intelligent* as described in Pilotti 2019). Complex innovations that today require greater sharing of risks on an extended basis and a "long" network-supply chain. Because we are often very good at doing—even quickly—in short networks and in contexts of creative proximity (only informally shared) but more limited and slow when we need to innovate or transfer the results because they are hampered in their sharing, especially if in team, on the net and/or in a community of subjects not characterized by family or clan ties. It is the current situation where the products are best identified through the double "layer" in the first place of the services that surround them to create and transfer them and, secondly, for the knowledge that makes it possible to innovate and transform in time and space through connectivity, accessibility, networking, and shared creativity. A trajectory of industrial policy where serendipity and exaptation can reemerge as fuelling of sharing creativity and open innovation crossing multiple level inter-industry: micro–meso-macro (Bianchi and Labory 2019).

This is a good frame to enhance strategy supporting *exaptation philosophy* of industrial policy in the European Union able to sustain the richness of a variety of SME, integration of multi-district manufacturing systems, and competitiveness of smart cities in coherent regional ecosystems looking for a new emergent Europe for the future.

8 Conclusion

The objective of this paper was to investigate the potential of exaptation as a tool for strengthening the competitiveness of regions through smart specialization strategy. In this perspective, we highlighted that exaptation is a spontaneous process in innovative intensive regions while it is not common in lagging-behind regions. Furthermore, we also show that the attitude toward exaptation is declining in some innovative intensive region. Therefore, there is a need for policymaking related to the role of exaptation as a tool of smart specialization. However, we highlight that the smart specialization strategy has only focused on the adaptive form of innovation, which is grounded in the recombination of knowledge across the different technological and lightly related fields of knowledge. Differently, exaptation has not been included as a tool to leverage smart specialization in regions. To this purpose, we highlight the main drivers of exaptation and the process through which exaptation emerges. Based on this analysis, in the last part of the paper, we drafted some initial policy indications to support exaptation in regions.

References

Andriani P, Carignani G (2014) Modular exaptation: A missing link in the synthesis of artificial form. Res Policy 43(9):1608–1620

Andriani P, Cattani G (2016) Exaptation as source of creativity, innovation, and diversity: introduction to the special section. Ind Corp Change 25(1):115–131

Andriani P, Ali A, Mastrogiorgio M (2017) Measuring exaptation and its impact on innovation, search, and problem solving. Organ Sci 28(2):320–338

Balland PA, Boschma R, Crespo J, Rigby DL (2019) Smart specialization policy in the European Union: relatedness, knowledge complexity and regional diversification. Reg Stud 53(9):1252–1268

Bianchi P, Labory S (2019) Le Nuove Politiche Industriali dell'Unione Europea. Il Mulino, Bo

Boschma R, Coenen L, Frenken K, Truffer B (2017) Towards a theory of regional diversification: combining insights from evolutionary economic geography and transition studies. Reg Stud 51(1):31–45

Cappellin R, Ciciotti E, Garofoli G, Marelli E, Pilotti L et al (2019) The industrial policy in Europe; Seminar Document presented in Bruxelles 4 December 2019

Castaldi C, Frenken K, Los B (2015) Related variety, unrelated variety and technological breakthroughs: an analysis of US state-level patenting. Reg Stud 49(5):767–781

Cattani G (2005) Preadaptation, firm heterogeneity, and technological performance: a study on the evolution of fiber optics, 1970–1995. Organ Sci 16(6):563–580

Cattani G (2008) Reply to Dew's (2007) commentary: pre-adaptation, exaptation and technology speciation: a comment on Cattani (2006). Ind Corp Change 17(3):585–596

Cattani G (2006) Technological pre-adaptation, speciation, and emergence of new technologies: how Corning invented and developed fiber optics. Ind Corp Change 15(2):285–318

De Noni I, Orsi L, Belussi F (2018) The role of collaborative networks in supporting the innovation performances of lagging-behind European regions. Res Policy 47(1):1–13

Dew N (2007) Pre-adaptation, exaptation and technology speciation: a comment on Cattani (2006). Ind Corp Change 16(1):155–160

Dew N, Sarasvathy SD, Venkataraman S (2004) The economic implications of exaptation. J Evol Econ 14(1):69–84

Foray D (2016) On the policy space of smart specialization strategies. Eur Plan Stud 24(8):1428–1437

Foray D (2018) Smart specialization strategies as a case of mission-oriented policy—a case study on the emergence of new policy practices. Ind Corp Change 27(5):817–832

Gould SJ, Vrba ES (1982) Exaptation—a missing term in the science of form. Paleobiology 8(1):4–15

Mastrogiorgio M, Gilsing V (2016) Innovation through exaptation and its determinants: the role of technological complexity, analogy making & patent scope. Res Policy 45(7):1419–1435

McCann P, Ortega-Argilés R (2015) Smart specialization, regional growth and applications to European Union cohesion policy. Reg Stud 49(8):1291–1302
Mokyr J (1990) Punctuated equilibria and technological progress. Am Econ Rev 80(2):350
Pilotti (2017) Produttività cognitive e Politiche industriali locali. EAI-Edizioni Accademiche Italiane, Berlin
Pilotti (2019) Organizzazioni emotive (creative e intelligenti). McGraw Hill Italia
Shane S (2001) Technological opportunities and new firm creation. Manage Sci 47(2):205–220
Shane S, Venkataraman S (2001) Entrepreneurship as a field of research: aresponse to Zahra and Dess, Singh, and Erikson. Acad Manag Rev 26(1):13–16
Simon HA (1962) New developments in the theory of the firm. Am Econ Rev 52(2):1–15
Simon HA (1995) Near decomposability and complexity: how a mind resides in a brain. In: Santa fe institute studies in the sciences of complexity-proceedings, vol 22. Addison-wesley publishing co, pp 25–25

The Technology Second Chance: Leveraging Creativity by Convergence of Serendipity and Exaptation Processes

Barbara Leporini, Marina Buzzi, and Luciano Pilotti

1 Introduction

Technology greatly enhances life for all. It is very interesting to be able to exploit technology in different contexts offering to the technology a "second life". Indeed discoveries can sometimes happen accidentally, for instance, as a side effect of other experiments, by accident, or the same invention can be translated in other fields, that the first inventor was unable to image. In both cases, it is required sagacity or creativity to figure out how to apply or exploit an observation and its connected data.

Serendipity refers to an interesting and unexpected event that apparently occurs due to chance and often appears when we are looking for something else. Serendipity has been the trigger for several innovations and crucial advances in science and technology.

Serendipitous discoveries are unexpected accidents that led to new discoveries totally unexpected and unsought for (Roberts 1989). Many everyday objects have been discovered by accident such as Teflon, Velcro, nylon, X-rays, penicillin, safety glass, sugar substitutes, polyethylene, and other plastics. Accidents indeed have enabled some of our deepest scientific knowledge to be conceived (Roberts 1989). It happens with high probability often because the emergent innovation is pushed up by borderline context among many fields crossing involuntarily with the interdisciplinary approach: when looking for target A is possible to find many other connected targets as B, C, n.

B. Leporini
ISTI – Istituto di Scienze e Tecnologie dell'Informazione "A.Faedo", CNR, Pisa, Italy

M. Buzzi
IIT - Istituto di Informatica e Telematica, CNR, Pisa, Italy

L. Pilotti (✉)
ESP – Department of Environmental Science and Policy, University of Milan, Milan, Italy
e-mail: luciano.pilotti@unimi.it

C. AM. La Porta et al. (eds.), *Understanding Innovation Through Exaptation*,
The Frontiers Collection, https://doi.org/10.1007/978-3-030-45784-6_9

However, are actually extraordinary people who note and exploit these events make it possible to translate it into a new scenario and to create a new invention between serendipity and exaptation. The first one is—as known—the occurrence and development of events by chance in a happy or beneficial way in a randomized process toward very open chance or solutions not necessarily connected with originally character or nature. The second one—more specifically—is a process by which features acquire functions for which they were not originally adapted or selected and for that reason exaptation is better defined as a counterpart to the concept of adaptation. The best case cited by Gould is the earliest feather belonged to dinosaurs not capable of flight.

It is remarkable to cite one between many, the Penicillin drug, which, still today, is saving innumerable human lives.

"In the fields of observation chance favours only the prepared mind" (Louis Pasteur) who are able to notice the unexpected and make it constructive, and to translate invention from one field to another one. The intuition can be refined thanks to a solid scientific preparation, and to the ability to observe and analyse the surrounding. Alexander Fleming, inventor of penicillin, and Wilhelm Röntgen, of the X-ray, discovered by chance during or in relation to scientific experiments. They were able to catch "side-effect" data and to intuit how to exploit them in different contexts. In a process more similar to exaptation more than serendipity.

The divergent thinking enables one person to think and link memory data in a creative way. Divergent thinking occurs in a spontaneous, with free "non-linear" process, such that many ideas are generated in an emergent cognitive fashion. Many possible solutions are explored in a short amount of time, and unexpected connections are drawn and in that case prevails a serendipitous process.

In this chapter, we discuss "second life" for technology by analysing famous discoveries and we try to link the related neuropsychology of inventors.

Section 2 focuses on technology applied in the field of disability and translated in different fields and vice versa as a prevailing case of exaptation. In Sect. 3, we show examples of translating discoveries from their original application fields to new sectors. Section 4 introduces a few examples of second chance technology applied in the medical field. Lastly, Sect. 5 introduces a short discussion on how fuelling new applications of technology or discoveries in different operative fields.

We propose—roughly speaking—in many cases of mass applied technology a sort of convergence between serendipity and exaptation as the same complex process of second chance (or in some case also third chance) by the source of emergent creativity.

2 Disability and Technology: The "Virtuous Camouflage" of Creative Differences in Personal Competences

Technology helps people with everyday tasks. In the field of people with disabilities, technology is crucial since it is able to greatly support persons, increasing their autonomy. However designing accessible products benefits all people, since temporary sense reduction can happen during life.

The ability to translate technology in different contexts, offers to technology a second or even third life. For instance, technology for blind people was translated to eye-free driving, vibration engine useful for delivering fast information to blind users was applied in smartwatches or wristband for easily perceivable notifications, and so on.

Smart devices such as Google Glass have multiple applications, from enabling hearing impaired people to see videos in a smooth environment.

Another example of technology was the Minitel (terminal emulation software) conceived in France, originally distributed to save paper delivering phone directory information, it was actually a revolution in the communication between people, and represent a revolution for enabling heard people to exchange information autonomously (Kessler 1995).

Text To Speech (TTS) (Dutoit 1997) is a tool largely used by blind people to interact with computer and mobile devices as well as for reading digital books (Hinterleitner et al. 2014). In fact, TTS technology allowed to propose voice synthesizers (Klatt 1987), which is exploited primarily for screen reading software for the visually impaired (Asakawa and Leporini 2009). Next, thanks to the enhancement in the quality of natural digital voices as well as multilingual synthesizers (Sproat 1997), voice synthesizers are used for several common and very popular applications, such as navigation tools, public announcements at the airport or on buses and trains and more recently for vocal Personal Assistants (PAs) (e.g., Google Assistant, Amazon Alexa, and Apple Siri).

Also for vocal assistants like Alexa, Google Home, etc., voice interaction has been heavily exploited to interact naturally by voice. This is an important step in the information society, but it represents a valuable support for people with motion impairments and with other special needs, such as elderly persons.

Speech recognition is an interdisciplinary field that develops methodologies and technologies that enables the recognition and translation of spoken language into text by computers (Bristow 1986). It incorporates knowledge and research in linguistics, computer science, and electrical engineering fields.

Since 1952, there has been much research interest in speech recognition (Juang and Rabiner 2005). Starting with a system for single-speaker digit recognition (Davis et al. 1952), technology and methodology evolved to propose solutions which were applied to various specific cases, up to having first commercial speech recognizers, like "Dragon Dictate" (released in 1990) (Hawley 2002).

Much of the progress in the field is owed to the rapidly increasing capabilities of computers. Today speech recognitions is largely used for numerous applications in Artificial intelligence domains as natural interaction between humans and machines. Thus, speech recognition applications include voice user interfaces such as voice dialing (e.g., "call Robert"), customized routing (e.g., "I am about arriving at home"), domotics appliance control, search keywords (e.g., find a podcast where particular words were spoken), simple data entry (e.g., entering destination and date to search for a train), preparation of structured documents (e.g., a medical report), speech-to-text processing (e.g., word processors or emails), and so on.

From an accessibility perspective, voice-controlled, home-based intelligent personal assistants have the potential to greatly expand speech interaction beyond dictation and screen reader output (Pradhan et al. 2018). All this has greatly favored the autonomy of persons with disability who can take advantage of the progress in the speech recognition, in order to be able to carry out numerous everyday activities independently (Sharma and Wasson 2012). Blind people, for instance, can find advantages in performing via voice some searches on the net, as well as it occurs for people with motion impairments. For example, with the Amazon Fair TV stick, thanks to Alexa integrated into the device, for those who cannot see or have difficulty typing it is now possible handling easily a smart TV and its apps. Voice interaction, therefore, allows people to handle not only household appliances and everyday tasks, but also a computer, mobile devices, and their applications. Speech recognition is also useful for people who have hearing problems. Voice interaction is, in fact, increasingly used by these people to practice speaking through specific software (Barker 2003), (Dalby and Kewley-Port 1999) and (Wald and Bain 2005). Applications based on speech interaction are more generally used for communication between persons with special needs (Eisenberg 2007) and (Venkatagiri 2002). Automatic speech recognitions is also used for supporting deaf people and students in real-time communication, thanks to specific software used to translate spoken content into written or sign languages (Wald 2006).

3 Translating Discoveries in Different Contexts for Emergent Innovation

Many things used every day are the result of discoveries by chance or the reuse of technology born for a certain purpose and then reused for others.

The opportunity to cook food by means of microwaves was discovered by chance in the United States of America by Percy Spencer, an employee of Raytheon, while making magnetrons for radar equipment (melting a chocolate bar in his pocket). Since then, billions of magnetrons have been established, some for radars, but most of them for an unsuspected application in the beginning: the microwave oven (Vollmer 2004) as a typical example of crossing between serendipity and exaptation processes.

Unfortunately, a huge amount of money invested in military research is carried out in military labs. A lot of invention originally for war aims are translated in the civil domain such as the Internet protocols (Arpanet). Similarly, we often reflect on how many billions of dollars are invested in space missions and research in the field of physics and astrophysics. At the same time, many do not know that dozens of inventions designed for space and created (in most cases) by NASA researchers have been used for years in our everyday lives. From the scratch-resistant coating of the glasses (originally dedicated to the visors of the astronauts' helmets) to the memory foam material of which many mattresses are made (used in space to protect astronauts from shocks), passing through cordless devices (the technology dates back to when in 1960 Black & Decker and NASA devised the first auger used on the Moon) and "invisible" orthodontic appliances (the TPA material—translucent polycrystalline alumina—was developed by the NASA Industrial Application Center). The list is very long and every year (since 1976) it is updated by the US space agency in a catalogue with which the 50 technological patents that have had the greatest effects in our life in the past 12 months are presented, from medicine to transport, from the environment to public safety (NASA 2019a). In the numerous pages of the reports present in the section of the NASA website dedicated to technological fallout, several interesting inventions are reported (NASA 2019b).

In the field of fabric technology, Gore-Tex was born for space-suits, next it was widely used for numerous other types of domains. In fact, Gore-Tex, like the other materials composed of polytetrafluoroethylene (Teflon), is used for a wide variety of applications: technical and high-performance fabrics, but also gaskets and insulators. In particular, it presented a big evolution for some sectors such as mountaineering and extreme sports in general, as it allowed the production of technical clothing (windbreakers) resistant to water, wind, breathable, and very light. It is also used in the surgical field for the production of artificial blood vessels and abdominal implants. Special textures for covering shuttles, during the moon missions, have been exploited for bulletproof vests. Many examples of mixing between exaptation and serendipity, and applied demonstration, are difficult to distinguish among them.

4 Medical Applications and Emergent New Functions by Old Technology

Several medical devices, tools, and therapies derive from previous inventions, discoveries, or observations especially in the field of physic experiments, devices, and tools such as echo/Doppler, radiotherapy, or laser applications, just for mentioning a few of them.

Wilhelm Röntgen discovered X-rays in 1895, while experimenting with high voltages, he noticed an anomalous effect: arousal of fluorescence at a distance from tubes in which cathode rays were elicited, a phenomenon which suggested the existence of a new kind of ray other than cathode rays (Widder 2014).

Nowadays radiation and radioactive drugs are used for diagnosis, treatment, and research activities. Radiation therapy or radiotherapy (RT), for instance, is usually exploited as cancer treatment to control the proliferation and/or destroy malignant cells, by using ionizing radiation. Passing through tissue cells, ionizing radiation releases electrons, killing cells or modifying genes in order to impede cells to grow up.

Since X-rays, for example, pass through soft tissues but are stopped by dense materials, showing broken bones or detecting cancers agglomerates. More assumption of radioactive substances enables monitoring the radiation given off as the substance moves through the body.

Another example of physics discovery applied to medicine is the echo/Doppler, which exploits the homonymous effect (observed by Christian Andreas Doppler), i.e., frequency of a wave depends on the relative speed of the source and the observer. Lazzaro Spallanzani, an Italian physiologist, studied phenomena related to ultrasound, in 1794, by observing echolocation among bats. After the piezoelectricity discovery in 1877 (Jacques and Pierre Currie) and the creation of a hydrophone (the "first transducer") to detect objects in the bottom of the ocean (after the Titanic sank) by Paul Langevin, many progresses were accomplished also in the medical field to exploit ultrasounds as therapy as well as a diagnostic tool (CME Science 2018).

Doppler ultrasonography was created in 1966 by Dennis Watkins, John Reid, and Don Baker. This device employs the Doppler effect for creating imaging of the movement of body fluids, and their relative velocity to the probe. Colour flow Doppler shows the velocity by colour scale. Colour Doppler images can be associated with grayscale images to obtain duplex ultrasonography images, in order to visualize area anatomy (CME Science 2018).

Concerning laser technology, the main principles were first suggested in 1917 by A. Einstein but the first LASER (light amplification by stimulated emission of radiation) was built in 1960 by the Russian N.S. Basov and A.M. Prokhorov, exploiting the theoretical base deducted by C.H. Townes. In 1964 those three physicians got the Nobel Prize for their work (Horstmann 2002). The first application of the laser was for military purposes.

Today laser has several applications in medicine, for surgery (especially eye surgery), laser healing, kidney stone disaggregation, ophthalmoscopy, and skin treatments for keratosis, acne, cellulite, and stretch marks. More uses of the laser is also exploited as treatment of superficial cancer by shrinking or destroying tumours or precancerous cell agglomerates. Many technologies are able to support and push advancements in personalization medicine (Pilotti 2017) as an important part of future medical treatments for long chains of serendipity–exaptation processes.

5 Discussion and Brief Conclusions

The human mind is able to work in different ways exploiting logic, creativity, and experience. By observing the surrounding, extracting, and connecting information, we are able to deduct new knowledge and compose it in a creative way, exploring both or new forms as new functions.

In this chapter, we briefly have discussed only a few between several inventions born for as a "side effect" of others experiments or inventions or designed for different goals and translated in different contexts.

Literature, as well as application cases, show how particular discoveries and experiments in technology can have a significant second fall in the society for everyone.

Technology for people with disability can benefit the whole society as well as technology for simplifying everyday tasks makes actually simpler the life of people with disability. For instance, the new interaction paradigms offered by voice-controlled PAs provide great potential for inclusive, accessible interaction. Unexpected use cases include speech therapy, learning and memory support (Pradhan et al. 2018). Benefits of using Alexa, for instance, are a reinforcement to make people with autism or with speech impairment put more effort in enunciating words slowly and more clearly. Children with autism, in particular, like the interaction with the technology, which provides repeatable answers and shows predictable behaviours, respect to unpredictable people (who may be a source of anxiety). Reading books and other printed resources make an assistive technology for people with dyslexia when studying. More people with memory disorder can benefit from asking Alexa the day, date, time, weather, set wake-up or reminder alarms (Pradhan et al. 2018).

The technology second chance refers to exploit technology for different purposes in a creative way. At this aim, the interaction with people with different knowledge and skills, working in different fields can create valuable synergies to translate and adapt inventions for different purposes.

In conclusion, we have demonstrated in a descriptive way the relevance of convergence between serendipity and exaptation to be able to support mechanism of creativity. Consequently, showing the importance of both research and applied policy (in science and industrial fields) oriented (a) to hybridization of knowledge and applied fields and, (b) continuous contamination of specializations and competencies in an organization and/or in the R&D department. Along that trajectory, we need to increase interdisciplinary or multidisciplinary approaches to improve the strategy of innovation in research and industrial fields of application able to inseminate diffuse creativity.

References

Asakawa C, Leporini B (2009) Screen readers. In: Stephanidis C (ed) Chapter in the book: universal access handbook, Taylor & Francis, June 11, 2009

Barker LJ (2003) Computer-assisted vocabulary acquisition: the CSLU vocabulary tutor in oral-deaf education. J Deaf Stud Deaf Educ 8(2):187–198

Bristow G (ed) (1986) Electronic speech recognition: techniques, technology and applications. Collins, London

CME Science (2018) Who Invented Ultrasound? https://cmescience.com/who-invented-ultrasound/

Dalby J, Kewley-Port D (1999) Explicit pronunciation training using automatic speech recognition technology. CALICO J, 425–445

Davis KH, Biddulph R, Balashek S (1952) Automatic recognition of spoken digits. J Acoust Soc Am 24(6):637–642

Dutoit T (1997) An introduction to text-to-speech synthesis, vol 3. Springer Science & Business Media

Eisenberg LS (2007) Current state of knowledge: speech recognition and production in children with hearing impairment. Ear Hear 28(6):766–772

Hawley MS (2002) Speech recognition as an input to electronic assistive technology. Br J Occup Ther 65(1):15–20

Hinterleitner F, Norrenbrock C, Möller S, Heute U (2014) Text-to-speech synthesis. In: Quality of experience. Springer, Cham, pp 179–193

Horstmann N (2002) Light amplification by stimulated emission of radiation. Phys Inform Technol, 1–4

Juang BH, Rabiner LR (2005) Automatic speech recognition–a brief history of the technology development. Georgia Institute of Technology, Atlanta Rutgers University and the University of California. Santa Barbara, 1, 67

Kessler J (1995) The French Minitel. D-lib Magazine

Klatt DH (1987) Review of text to speech conversion for English. J Acoust Soc Am 82(3):737–793

NASA (2019a) Table of Contents INSIDE 2019 at https://spinoff.nasa.gov/Spinoff2019/toc_2019.html

NASA (2019b) Spinoff at https://spinoff.nasa.gov/Spinoff2019/index.html

Pilotti L (2017) Produttività cognitiva e Politiche Industriali Locali – Linee di azione per il caso italiano tra innovazione sociale, creatività condivisa, responsabilità e sostenibilità. Edizioni Accademiche Italiane, Berlin Morebooks, EAI

Pradhan A, Mehta K, Findlater L (2018, April). Accessibility came by accident: use of voice-controlled intelligent personal assistants by people with disabilities. In: Proceedings of the 2018 CHI conference on human factors in computing systems. ACM, p 459)

Roberts RM (1989) Accidental discoveries in science. In: RM Royston (ed) Serendipity: accidental discoveries in science. Wiley-VCH, p 288. ISBN 0-471-60203-5

Sharma FR, Wasson SG (2012) Speech recognition and synthesis tool: assistive technology for physically disabled persons. Int J Comput Sci Telecommun 3(4):86–91

Sproat, R. W. (1997). Multilingual text-to-speech synthesis. KLUWER academic publishers

Venkatagiri HS (2002) Speech recognition technology applications in communication disorders. Am J Speech Lang Pathol

Vollmer M (2004) Physics of the microwave oven. Phys Educ 39(1):74

Wald M (2006, July). Captioning for deaf and hard of hearing people by editing automatic speech recognition in real time. In: International conference on computers for handicapped persons. Springer, Berlin, Heidelberg, pp 683–690

Wald M, Bain K (2005) Using automatic speech recognition to assist communication and learning

Widder J (2014) The origins of radiotherapy: discovery of biological effects of X-rays by Freund in 1897, Kienböck's crucial experiments in 1900, and still it is the dose. Radiother Oncol 112(1):150–152

Innovation-Oriented Programming: Software Development as a Medium for Exaptation and Implications for the Active Facilitation of Innovation Within Virtual Environments

David King

1 A Tale of Two Researchers: Serendipitous Exaptation in the Software Domain

> It started with a Harvard astronomy professor, Alyssa Goodman, serendipitously meeting a computer scientist and imaging specialist from Brigham and Women's Hospital, and their recruitment of a very adventurous, open-minded, young student.
>
> Michelle Borkin, TEDx Talk Boston, 2011

This is how Michelle Borkin, then Ph.D. candidate in applied physics at Harvard, now an Assistant Professor specializing in data visualization at Northeastern University, described the beginning of the interdisciplinary collaboration that launched her career. She was speaking at TEDx Boston in July 2011, and she was the "adventurous, open-minded, young student" recruited by astronomer Dr. Alyssa Goodman and imaging specialist Dr. Michael Halle. In September of 2004 Halle and Goodman found themselves at the same conference on visualization. Johnson et al. (2006) Halle had been working in the Surgical Planning Lab at Brigham and Women's Hospital for over a decade and was there to participate in a panel related to advances in visualization technology. Goodman was there to give a separate presentation titled "Visualization Challenges in Astrophysics." During her presentation, Goodman told the crowd that answering fundamental questions in astrophysics involved three spatial dimensions and many more non-spatial dimensions, but that researchers were greatly hindered by being limited to only viewing 2 dimensions at a time. Goodman (2004) After her presentation, Halle approached her. "I can solve your problem," he said. Seo (2008) A bold statement indeed, but it turned out he was right.

There are a variety of medical imaging technologies, most notably Computed Tomography (CT) and Magnetic Resonance (MR), that involve taking multiple 2-dimensional images ("slices") of a portion of the body in order to obtain information

D. King (✉)
Exaptive, Inc, 124 NW 12th Street, Oklahoma City, OK 73103, USA
e-mail: king@exaptive.com

C. AM. La Porta et al. (eds.), *Understanding Innovation Through Exaptation*,
The Frontiers Collection, https://doi.org/10.1007/978-3-030-45784-6_10

about the 3-dimensional volume under study. These technologies were revolutionary diagnostic tools—CT inventors won the Nobel Prize in 1979—however, due to limitations of computing performance it was a slow and difficult process to reconstruct accurate 3d models from the 2d slices. Medical professionals were often limited to using the multiple 2d images, and suffered the same challenge articulated by Goodman—they were trying to infer a 3-dimensional reality while only being able to see 2 dimensions at a time.

In the Surgical Planning Lab at Brigham and Women's Hospital, Halle worked with a team of software developers on a program called "3d Slicer" which aimed to solve this problem. The goal was to use recent advances in computer graphics to support fast, flexible, and interactive rendering of 3d volumes that could assist surgeons performing delicate brain surgery. First invented in 1999, 3d Slicer had been successful in reconstructing 3d brain volumes from collections of 2d MRI images. Gering et al. (1999) Halle was confident that the same technology could be used with Goodman's astronomy data. Goodman was intrigued. To pursue a collaboration they created the AstroMed project within Harvard University's Initiative in Innovative Computing and recruited Borkin. In 2007 Borkin published "Application of Medical Imaging Software to 3D Visualization of Astronomical Data" showing that the same software that allowed surgeons to more easily and accurately explore the brain could also allow astronomers to more easily and accurately explore the cosmos (Fig. 1).

Not only was the use of medical 3d imaging software in the field of astronomy possible, but also it was valuable: it allowed Borkin to study the stellar outflows (mass being emitted from newly forming stars) in the Perseus region of the sky with such speed that she could analyze a section larger than was previously feasible with

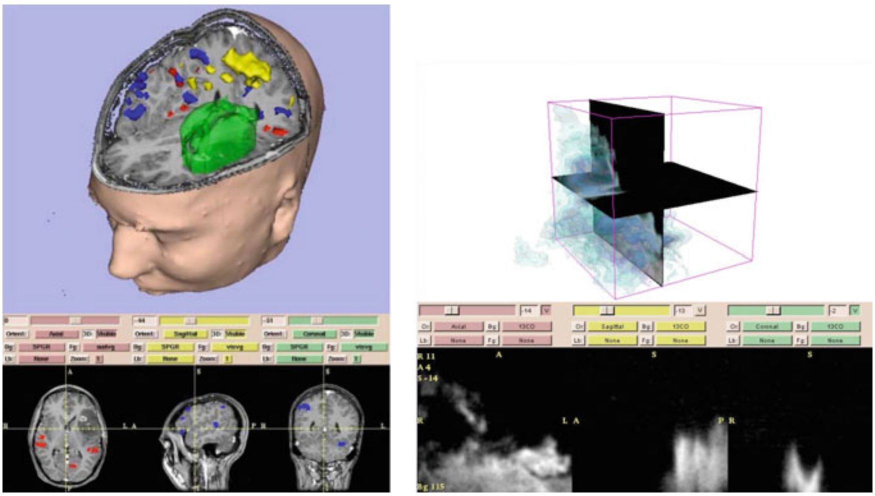


Fig. 1 3d Slicer software being used to model human brain based on MRI data (left) and 8 years later being used to model star-forming phenomena in the Perseus region based on astronomical data (right) (Borkin et al. 2005)

prior tools. With this increased area of study came discovery—Borkin found undocumented outflows that resulted in a more nuanced understanding of the phenomena related to star formation (Seo 2008; Borkin et al. 2007).

The AstoMed project led to a number of other successful innovations, not only through the co-opting of medical imaging techniques for use in astronomy, but also through the reciprocal pathway as well. Just as medicine helped astronomy by lending 3d techniques to a problem astronomy had with 2d images, astronomy helped medicine by lending a 2d technique to a problem medicine had with 3d images. Radiologists using 3d CT models of coronary arteries in order to diagnose cardiovascular disease were only able to identify, on average, 39% of the high-risk regions present in a patient. By co-opting a technique astronomers used to represent 3d nebula data as 2d "tree maps," radiologists found that they could improve their diagnostic performance substantially. With the astronomy-inspired tree maps, they were able to detect 62 % of the high-risk regions—a 23% increase just by using a new visualization method on existing data (Borkin 2011) (Fig. 2).

These two anecdotes of cross-disciplinary innovation are much the same as the other examples detailed throughout this book in that they are exaptations: the co-opting of techniques developed in one field, for one purpose, to an application in another field, for a different purpose. But these examples are also different in one very important aspect—they are both exaptations implemented in software. On the surface that may not seem like an important distinction. Why should it matter whether an exaptation is implemented through software or by some other means? Why should we care whether the innovation is built with 1s and 0s in the memory of a computer, versus ink on a page, or metal from a forge? If our goal is simply to be historians of

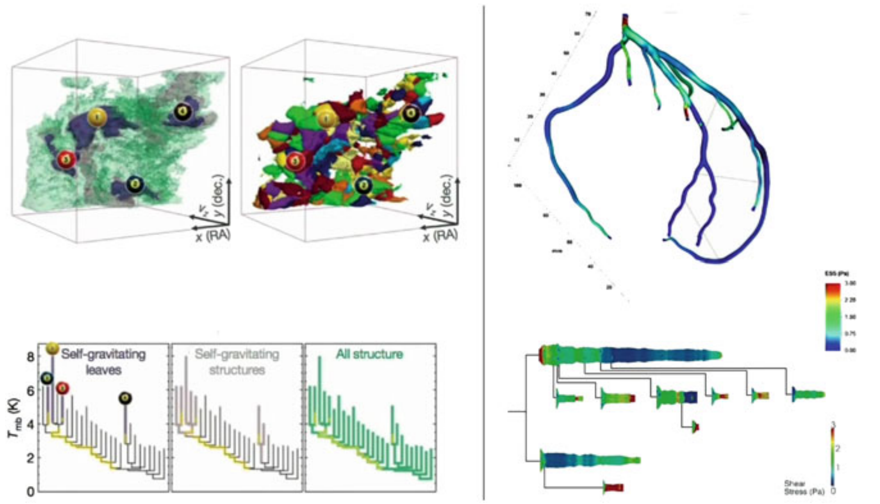


Fig. 2 On left, astronomical technique for augmenting 3d nebula images (top) with 2d treemap visualizations (bottom). On right, 2d treemap technique (bottom) applied to 3d coronary artery data (top) (Borkin 2011)

exaptation, then it matters little. However, if our goal is to be engineers of exaptation—to experiment with the phenomenon until we not only understand it but also can control it, and not only control it, but also create it, then I will show that the distinction is critical.

2 Software's Unique Position: The Characteristics of Evolutionary Biology but with Levers We Can Control

The current discourse on innovation via exaptation is based on an analogy between the cognitive "ah-ha" moment of radical innovation and evolutionary biology. The path of that analogy is shown with green arrows in Fig. 3 as follows: that biological evolution demonstrates the specific phenomenon of exaptation (arrow A), that this phenomenon is analogous to a mental process, often based on serendipitous triggers, in which it becomes apparent that some knowledge can be co-opted for a new purpose (arrow B), that this realization can remain in the knowledge domain without being reduced to practice (arrow C), or can give rise to (arrow D) a tangible manifestation usually considered to be a radical innovation (arrow E).

The green pathway operates across the domains of the natural and cognitive sciences, building an analogical bridge between the two, and, if it results in a tangible artifact, produces one that lives in the physical domain, which is a domain distinct from either of the previous two. This pathway is valuable in furthering our understanding of innovation, but it does not help us facilitate it because all three of the domains in which it operates are domains in which it is ineffective or difficult to exert

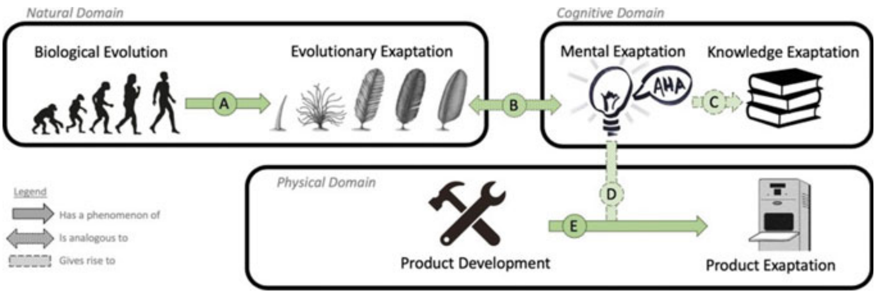


Fig. 3 Conceptual pathway linking biological exaptation to innovation through the cognitive and physical domains

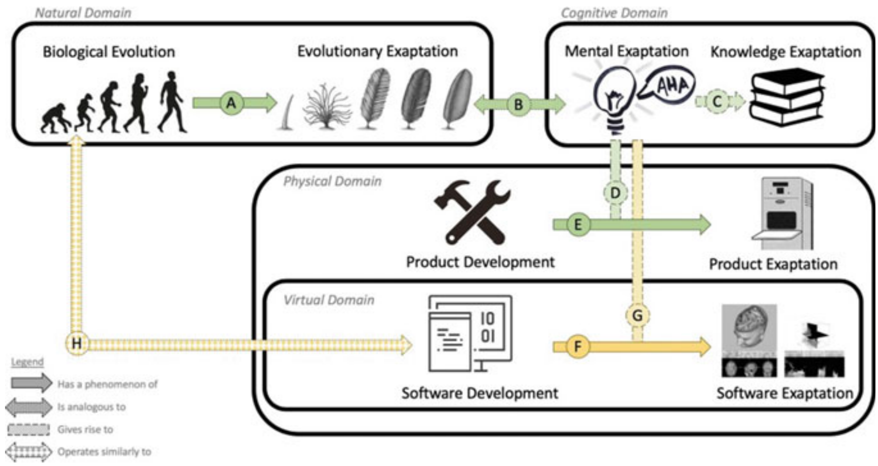


Fig. 4 Conceptual pathway linking biological exaptation to innovation through the virtual domain

influence,[1] as well as being difficult domains in which to interrogate the processes occurring within.

The yellow pathway of Fig. 4 shows a way to link the concepts of biological evolution, exaptation, and innovation, but through an explicit "virtual domain," the domain of software.

This pathway is based on the recognition that software development is a subset of product development, and that it exhibits similar exaptation phenomenon (arrow F) due to mental exaptation processes (arrow G). The AstoMed case study shows this to be the case. I will use the term "innovation arena" to describe a specific area in which innovation occurs, identifying software development as an innovation arena within the broader innovation arena of product development. There are three important distinctions between the yellow pathway through the software arena and the green general pathway through the larger product arena, each of which has implications for the facilitation of innovation. Firstly, the software arena pathway operates in the virtual domain, which is a domain over which we can exert a larger degree of influence at a much lower cost of time, money, or overhead compared to the domains traversed by the more general product arena pathway. Secondly, the software arena pathway supports easier interrogation of the processes at play within the arena because the

[1] The natural domain is simply an analogical domain to the cognitive domain, so our ability to exert control in this domain does not help us facilitate mental exaptation unless the organisms we are exerting control over are somehow analogous to the problem space we are trying to innovate in. Interestingly, if we did encode our problem organically, this would be a form of biological computing and it could be argued that it was, therefore, equivalent to software development using chemistry instead of code. As for the cognitive domain, there are some ways to exert control, through methods like priming and through processes like brainstorming, but since cognition remains a mostly black-box process it is difficult to assess the effects of these interventions or tailor them to the thought process of the individual. The physical domain offers many opportunities to exert control, but these are frequently expensive from a financial, time, and/or process overhead perspective.

design, implementation, and iteration of the innovation artifacts also occur in the virtual domain, leaving audit trails that can be inspected with a variety of tools and techniques in standard and structured ways. Lastly, but most importantly, today's software arena operates in a manner more analogous to biological evolution than can be claimed for more general, non-virtual, product development (arrow H). As I'll show, the existence of this operational similarity, not just a conceptual analogical similarity, between biological evolution and software development opens up new opportunities for the active facilitation of innovation via exaptation.

In the anecdotes of exaptive innovation like the ones so far presented in this book, we see ideas from one domain co-opted for use in another in order to solve particular problems in novel ways. But what if the problem we want to solve is the act of problem-solving itself? Biological evolution has been consistently producing radical innovations for billions of years through the process of exaptation—can we exapt exaptation? In order to co-opt exaptation from the innovation arena of nature for use in an innovation arena of human endeavor, we must show that arena to be compatible with receiving it. That is, if we wish to facilitate mental exaptation by leveraging what we know about evolutionary exaptation, we must show that the innovation arena in which we plan to do so is not only analogically similar to evolutionary biology but also that it actually operates similarly as well.

Software engineers have a long history of using biological analogy to inspire and refine their designs. Alan Kay, considered the father of object-oriented programming, described biology as one of his "favorite sources of fruitful analogies" (Kay et al. 2006) and credited biological inspiration for his vision for object-oriented programming saying, "I thought of objects being like biological cells… only able to communicate with messages." (Kay 2003) Despite many recorded anecdotes of biological-inspired software designs and many software programs emulating biological processes, Conway's Game of Life being a specific example (Bays 2010) and genetic algorithms being a general one (Whitley 1993), I have found no rigorous comparison of software development as a phenomenon to biology. I lay out the comparison myself below, focusing specifically on the conditions and mechanisms required for biological evolution to occur and showing that software development environments are rich with the same.

There is no single universally adopted definition of the requirements for biological evolution via natural selection, partially because there are multiple mechanisms by which evolution can occur. Vertical Gene Transfer (VGT), the transmission of genes hierarchically from parent to child, made famous by Darwin, is not the only available evolutionary mechanism. Many single-celled organisms, like bacteria, evolve by passing and/or receiving genetic material through cell membranes from peer organisms, including those of other species, through a process called Horizontal Gene Transfer (HGT) made famous by Woese. It has been argued that HGT was in fact the chief driver of early evolution before organisms reached a "Darwinian Threshold" at which point VGT became a more effective evolutionary mechanism. Woese (2002) From the perspective of facilitating innovation, we are not wedded to either horizontal or vertical models but instead desire to develop a comprehensive framework that accounts for all the ways that an organism can evolve and produce a biological innovation. Toward this aim, the list below enumerates the accepted conditions that must be present to support evolution, either horizontally or vertically. In the case of vertical transfer I refer to the recipient of the transmitted genes as the offspring, receiving from a parent. In the case of horizontal transfer I refer to it as the recipient, receiving from a donor. Recipients of horizontally transferred genes still need to produce offspring, as natural selection acts the same regardless of the mechanism of transfer.

- ***Differential fitness***: Evolution will not occur if organisms are all equally "fit" for all environmental contexts in which they find themselves. The environment must favor certain organisms as being "more fit" relative to others (Gildenhuys 2019).
- ***Reproductive capability:*** Evolution will not occur if organisms do not have the potential to produce offspring, and to produce them in equal or greater quantity than the number required to reproduce (Gildenhuys 2019).
- ***Existential selection***: Evolution will not occur if variations in fitness are without reproductive consequences. Organisms with greater fitness are afforded reproductive advantages while those with lesser fitness are less likely to reproduce (Gildenhuys 2019).
- ***Feature transmission:*** Evolution will not occur if features from one organism cannot be passed on to others. In vertical gene transfer this is accomplished via heredity—a parent passing genes on to its children. In horizontal gene transfer this is accomplished via transformation, transduction, or conjugation (Gildenhuys 2019; Rogers 2019).
- ***Feature continuity:*** Evolution will not occur unless a transmitted feature is able to manifest in the offspring or recipient in a way similar to its original manifestation. That is, evolution will not occur if an offspring or recipient does not at least partially resemble its parent or donor with regard to the characteristics that gave the parent or donor a fitness advantage (Gildenhuys 2019).
- ***Feature variation:*** Evolution will not occur if feature transmission produces exact copies of the parent or donor (Gildenhuys 2019; Rogers 2019).

The tension between the last two requirements creates the need for evolutionary systems to exhibit related but non-exact reproduction. The offspring/recipients must represent the parents/donors in the most important ways for the current context—fitness—but must also be different from them in enough ways to provide the diversity required for continued evolution in response to environmental changes. Research that has explored the mechanisms by which biological systems are able to support both the requirements of heredity and variation have identified modularity as a "central concept in evolutionary biology." (Melo et al. 2016) Modularity allows for three distinct processes that support evolution in different ways:

- ***Dissociation***: The ability for one feature of an organism to grow, develop, and change, without affecting a different feature of the organism (Raff 1996).
- ***Divergent Duplication***: The ability for a feature of an organism to be copied but for the copy to develop differently than the original (Raff 1996).

- ***Co-option:*** The ability for one instance of a feature of an organism to be used in a different context, for a different purpose, than another instance of the same feature (Raff 1996).

Just because a system is theoretically capable of evolving doesn't mean that it will, or that the process will proceed at a pace necessary to produce diversity within a specific time frame. I therefore add two evolutionary accelerants to our growing list of evolutionary requirements:

- ***Mobility***: "Horizontal gene transfer is made possible in large part by the existence of mobile genetic elements" (Rogers 2019) There is a similar analog in the case of vertical gene transfer: siloed populations that are unable to find a variety of mates lose genetic diversity.
- ***Scale***: Increased population size speeds evolutionary processes (Olson-Manning et al. 2012).

The three lists above encompass six conditions, three mechanisms, and two accelerants for biological evolution. All eleven items have strong analogs in the field of software development. Table 1 aligns these biological concepts to their counterparts in the software development arena.

Table 1 shows the commonality between the natural phenomenon of biological evolution and the human phenomenon of software development, suggesting that the software environment not only exhibits exaptation phenomenon similar to biology, but also may do so through similar mechanisms.[2] However, this does not mean that every observed software exaptation was created due to evolutionarily analogous software mechanisms. I will argue that most software exaptations are not. The AstroMed example, while clearly being an exaptation of software was not exapted in software or through software. What I mean is that the exaptation occurred in the cognitive domain, not in the virtual domain. It was simply implemented in the virtual domain after being conceived in the cognitive domain.

In this way the AstroMed exaptation is not unique to the other examples of exaptation shared across the chapters of this book—it is just another mental exaptation, and that is precisely why it relied on serendipity. In order to have software that creates exaptations in concert with our thinking, instead of software that simply implements exaptations at the command of our thinking, we need to change the way we program. I'll use the rest of this chapter to show how. But we also need to change the way we think about thinking. We need to fall out of love with the myth of the lone genius (Satell 2016; Shenk 2014) and stop seeing innovation as something that occurs only inside our head—it's too dark in there. Despite advances in cognitive psychology,

[2]Programs can be written to be self-modifying or use non-deterministic algorithms that may return different results based on the conditions in which they are run. For example, the object code of a program might generate random numbers based on the time on the clock of the computer it is running on. In these cases, the reproduction of exactly the same object code could exhibit high variation when run. However, I will argue that these variations can be thought of as analogous to source code modifications performed at run-time by the computer instead of at design-time by the programmer. For the purposes of this chapter, I will choose to consider just the simpler case of human-programmed source code.

Table 1 Software analogs to the biological conditions, mechanisms, and accelerants of evolution

Biological concept	Software analog
Differential Fitness The environment must favor certain organisms as being more fit relative to others	Not all software programs designed to do the same thing do it equally well, and there are a large number of dimensions available for assessing the fitness of a piece of software beyond just whether it gets the right answer or achieves the desired objective. Some software implementations may reach the same result at different speeds, or with different size memory footprints. Some may exhibit differences in the graphic design or user interface, leading to different levels of user adoption. Different implementation practices may make some software more or less maintainable by other developers, or more or less interoperable with different hardware. This non-exhaustive list of software properties illustrates the variety of dimensions by which a program may be deemed "fit"
Reproductive Capability Organisms have the potential to produce offspring, and to produce them in equal or greater quantity than the number required to reproduce	Software supports two modes of reproduction: reproduction via duplication of object code (the code that is executed by a computer) and reproduction via recompilation of source code (the code that is written by a developer). Software is inherently designed to support both modes of reproduction with much lower overhead than that of initial creation. This fulfills the biological requirement of reproductive "over production," allowing the object code of a single program to be replicated and distributed millions of times over, or the source code of a program to be "checked-out" by thousands of developers so that they can each work with their own individual copy
Existential Selection Organisms with greater fitness are afforded reproductive advantages while those with lesser fitness are less likely to reproduce	The fitness of a software program certainly affects its chances of reproduction, especially within a capitalist free-market economy where software requires capital to maintain and users are required to pay for usage, either directly or indirectly via advertising or other mechanism. Software that isn't fit enough for user adoption is not funded, which leads to it not being maintained and eventual obsolescence
Feature Transmission Features from one organism can be passed on to others. In vertical gene transfer this is accomplished via heredity, while in horizontal gene transfer this is accomplished via transformation, transduction, or conjugation	Software supports the incorporation of existing code into new programs in ways analogous to both vertical and horizontal gene transmission. A single program can be used to create a new program in a method analogous to asexual reproduction. Two (or more) programs can be combined to make a new program that uses features from each in a process similar to sexual reproduction. And portions of a program can be incorporated into other pre-existing programs via methods analogous to HGT transformation, transduction, and conjugation

(continued)

Table 1 (continued)

Biological concept	Software analog
Feature Continuity A transmitted feature is able to manifest in the offspring or recipient in a way similar to its original manifestation	The replication of both software object code and source code produce exact copies of the original, thus preserving all the characteristics of the original that bestowed a fitness advantage
Feature Variation Feature transmission does not always produce exact copies of the parent or donor	The replication of software object code is specifically designed to prevent variation, however, the replication of source code is specifically designed to allow programmers the opportunity to modify it. These modifications typically fall into one of three categories: modifications intended to fix errors, modifications intended to improve the capability of the program in its current use-case, or modifications intended to leverage the program, or portions of the program, in a different use-case
Dissociation The ability for one feature of an organism to grow, develop, and change, without affecting a different feature of the organism	Software applications provide a variety of different features and developers are able to extend the functionality of one feature without changing others. As some features are more popular than others they get more developer attention and grow disproportionately than the less popular features. Unpopular features can be removed without affecting other features
Divergent Duplication The ability for a feature of an organism to be copied but for the copy to develop differently than the original	This is one of the central tenants of the open-source programming movement—the ability for a codebase (set of features) to be made available so that different groups can copy it and modify their copy to be optimized for different use-cases. The Linux kernel, for example, was copied and modified by multiple organizations to produce a variety of different operating systems including Ubuntu, SUSE, and Red Hat Linux
Co-option The ability for one instance of a feature of an organism to be used in a different context, for a different purpose, than another instance of the same feature	Subroutines, functions, and libraries allow the same features of a program to be used in different ways within the same program. Object-oriented programming extended the ability for code co-option by allowing different instances of the same object to be used for different purposes, and the support for programming libraries—collections of sub routines and/or objects that could be imported into larger programs—made it possible for the same computational features to be used for different purposes through separate instantiations in separate programs

(continued)

Table 1 (continued)

Biological concept	Software analog
Mobility "Horizontal gene transfer is made possible in large part by the existence of mobile genetic elements" (Rogers 2019) There is a similar analog in the case of vertical gene transfer: siloed populations that are unable to find a variety of mates lose genetic diversity	The spread of the internet in the 1990s dramatically increased the mobility of software code. Software, which used to be sold on media like CDs, to be installed on individual computers, is now predominantly accessed through a web browser which transmits the necessary code on demand anywhere in the world. In addition to the increased mobility of executable code, the adoption of cloud-based distributed version control systems like GitHub has increased the mobility of source code as well, allowing developers that are geographically distant to easily share their code
Scale Increased population size speeds evolutionary processes	With 2020 reporting over 4.5 billion active internet users, over 2 million apps in the Apple AppStore, and software programs and libraries estimated in the billions, software has pervaded almost every field. At the same time decreasing costs for storage and data transmission have made the cost of duplicating and distributing code negligible, allowing for rapid proliferation of software whenever desired

our brains remain very mysterious black-boxes, especially with regard to innovative idea generation. We might find it useful to describe the act of thinking like a gene pool of ideas that mate in our consciousness while our brain [3] applies a fitness function to the offspring until a solution is found, but this is little more than metaphor. We don't really know how ideas get developed, combined, and tested in the brain, and as result we have few tools to steer those processes. We do know how ideas get developed, combined, and tested in software, and we now know they do so in an environment remarkably similar to the environment that gives rise to evolutionary exaptations. If we could shift some portion of our thinking out of the brain and into software, it would allow us to also shift from just passively studying mental exaptation to actively experimenting with producing it. We would move away from an idea substrate governed by forces that appear serendipitous to an idea substrate that we can actually design, test, and optimize for radical innovation.

[3] There is much interesting research about the neurology of insight, in which researchers use brain imaging techniques including EEG and fMRI to understand what roles different parts of the brain play during problem-solving, and how brain activity differs when solving "insight" problems versus brute-force problem solving (Kounios and Beeman 2014; Bowden et al. 2005; Kounios et al. 2008; Luo et al. 2004).

3 The Need for a New Software Paradigm: Programming Is Now Efficient Enough to Trade Productivity for Innovation

Moving our thinking outside of our brains and into some other system is not as far-fetched an idea as it might sound. Historian Charles Weiner and Nobel-prize winning physicist Richard Feynman once got in a debate about whether Feynman's thinking was done in his head and then captured on paper, or actually done using the paper as part of the thinking:

> Weiner: "…we dug up four notebooks. And so this represents the record of the day-to-day work."
>
> Feynman: "I actually did the work on the paper"
>
> Weiner: "That's right. It wasn't a record of what you had done but it is the work."
>
> Feynman: "It's the doing it—it's the scrap paper."
>
> Weiner: "Well, the work was done in your head but the record of it is still here."
>
> Feynman: "No, it's not a record, not really, it's working. You have to work on paper and this is the paper. OK?"
>
> *Transcript of interview (Feynman and Weiner,* 1973*)*

Twenty-five years after this exchange between Feynman and Weiner, Andy Clark and David Chalmers published "The extended mind" in which they discussed "the active role of the environment in driving cognitive processes." (Clark and Chalmers 1998) Ten years later Clark included the Feynman-Weiner anecdote in his book "Supersizing the Mind" in which he argued that Feynman was justified in elevating the status of lowly pen and paper to that of brain augmentation tool. Clark (2011) It is perhaps worth noting that when Feynman won the Nobel prize (along with Sin-Itiro Tomonaga and Julian Schwinger) it was in no small part for having invented Feynman diagrams: "a graphical interpretation which have become an important feature of modern physics." (Waller 1965) The man who argued that pen and paper helped him think won a Nobel prize for coming up with a new way for other physicists to use their pens and paper to help them think.

In Feynman's era he had to do his work with paper and pen because computers were slow and expensive. Having a computer perform one billion floating-point operations (one gigaflop) in the 1970s cost approximately $19 billion dollars. Personal computers today routinely execute gigaflops of computation at less than 3 cents each—almost a trillion times cheaper. FLOPS (2020) We no longer work predominantly with paper and pen but with computers and software, and their use augments our cognition with far greater power and capability than their paper predecessors. As computers have evolved so have the ways to develop software for them, but I will claim that no software development methodology has been developed yet expressly for the purpose of augmenting cognition in ways that facilitate innovation. That's not to suggest that programming systems (and non-programming systems as well for that matter) haven't secondarily facilitated innovative thought—they certainly have—but I will stand by my claim that any such innovations were happy accidents and not their primary motivation.

There exist many attempts at navigating software's history (Éric Lévénez 2019; Vullum 2020; Pigott 2015; Museum 2020; Rigaux 2020; Steinberg 2013), resulting in numerous tangled timelines of programming languages like that of Fig. 5. However, I know of no such analysis that organizes programming advances by motivation. The suffix "-oriented" was made popular by the introduction of object-oriented programming and has been frequently employed to demarcate other important programming paradigms, but the term seems only to illuminate the orientation of the approach taken, not the orientation of the rationale for taking that approach.

Computer science professor Robert Harper suggests that we're going about our analyses of programming paradigms all wrong:

> Everyone who writes about programming languages seeks to impose order on the chaos of extant languages… software development practices are codified as programming paradigms, such as imperative, functional, object-oriented, concurrent, and logic programming, to name a few popular classifications. The trouble with programming paradigms is that it is rather difficult to say what one is, or how we know we have a new one… It is more important to study the genome, and the evolutionary processes that influence it and are influenced by it…
>
> Harper (2017).

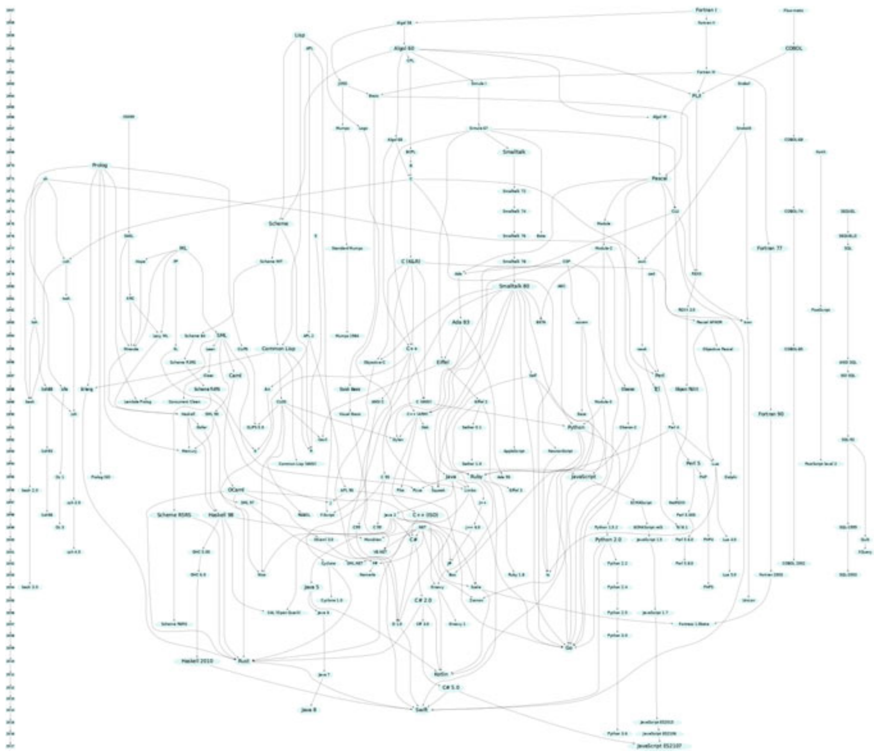


Fig. 5 History of ~150 Major Programming Languages from 1957 to 2017 (Rigaux 2020)

Harper then goes on to organize programming languages by their underlying type systems. I'm willing to agree that type systems might be considered the "genome" of a programming language, but I don't believe they illuminate the "evolutionary processes" that made that genome fit for purpose. I therefore look at the history of programming asking not what the languages are but why they are. In looking to their motivation instead of their mechanism, I find a clear set of themes. As I describe these themes I will co-opt the "-oriented" suffix to identify not the orientation of methodology but the orientation toward objective.

Early programming was "execution-oriented"—the objective was simply to show that a set of linear instructions could make a computer, even just a theoretical one, do something useful. The first computer program, written by Ada Lovelace in 1843, was completed before the computer that it was intended to run on, Charles Babbage's Analytical Engine, was even finished. This execution orientation would be the focus of programming for almost 100 years. As of 1940 computers were still mostly mechanical and programming was still just about getting them to run a single algorithm without halting in the middle, like running the algorithm that Alan Turing and the Bletchley Park team needed the British "Bombe" computer to execute in order to determine the settings that World War II Germans were using to encode messages on their Enigma Machines.

It wasn't until the mid-1940s, when the Electronic Numeric Integrator and Computer (ENIAC) made fully electrical computing possible, that programming shifted motivations. The next paradigm was programmer-oriented because programming a computer was extremely difficult and time-consuming. As the demand for programs increased, programmers began to implement features in programming languages that would make their own jobs easier. This resulted in the first elements of modularity being introduced to programming—the concept of subroutines—a critical development in terms of beginning to align programming with the evolutionary requirements laid out in the previous section.

By the 1950s programming was getting easier but was still far from being easy. Programmers began to develop "higher-level languages" that used vocabulary and syntax resembling natural language instead of requiring the use of cryptic numeric codes that were specific to each computer's hardware. This allowed programmers to write programs more like they thought, but came at the expense of performance due to the execution costs of the abstractions. It was only because computing power had increased so dramatically from 1940 to 1960 that programmers could even entertain the notion of implementing these higher-level languages which introduced layers of computational overhead like compilation and linkage. The abstractions of higher-level languages made programming much easier, but their poor performance left them struggling to gain adoption.

Programmers knew that they needed the benefits of higher-level languages if they were to be able to write increasingly complex programs, but they knew these programs would never be supported if they couldn't execute quickly enough, so language development entered a performance-oriented paradigm in the 1960s. Computers continued to become more computationally powerful at the same time that languages continued to be optimized. Eventually the two trajectories reached a combined point that allowed for widespread adoption of higher-level, abstract, languages. It was a major milestone, and one that allowed for another shift of motivation.

It was now much easier to develop programs for particular classes of problems, but it wasn't equally easy to develop programs for all classes of problems. Depending on the task to which one was applying programming, one language would be better than another, so programmers focused on building specific languages for particular problem domains, leading to a rapid proliferation of languages in the 1970s. I will refer to this period as application-oriented programming, intentionally leveraging the dual meaning of the word "application." At the same time that programmers were becoming increasingly concerned with the domains in which their programs were applied, the demand for computing shifted from the creation of "programs" to the creation of "applications." Computers were no longer being used to perform a single calculation or task, but sets of calculations and tasks connected together in workflows of increasing complexity.

Computer scientists had seen the challenges of this increasing complexity coming. As early as 1968 the NATO Science Council had brought more than 50 experts together to discuss the need for a new domain they called "software engineering." One participant commented, "One of the problems that is central to the software production process is to identify the nature of progress and to find some way of measuring it. Only one thing seems to be clear just now. It is that program construction is not always a simple progression in which each act of assembly represents a distinct forward step and that the final product can be described simply as the sum of many sub-assemblies." (Naur and Randell 1969) Another participant observed, "Today we tend to go on for years, with tremendous investments to find that the system, which was not well understood to start with, does not work as anticipated. We build systems like the Wright brothers built airplanes—build the whole thing, push it off the cliff, let it crash, and start over again." (Naur and Randell 1969) Despite the warnings, it wouldn't be until the 1980s that software engineering would become a profession unto itself, alongside, but distinct from, computer science and engineering. That marked the beginning of a new programming paradigm I will call system-oriented.

System-orientation represented the recognition that the application was no longer the most important thing—it was the overarching system in which the application operated that mattered. As software became embedded in more and more everyday systems, including ones where a malfunction could be the difference between life and death, issues of reliability became a chief motivator. Software development was no longer just about language design, but about all of the other needs that were intertwined with the act of programming. The features of the language became secondary to the features of debugging, documenting, versioning, testing and all of the other processes that were necessary to allow large numbers of developers to work concurrently on larger and larger systems.

The 1990s ushered in the "Internet Age" and the paradigm shifted again. Software applications had grown into software systems and those systems now linked the globe with universal protocols that ran sufficiently reliably to support an entrepreneurial revolution of new software-based products and services. In the cutthroat first-to-market winner-takes-all frenzy of the dotcom boom, programming became productivity-oriented. A focus on "Rapid Application Development" (RAD) led to the creation of scripting languages that had much more relaxed rules than earlier programming languages. With all of the previous motivations at least partially addressed, the goal became to increase programmer output. We continue to live in the era of productivity-oriented programming today. The sequence of the periods I've described are laid below, though the boundaries are far fuzzier than the neatly delineated list suggests.

- 1842–1940 Execution-Oriented Programming
- 1940–1960 Programmer-Oriented Programming
- 1960–1970 Performance-Oriented Programming
- 1970–1980 Application-Oriented Programming
- 1980–1990 System-Oriented Programming
- 1990–2020 Productivity-Oriented Programming.

The periods certainly overlapped. Within each period there were experts that devoted their energy to refining the ideas of the previous period at the same time that others raised awareness of the need for the next. And that is precisely the goal of this section—to raise awareness regarding not only the need, but also the timely opportunity, to shift our motivation and turn our collective attention to the development of software languages and software systems that are first-and-foremost innovation-oriented.

Just as it required advances in computing power to allow programmers to pursue higher-level languages, it is only because of all of the advances of the preceding periods that we are now positioned to pursue innovation-oriented systems. Computers are now fast, reliable, and prolific. We can afford the additional abstraction costs that will be incurred by shifting toward innovation-orientation. And what does that shift entail? Innovation-oriented programming changes the goal of software design from striving for modularity to striving for combinatorics. Evolutionary biology can be our teacher regarding this distinction.

Evolution doesn't occur just because cell components are modular, but because cellular components, the DNA that creates them, and the underlying chemistry itself, are combinatorial. Modularity is indeed a necessity, but it is ultimately an insufficient condition for evolution and evolution associated innovation. A jigsaw puzzle (Fig. 6, left) is clearly modular but has only one way to connect its modules. Innovation in jigsaw puzzles is, therefore, only possible if different puzzle images are cut with the same die pattern—allowing pieces from the different puzzles to be substituted for each other. Games like Tetris or Pentominos, on the other hand (Fig. 6, right), are both modular and combinatorial. Weisberger (2016) The diversity of possible Tetris games is made possible not because each piece can fit with another piece, but because every piece can fit with every other piece in multiple possible ways Johnston (2015).

In his paper, "On the evolution of cells", Carl Woese writes, "From the start the course of cellular evolution is a march toward greater complexity, integration, precision, specificity of cellular design, etc. All of this results in increased idiosyncrasy, which, of course, leads to decreased interactivity with other cell types, decreased

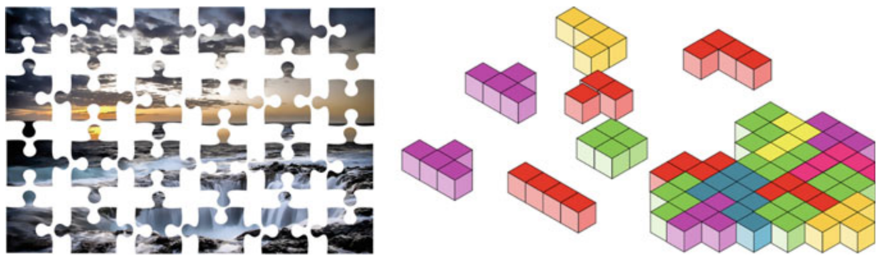


Fig. 6 Modularity, as embodied in a jigsaw puzzle (left) vs. Combinatorics, as embodied in the video game Tetris (right)

capacity to benefit from the universal gene-exchange pool. But in becoming complex, the cell design has created many new directions in which it can evolve on its own; it remains evolutionarily versatile, albeit in a different, more restricted way than when its organization allowed it to partake more freely of the novelty contained in the universal gene-exchange pool." (Woese 2002).

Even though Woese's passage is a description of a cell becoming increasingly complex and specific (a trajectory we've seen that our software systems share), Woese makes it clear that what preserves the cell's "evolutionary versatility" is that the additional complexity has provided "many new directions in which it can evolve," not that it has limited it to just one. The cell remains a Tetris game and not a jigsaw puzzle, combinatorial, not just modular. Woese also makes it clear what provided the cell even greater evolutionary versatility earlier in its life was its ability "to partake more freely of the novelty contained in the universal gene-exchange pool." The image of partaking freely in a universal exchange pool of novelty is not an image of casually drawing pieces from a jigsaw puzzle box and hoping that they will fit somewhere. Even though Woese is not specifically identifying the need for combinatorics, his notion of "universality" alludes to it.

Because this difference between modularity and combinatorics seems so critical for the innovation potential of systems, I find it surprising that the word "combinatorial" is not used once in Woese's paper and seems underused in evolutionary biology literature in general. It appears as if combinatorial flexibility is simply assumed to accompany modularity in discussions of biology. Perhaps in the biological domain that is a safe assumption, but in the software domain, where modularity is implemented in accordance with the block diagrams of engineers instead of by the laws of nature, it is not a safe assumption at all. We build our software systems much more like jigsaw puzzles than Tetris games, mostly because it's both safer and easier that way, and because we're still adhering to system-oriented and productivity-oriented motivations.

In many cases our jigsaw-like modularity hinders our innovative potential instead of helping it. It turns out that some jigsaw puzzle manufacturers do reuse die patterns across multiple different puzzle images. A few artists have made an art form out of finding the puzzles that share these patterns and exapting the pieces to form innovative new hybrid images like shown in Fig. 7.

Fig. 7 A puzzle montage by Tim Klein in which pieces from a waterfall puzzle have been substituted for pieces of a car puzzle that shared the same die-cut pattern (Klein 2020)

In a productivity-oriented programming paradigm, programmers seeking innovation are very much like these puzzle montage artists. They scour endless repositories of code libraries looking for the pieces that might fit the puzzle they are working on. When the piece they want is not shaped quite right, they hope they can get the source code so that they can make the adjustments needed to make it fit. After painstaking work, they have made the waterfall-car of Fig. 7 and it is indeed an innovation. They delight in it, as they should, but don't question why the innovation required such labor. Instead of relying on the puzzle metaphor I can share a real software example.

On March 18, 2011, mathematician and programmer Martin Wattenberg addressed a room full of geneticists at the Broad Institute in Cambridge, Massachusetts and told them about a visualization technique he had invented called the arc diagram. VIZBI (2011) He had developed the visualization while working at the IBM Research Lab and explained that it was motivated by his desire to visualize music (Fig. 8).

The geneticists quickly pointed out that what Wattenberg was calling music was really just a long sequence of letters and that they worked with long sequences of letters for a living. The scientists' sequences weren't made up of the 7 letters, A-G, of the musical scale—they were made up of the 4 bases, A, T, G, and C, of DNA.

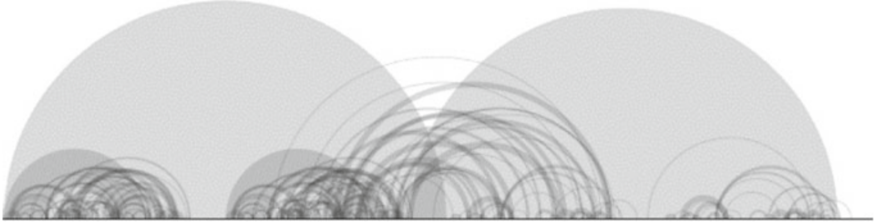


Fig. 8 Arc diagram visualization technique used to visualize Bach's Minuet in G Major (Wattenberg 2002)

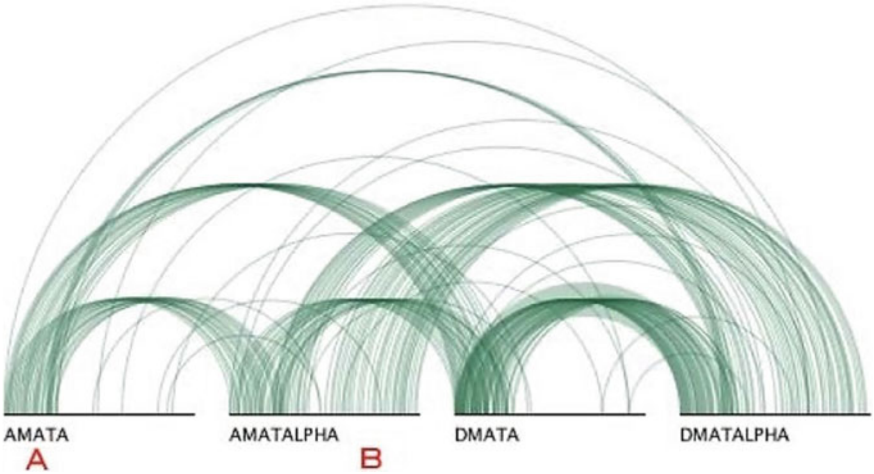


Fig. 9 Arc diagram visualization technique used to visualize gene sequence of C.neoformans (Spell et al. 2003)

Could Wattenberg's arc diagrams, they asked, be used to illuminate hidden structure in their gene sequences? (Viégas and Wattenberg 2011).

The answer was no. At least not as Wattenberg's code was written. Wattenberg pointed out that he had mentioned DNA when he had published about the technique[4] but that it took another team a non-trivial amount of effort to modify his code in order to make it work in a genetics context. A team of researchers at Duke University, supported by the National Library of Medicine and pharmaceutical giant Merck, released a software package called Biological Arc Diagrams (BARD) for visualization of gene sequences approximately a year after Wattenberg published on his music-centric implementation. Their modification to Wattenberg's software allowed the arc diagram technique to be applied to gene sequences as shown in Fig. 9.

The user feedback the Duke team received confirmed that their work was an exciting innovation on the traditional dotplots method used up until then. "Initial feedback from scientists… that used BARD as a comparative genomic tool were very positive. Specifically, BARD's visualizations have already been proved useful for clearly showing syntenic sequence regions, and highlighting genomic rearrangements that show sequence divergence due to evolution." (Spell et al. 2003).

The Duke team should take great pride in their innovation. It was another successful software exaptation, like AstroMed, that produced tangible value. Unfortunately, it was also the success of the jigsaw artist painstakingly fitting a piece where it didn't originally want to go: "BARD expands Wattenberg's approach by making the

[4]While Wattenburg recognized, and even demonstrated, the possibility of applying the arc diagram technique to gene sequences, he didn't view biology as the best use-case. He wrote in the summary of his paper explaining the arc diagram, "We have shown examples of their potential use in domains ranging from text to DNA, although analysis of musical form is perhaps the most promising application." (Wattenberg 2002).

visualization independent of the underlying matching algorithm… We thank Martin Wattenberg for generously sharing the original arc diagram source code." (Spell et al. 2003).

In a productivity-oriented paradigm of tightly coupled modularity, this is success, but in an innovation-oriented paradigm of loosely coupled combinatorics, success is being able to plug in a different matching algorithm the moment the researcher questioned whether it might be valuable to do so, not a year after receiving funding and asking for the source code. It's natural to rejoice in mastering jigsaw puzzles, but we should be asking ourselves why we aren't playing Tetris instead.

4 Innovation-Oriented Programming: Ideas Are Networks, Computer Programs Should Be Too

Carl Woese ends his article "On the evolution of cells" with a 7-point framework for cellular evolution. His fourth point is critically relevant to our topic of modularity versus combinatorics, as it holds within it the design principles for innovation-oriented programming.

> Therefore, cellular evolution must begin in a collective mode. (i) The (early) evolution of a cell design can occur only in a context wherein a variety of other cell designs are simultaneously evolving. (ii) Mechanisms must exist whereby novelty can be globally disseminated (horizontally exchanged), which include a universal genetic code (lingua franca) carried by a standard, generic translation apparatus, one readily exchanged among the various cell types. (iii) The componentry of primitive cells needs to be cosmopolitan in nature, for only by passing through a number of diverse cellular environments can it be significantly altered and refined. (iv) Early cellular organization was necessarily modular and malleable.
>
> Woese (2002)

To develop an innovation-oriented architecture, we must implement software analogs for the five concepts Woese includes in the passage above. The first two of these analogs already exist in non-innovation-oriented programming systems, but, importantly, the remaining three do not.

- ***"Collective mode":*** This collective mode is a necessary condition for the existence of a "universal gene pool" (Woese 1998) and software has a nice analog to this. Especially with internet connectivity and growth of open-source code repositories, software development is moving toward an increasingly collective mode. It's worth pointing out that while open-source is one way to achieve a fluid collective environment, it is not the only way. Intellectual property law, by issuing protective copyrights and patents, seeks to create a collective mode as well, as do industry standards like Microsoft's ActiveX standard and jQuery's widget framework.
- ***"Novelty can be globally disseminated":*** Dissemination of software has never been easier, providing an excellent analog to this requirement.
- ***"A lingua franca carried by a standard translation apparatus, one readily exchanged among the various cell types"***: This is where the software analogs begin to break down. A lingua franca is a common language that allows communication between native speakers of different languages. Mostly software tries to avoid this challenge by using the same language throughout a system whenever possible. Creating a robust lingua franca and corresponding translation apparatus is difficult. Where the investment has been made to do so in the past, the results have been stunning. The http and html protocols and standards that allow a web browser to jump from one page to another regardless of the language or architecture of the page's web server have certainly resulted in accelerated innovation. Those standards and apparatus have allowed us to create a universal gene pool of text-based ideas and hyperlinks but not of more structured programmatic elements. It is exactly this higher-level lingua franca that needs to be created for true innovation-oriented programming.
- ***"The componentry needs to be cosmopolitan":*** Evolution thrives on diversity and current software systems struggle to be cosmopolitan. Most programming languages do not play nicely with each other, meaning that the adoption of one language and/or technology tends to create a silo in which developers are restricted to operate. Innovation-oriented programming requires increasing the degree to which our systems are agnostic not only to language and technology but also to data model as well.
- ***"Modular and malleable":*** This is the lynchpin that we spent the previous section discussing—that modularity alone is not enough. Woesian malleability is really combinatorial flexibility—the most important ingredient to innovation-oriented programming.

I will summarize the five factors above as follows: community, fluidity, translatability, diversity, and combinatorial flexibility. These are not the usual priorities for software development systems. That is why most software looks like Fig. 10—a linear text.

We say that we "write" programs, so it's no surprise that programs have traditionally been linear, text-based, tomes. Even though a program will execute non-linearly, we have adopted all the tooling for a linear process. Ideas are not large, linear, monolithic entities—they are intricate networks. If we want to build a programming environment that facilitates idea generation, we need to make our programs look more like networks too.

```c
/*
 * This line basically imports the "stdio" header file, part of
 * the standard library. It provides input and output functionality
 * to the program.
 */
#include <stdio.h>

/*
 * Function (method) declaration. This outputs "Hello, world\n" to
 * standard output when invoked.
 */
void sayHello(void) {
    // printf() in C outputs the specified text (with optional
    // formatting options) when invoked.
    printf("Hello, world!\n");
}

/*
 * This is a "main function". The compiled program will run the code
 * defined here.
 */
int main(void)
{
    // Invoke the sayHello() function.
    sayHello();
    return 0;
}
```

Fig. 10 Traditional, linear, text-based, software program

The right side of Fig. 11 shows a list of text-based statements not that different from the linear text-based program of Fig. 10. However, the code in Fig. 10 is what I will call the "action code"—it is the code that determines what the computer will do, how it will act. The code shown on the right side of Fig. 11 is different—it is not the code that actually performs actions, it is a higher-level abstraction, called a "dataflow." Dataflow programming was originally developed during the 1970s (performance-oriented period) in order to better support the creation of programs that could perform parallel processing. Johnston et al. (2004) Because dataflow programming uses a graph-based paradigm, instead of a linear text-based paradigm, it is an excellent programming methodology for defining how parts of a program are connected. In this regard the dataflow code is very different from the action code. The dataflow simply defines what action code is required and how it is connected. It is that network of action code components that is being visualized as a network on the left side of Fig. 11. The dataflow is the blueprint of the program, not the execution of the program. In cellular biology terms, the action code components are the proteins, making the cell actually work, but the dataflow is the DNA—the instructions about which proteins need to be made in the first place. This dataflow abstraction, and the engine that parses it and instantiates the necessary components (acting much like

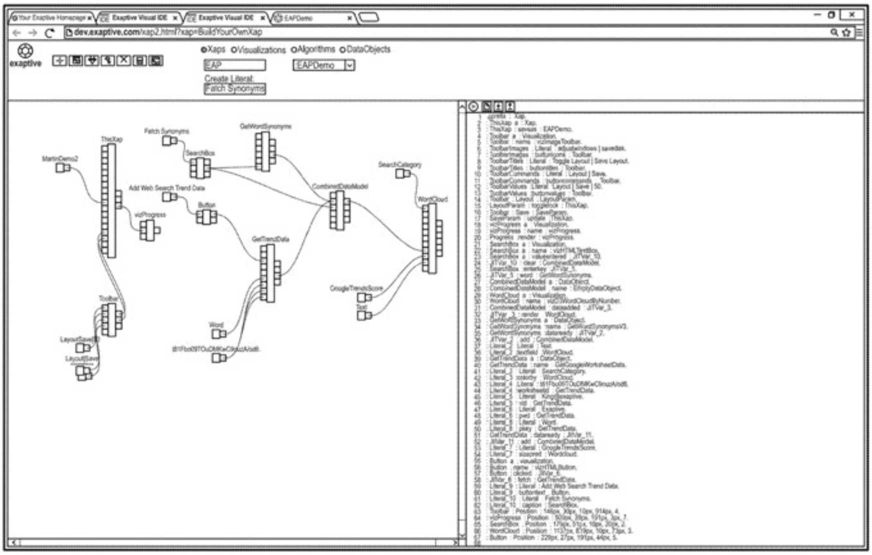


Fig. 11 A program-as-network implementation in which the list of statements that define the program (right) represent a network graph structure (left) of connected code components as shown in US Patent 10,530,894 (King 2020)

RNA and ribosomes act in a cell, to continue the analogy), are the Woesian lingua franca and translation apparatus that most software systems lack.

Just like in the 1950s when programmers decided it was worth the overhead to create higher-level languages in order to be more efficient, I argue that it is now worth the overhead to create systems with these lingua franca abstractions, like the dataflow, in order to be more innovative. The dataflow abstraction is like an additional programming language, but not one that can operate alone. It is just connective tissue, useless without things to connect. Where do those things come from? From the Woeseian collective, or in software terms, from the developer community. Figure 12 shows an evolved version of the programming environment of Fig. 11, with a left side-panel containing a repository of available components that a user can pull from.

The benefit of the dataflow being an abstract language designed only for translatability and combinatorial flexibility is that it can be completely agnostic to the technologies of the individual components it connects. This allows us to achieve the truly diverse cosmopolitan environment needed for rapid evolution, as well as supporting the dissemination of novelty by allowing components to join the community regardless of language they were written in or technology they employ. To maximize fluidity, we build the system as a web application in order to allow dataflows to pull components from anywhere that can serve them, just as web browsers can render any page with a valid URL.

The last and most difficult condition to meet is that of Woesian malleability. The dataflow must do more than just connect components—it must support connecting

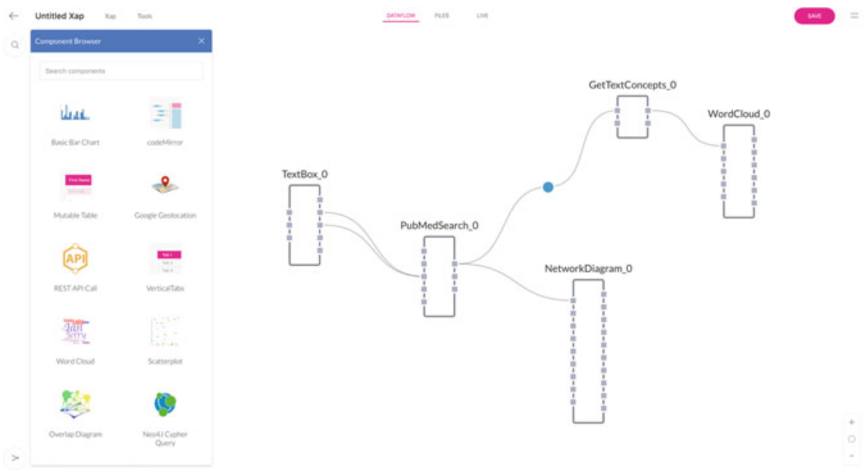


Fig. 12 An evolution of the innovation-oriented system shown in Fig. 11 which implements a "component browser" (left) that provides access to a community of components

them in many different ways. To facilitate this we must implement the dataflow not at just one level of abstraction but at multiple levels.

Figure 13 shows the top-level dataflow abstraction on the left. This embodies the connectivity of the components but contains no information about their configuration. Expanding a component (Fig. 13, middle) brings the user to the second-level of abstraction—the ability to configure the parameters of the component while remaining insulated from the code. When necessary, the third level of depth (Fig. 13, right) allows the user to access the underlying code of the component, but still within a dataflow abstraction that requires the programmer to align the underlying code with the input and output ports that the higher-order abstractions rely on.

These three levels of abstraction do more than just allow a single programmer to operate at different cognitive levels of detail. They allow the act of programming to be divided up in ways that change what it means to be a programmer. Only users that operate at the third level of depth need to be able to actually write code. Technical programmers will operate here, but they aren't making programs, they are making

Fig. 13 Connection-level dataflow (left), Configuration-level dataflow (middle), Code-level dataflow (right)

components of programs. The dataflow builder makes the program, but they are insulated from the usual challenges of technical programming. Their work is not to understand the syntax of a particular programming language but to understand the requirements of a particular use-case and select, connect, and configure the appropriate components to add value to that use-case. This both distributes and democratizes the act of programming, allowing subject matter experts to actively take part in the development process, and allowing technical programmers to build units of computation value within the domains they are knowledgeable without worrying about how to translate to other use-cases. That translation becomes the job of the dataflow builder, who can make components work together using a variety of dataflow tools designed specifically for the purpose of translation and interoperability. The dataflow language can be optimized for these tasks because its only job is to be the lingua franca—it doesn't have to make components work, it only has to make them work together.

This emphasis on supporting the interoperability of elements not originally intended to work together is the essence of exaptation and the essence of the patent awarded to this architecture: "The 'Combinatorial Application Framework' (CAF) is an event-driven dynamically compiled software model for defining, implementing, and executing a software application so that it can be comprised from a plurality of independent components that interact in a coordinated fashion and support design-time and run-time component repurposing by users other than the component authors or framework authors, even if created in different programming languages and never intended to function together… semantic normalization coupled with the modularity of the components available in the CAF facilitates collaboration, reuse, and use in novel ways (exaptations), which cannot otherwise be achieved in other architectures without much more explicit developer coordination and interaction." (King 2020).

Since our goal has been to develop an improved version of Feynman's pen and paper, we must not forget in our design two aspects of paper and pen that few other tools can match—its speed and ease. Drawing has no barrier to entry. It is instantaneously available and almost infinitely expressive. It's no wonder that it continues to be the cognitive augmentation tool of choice for many creatives. Einstein famously said that "combinatory play seems to be the essential feature of productive thought." Popova (2020) We've focused much attention on being combinatory, but we must not forget the importance of play. Innovation-oriented programming must lower the barriers to experimentation so drastically that developers can pursue ideas that seem pointless, combine components in ridiculous ways, and truly play. In his paper titled "More is Different," P.W. Anderson guides the reader through the phenomenon of "scale change causing fundamental change." (Anderson 1972) I will argue that with regard to innovation faster is different too. When certain investigations are slow, it's not that people take longer to complete them, it's that they don't do them at all. And when certain activities become easy enough and fast enough, we can witness the "phase transitions" Anderson describes where categorically different behaviors emerge. Figure 14 shows the innovation-oriented combinatorial applica-

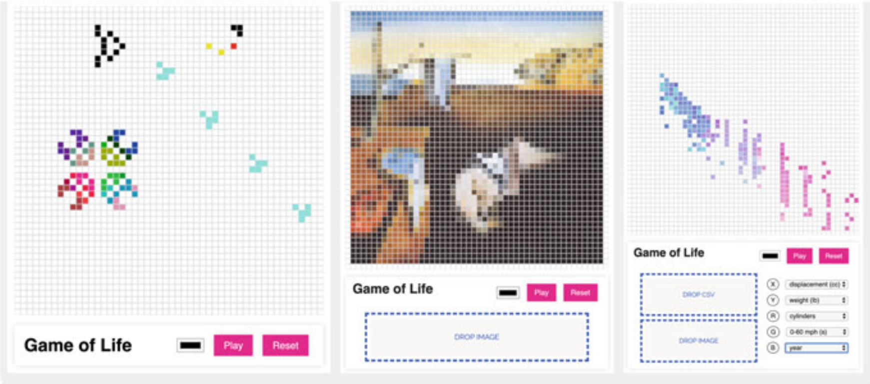


Fig. 14 Conway's Game of Life (GoL) modified to support colored cells (left). The left application modified to support images as GoL starting seeds (middle). The middle application modified to support seeding the GoL simulation with arbitrary data (right)

tion framework being used in such a state of fast and easy combinatory play, leading to three iterations of a program, each iteration pushing the application into innovative territory.

The first application shown in the left panel of Fig. 14 is a version of the well-known cellular automaton program invented in 1970 by mathematician John Conway, called Conway's Game of Life. Bays (2010) In the original simulation each cell could be only either black or white—the version in Fig. 14 has been modified to support color.

This modification led the programmer to the realization that the colored cells were analogous to pixels in an image. The low barrier to experimentation allowed the application to be quickly updated to load an image into the grid by simply adding image loading and parsing components into the dataflow. This resulted in the application shown in the middle frame of Fig. 14 in which the Game of Life board has been loaded based on a JPEG image of Dali's painting The Persistence of Memory.

This experiment of using images to seed the board led to another realization—that an image was just a five-dimensional dataset comprised of x and y position, and red, green, and blue values. With a few more minor adjustments to the dataflow the developer added excel upload and parsing components, allowing any excel data file to be used to set the starting configuration of the Game of Life board. The right image of Fig. 14 shows this version of the application being used to seed the Game of Life board with data about different make and model cars.

The three images show the evolution of the application. They depict not the linear evolution of one particular use-case being incrementally refined but the lateral evolution of one use-case getting exapted across domains, within a platform designed specifically to make such boundary crossing easy. Whether the result is an innovation is debatable, but it is interesting nonetheless because the ability to load arbitrary data into the Game of Life isn't just about co-opting the game's grid to become a

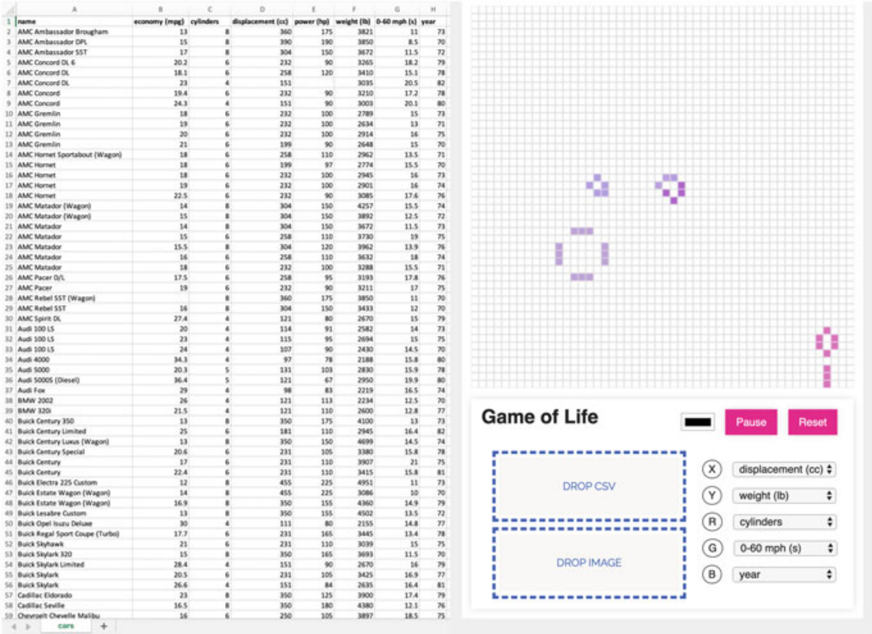


Fig. 15 A dataset about cars (left) after being run through Conway's GoL (right)

scatterplot, it's about applying the game's underlying algorithm to a data landscape that actually represents something.

When data about cars (Fig. 15 left) is loaded into the game and Conway's simple four rules are allowed to execute, the simulation ends in the stable state shown on the right side of Fig. 15. The developer's combinatory play has taken him from computational art to data-driven simulation with new ideas being generated along the way about the nature of data, visualization, and simulation.

Using Conway's Game of Life on data different than originally intended for it is an exaptation in many ways similar to the AstoMed example that started the chapter. In that case, a combined algorithm/visualization was applied to data from a different domain. But whereas the AstroMed exaptation was the result of a mental exaptation that occurred outside any technological system, this exaptation occurred directly as a result of operating within a technological system designed to facilitate exaptation. What if Wattenberg's musical arc diagrams had been built within an innovation-oriented combinatorial system? What about Feynman's Nobel prize-winning diagrams? As the next section will show, while there will always be a role for serendipity in creative thought, innovation-oriented systems can shift the odds in favor of those serendipitous ah-ha moments happening far more reliably.

5 Another Tale of Two Researchers: Facilitated, Instead of Serendipitous, Exaptation in the Software Domain

Dr. Kristophe Diaz and Dr. David Vishanoff had no real reason to ever talk. Diaz lived in Boston, Massachusetts, had a Ph.D. in molecular and cellular biology, and was a Senior Program Officer at Cohen Veteran's Bioscience running projects related to research on Post-Traumatic Stress Disorder (PTSD). Vishanoff lived in Norman, Oklahoma, had a Ph.D. in West and South Asian Religions, and was a tenured professor at the University of Oklahoma focusing his research on Islamic hermeneutics. Besides for both having visited Fez, Morocco at different points in their lives, it appeared that they had absolutely nothing in common (Fig. 16).

One of the points of section two was that the virtual domain was an ideal substrate upon which to experiment with innovation not only because it was easier to exert influence, but also because it was easier to interrogate ideation processes. While Diaz and Vishanoff looked dissimilar from almost every perspective, there was one perspective from which their commonality was clear—the dataflow programs they were using as part of their projects looked almost identical.

Both Diaz and Vishanoff were using the innovation-oriented combinatorial application framework to apply natural language processing algorithms on unstructured texts. Diaz was analyzing medical journal articles related to PTSD, while Vishanoff was analyzing book summaries related to Islamic textual studies in Indonesia. The content was very different but the methodologies were the same. Once alerted to each other's work, they agreed to meet. Cross-disciplinary conversations can be challenging, especially between scientists and humanists, but in this case the two researchers did not come to the meeting empty-handed. They each had their own tangible digital artifacts of their ideation processes—the iterations of the applications that they had

Fig. 16 Dr. Kristophe Diaz (left), Dr. David Vishanoff (right)

been experimenting with in their research. These became Rosetta Stones that allowed them to successfully translate across their own domain-specific languages.

– Diaz, demonstrating his "PTSD Knowledge Map" application to Vishanoff:

> To give an example, if you pick this one you see how you go from Dopamine to this other concept. You can see between those two concepts you get different paths. And this represents biological experiments and results that people have been producing in the literature.

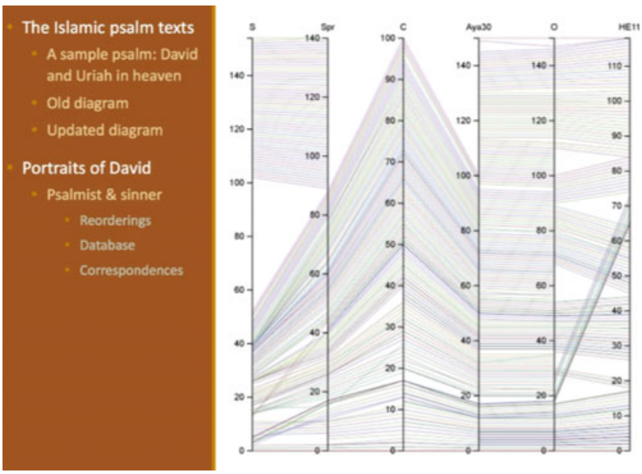
– Vishanoff, pointing at the dopamine pathways visualized in Diaz's application:

> "The huge leap here is that with the other [application] co-occurrence is the only sort of meta concept that I have. You've had to try to look at the content of your articles and determine, 'Oh, when dopamine and something else appear in this article there's a specific kind of relationship in the real world, or in the scientific literature. You've had to define an ontology, 'how does the world work?'… and that's what I'm interested in."

As the two researchers realized they were interested in similar meta-challenges, even as their domains were radically different, they quickly aligned on shared vocabulary and began to share other versions of their work with each other, using the concepts they had earlier established they had in common to bridge their differences.

– Vishanoff, sharing the visualizations he had produced for his latest project:

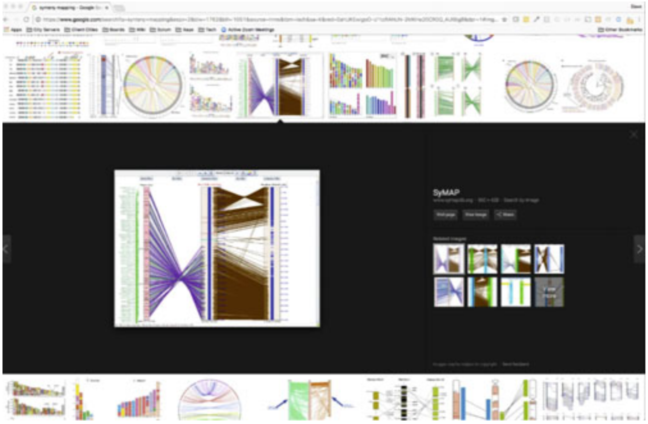
> "[I'm working with] 30 different manuscripts of the Psalms of David—not the ones you know from the Bible but ones Muslims wrote.



> There's some overlap between those texts, but they did a lot of editing, and a lot of re-writing, and then they added more, and dropped stuff here—so you have these 30 manuscripts that have sort-of the same text and I'm trying to figure out which was the earlier text, and what did each editor do?"

– Diaz, excitedly:

"Sorry, I have to interrupt you! Can you just image google 'synteny map'?"



"So it looks like genome reallocation between different species—and if a gene is in this part of the chromosome in humans where is it in a mouse?"

– Vishanoff:

"Yes, yes!"

An exaptation had occurred. Vishanoff understood immediately that the synteny maps Diaz was referring to applied not just to genetic mutations but to his challenge of textual mutations as well. Vishanoff went on to win two prestigious grants for studying the genealogy of these ancient Islamic psalms. One of his competitive advantages—he was using techniques from biology to study hermeneutics.

This example and the one before it are still small-scale anecdotes of facilitated innovation, but they offer the promise of repeatability and, even more importantly, of scalability. These are not the serendipitous ah-ha moments of researchers happening to run into each other at a conference, or stumbling upon a paper they wouldn't normally take the time to read. These are ah-ha moments emerging from human-computer systems built very intentionally in the software domain to align with fundamental principles of evolutionary theory, and based on a structured model of facilitated innovation via exaptation. I hope that this early work will encourage others to similarly experiment with innovation-oriented system design. Over the last decade we've seen the incredible power of technological platforms to connect people. We've seen the tremendous rise of social networks that help people share, but have yet to apply the same tools to create cognitive networks that help people think. We've used advances in technology to take luck out of many aspects of life that used to involve it—online music services use algorithms to connect people to songs they didn't know they would like, online dating services use data to make matches that wouldn't ordinarily meet, and app-based ride shares use GPS to take the serendipity out of catching a cab. Now we need to take the serendipity out of catching the next big idea.

6 Looking to the Future: The Problem with Problem-Solving and Why We Need Actively Facilitated Innovation

There is growing evidence that the very act of problem solving has a problem. Innovations are getting harder to discover. We are throwing more "knowledge workers" at problems and getting smaller and smaller proportional returns on those investments.

The disparity in the slopes of the two curves of Fig. 17 might not be so concerning if the problems of the world were getting smaller and less pressing, but the opposite is occurring. The world is faced with increased disparity—wealth disparity, health disparity, education disparity. A growing world population consumes a set of shrinking natural resources in a frenzy of inefficient transactions, the byproducts of which threaten our planet and our existence. Roser (2020) At the very moment where we need innovative solutions the most, we find ourselves the least capable of generating them at the pace and scale required.

When we think of the term "innovation" we tend to think of novel and useful solutions to problems. This book has explored exaptation as a model and mechanism for the generation of such innovations, and has shown that exaptation's utility is not limited to a specific problem domain but that it is equally viable and useful in many different problem domains: medicine, economics, aerospace, industrial design, etc. But the mission of this chapter has been to use software to do what software does best—abstract the problem up a level and get meta. What about the domain of problem-solving itself? Can exaptation help solve the problem of problem-solving? Aligning the curves of Fig. 17 will require more than just a collection of innovations in many fields. It will require innovation in the very way we innovate.

Early humankind appreciated the value and enjoyed the benefits of fire about 1.5 million years ago, but it's believed that early humans did not learn to start fire for themselves until less than 250 thousand years ago (James et al. 1989) (Fig. 18).

In the savanna where early humans lived, fire occurred naturally through a serendipitous confluence of events. Lightning striking a dry area would start a blaze

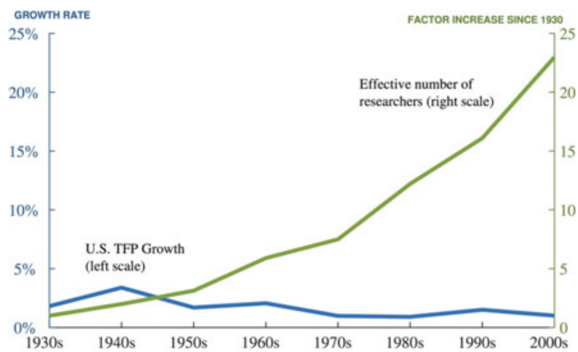


Fig. 17 US Total Factor Productivity (TFP) compared to number of researchers (Bloom et al. 2017)

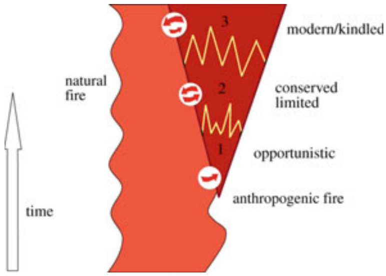


Fig. 18 Humankind had an opportunistic relationship with fire until they learned how to conserve it, then kindle it (Gowlett, 2016)

and humankind learned to embrace these wildfires instead of run from them. Eventually they learned how to be good stewards of this magical phenomenon they stumbled upon, but it would take hundreds of thousands of years before they would be able to summon it at will (Gowlett 2016).

While society has developed a number of techniques for facilitating incremental innovation, most notably specialization and the incentive structures that reward it, the area of radical innovation remains as mysterious to us as fire was to early humans 1.5 million years ago. We are still prehistorically passive—waiting for lightning to strike, our energy devoted to scouring the savanna looking for flames instead of building the tools that allow us to create them.

Searching the web for images related to innovation shows that the lightning strike metaphor is not far from our current cultural mindset. We see the ubiquitous light bulb, often outside and above one's head, with no shortage of lightning bolt imagery accompanying it and phrases like "flashes of insight" (Fig. 19).

In his book, "Metaphors we live by," George Lakoff cautions that metaphors "can shape our perceptions and actions without our ever noticing them," and that the metaphors we use play a critical and underappreciated role in defining and constraining the activities we perform (Lakoff and Johnson 2003). I contend that we are doing just this when we depict the ah-ha moment as a lightning bolt or the new idea

Fig. 19 Images returned for a Google image search for the phrase "new idea"

as a light bulb. We are equating novel idea generation as something external to us instead of as an internal capability. The more we do this the more we reinforce radical innovation as something beyond our control. I am struck that even with the light bulb metaphor, which is a human invention we do control, what is being represented is the instantaneous power of electricity, not our control of it. In the hundreds of light bulb images returned by a Google image search for "new idea," there is not a single picture of a light switch.

At least we have started to become better stewards of the phenomenon. Much like early humankind had to learn first to care for fire before they could create it, with books like this one we have started the process of collecting and analyzing the lightning strikes of radical innovation in the hopes that better understanding will provide us better control. In that process we've refined our models and moved away from the metaphor of lightning to the metaphor of exaptation, and this is a tremendous step in the right direction. Instead of being a model based on the spontaneous, short-lived, and poorly understood phenomenon of lightning, we are now using as our model the slow and methodical, well-behaved, and increasingly well-understood phenomenon of biological evolution. By exploring radical innovation from the perspective of biology, we are giving ourselves a much richer and more nuanced language with which to discuss the phenomenon, and we are giving ourselves the opportunity to learn from nature, which has consistently produced innovations since life first emerged on the earth four billion years ago. However, the comparison with biological evolution is still problematic in that we are no more able to meaningfully control biological evolution than we are to effectively direct lightning.

I believe the secret to making sparks for ourselves is resting in the virtual domain. It is an environment abundant with everything we need to practice the fire-starting of facilitated exaptation. Our success will be not when new knowledge is illuminated by the light of a million fires, but when a new societal trajectory is established from the matches we have put in everyone's pockets.

References

Anderson PW (1972) More is different. Science 177(4047):393–396

Bays C (2010) Introduction to cellular automata and Conway's Game of Life Bloom N, Jones C, Reenen JV, Webb M (2017) Are ideas getting harder to find?

Borkin M (2011) Astronomical Medicine TEDx Boston. https://www.youtube.com/watch?v=kU7veyGGps4

Borkin M, Ridge N, Goodman A, Halle M (2005) Demonstration of the applicability of 3D slicer to astronomical data using 13CO and C18O observations of IC 348 Junior Thesis. Harvard University, Cambridge

Borkin M, Goodman A, Halle M, Alan D (2007) Application of medical imaging software to 3D visualization of astronomical data. ASP Conference Series 376

Bowden EM, Jung-Beeman M, Fleck J, Kounios J (2005) New approaches to demystifying insight. Trends Cogn Sci 9(7):322–328

Clark A (2011) Supersizing the mind: embodiment, action, and cognitive extension. OUP USA

Clark A, Chalmers D (1998) The extended mind. Analysis 58(1):7–19. Feynman R, Weiner C (1973) Oral history interview with Richard Phillips
Feynman, Session V. https://www.aip.org/history-programs/nielsbohr-library/oral-histories/5020-5
FLOPS (2020) Cost of computing. https://en.wikipedia.org/wiki/FLOPS
Gering DT, Nabavi A, Kikinis R, Grimson WEL, Hata N, Everett P, Jolesz F, Wells WM (1999) An integrated visualization system for surgical planning and guidance using image fusion and interventional imaging. Medical image computing and computer-assisted intervention—MICCAI'99 pp 809–819
Gildenhuys P (2019) Natural selection
Goodman A (2004) Visualization challenges in astrophysics, Powerpoint presentation
Gowlett JAJ (2016) The discovery of fire by humans: a long and convoluted process. Philos Trans R Soc Lond B Biol Sci 371(1696)
Harper R (2017) What, if anything, is a programming paradigm?
James SR, Dennell RW, Gilbert AS, Lewis HT, Gowlett JAJ, Lynch TF, McGrew WC, Peters CR, Pope GG, Stahl AB, James SR (1989) Hominid use of fire in the lower and middle pleistocene: a review of the evidence [and Comments and Replies]. Curr Anthropol 30(1):1–26
Johnson C, Moorhead R, Munzner T, Pfister H, Rheingans P, Yoo TS (2006) NIH-NSF visualization research challenges final report. In NIH-NSF visualization research challenges, IEEE Computer Society
Johnston WM, Hanna JRP, Millar RJ (2004) Advances in dataflow programming languages. No 1:1–34
Johnston J (2015) Personal conversation. Why the shape of the sticker on the air conditioner he was moving would not "make an awesome Tetris piece": modular isn't the same as combinatorial.
Kay A (2003) Meaning of "Object-Oriented Programming" according to Dr. Alan Kay. http://www.purl.org/stefan_ram/pub/doc_kay_oop_en
Kay A, Ingalls D, Ohshima Y, Piumarta I, Raab A (2006) Steps toward the reinvention of programming—NSF proposal
King D (2020) Combinatorial application framework for interoperability and repurposing of code components
Klein T (2020) Puzzle montage art. https://puzzlemontage.crevado.com/puzzle-montage-art-by-tim-klein
Kounios J, Beeman M (2014) The cognitive neuroscience of insight. Annu Rev Psychol 65:71–93
Kounios J, Fleck JI, Green DL, Payne L, Stevenson JL, Bowden EM, Jung- Beeman M (2008) The origins of insight in resting-state brain activity. Neuropsychologia 46(1):281–291
Lakoff G, Johnson M (2003) Metaphors we live by. University of Chicago Press
Éric Lévénez (2019) Computer languages timeline. https://www.levenez.com/lang/
Luo J, Niki K, Phillips S (2004) The function of the anterior cingulate cortex (ACC) in the insightful solving of puzzles: the ACC Is activated less when the structure of the puzzle is known. J Psychol Chinese Societies 5
Melo D, Porto A, Cheverud JM, Marroig G (2016) Modularity: genes, development and evolution. Annu Rev Ecol Evol Syst 47:463–486
Museum CH (2020) Timeline of computer history. https://www.computerhistory.org/timeline/1946/
Naur P, Randell B (1969) Software engineering: report on a conference sponsored by the NATO science committee
Olson-Manning CF, Wagner MR, Mitchell-Olds T (2012) Adaptive evolution: evaluating empirical support for theoretical predictions. Nat Rev Genet 13(12):867–877
Pigott D (2015) Historical encyclopaedia of programming languages. http://hopl.info/
Popova M (2020) How Einstein Thought: Why "Combinatory Play" Is the Secret of Genius. https://www.brainpickings.org/2013/08/14/how-einstein-thought-combinatorial-creativity/
Raff RA (1996) The shape of life: genes, development, and the evolution of animal form. University of Chicago Press
Rigaux P (2020) Diagram and history of programming languages. http://rigaux.org/language-study/diagram.html

Rogers K (2019) Horizontal gene transfer. https://www.britannica.com/science/horizontal-gene-transfer
Roser M (2020) Global economic inequality. Our World in Data
Satell G (2016) It's time to bury the idea of the lone genius innovator. Harv Bus Rev
Seo HK (2008) Brains shed light on the stars. Harvard crimson Shenk JW (2014) The End of 'Genius'. The New York Times
Spell R, Brady R, Dierich F (2003) BARD: a visualization tool for biological sequence analysis
Steinberg J (2013) Hello, World!: the history of programming. CreateSpace Independent Publishing Platform
Viégas F, Wattenberg M (2011) Fernanda Viégas & Martin Wattenberg: Keynote on Design. https://vimeo.com/26208254
VIZBI (2011) VIZBI 2011 conference program. https://vizbi.org/2011/Program/
Vullum E (2020) Programming languages timeline. http://www.vullum.io/timeline/programming-languages/
Waller I (1965) Physics nobel prize presentation speech
Wattenberg M (2002) Arc diagrams: visualizing structure in strings. In {IEEE} Symposium on information visualization, INFOVIS 2002, pp 110–116
Weisberger M (2016) The Bizarre History of 'Tetris'. https://www.livescience.com/56481-strange-history-of-tetris.html
Whitley D (1993) A genetic algorithm tutorial
Woese C (1998) The universal ancestor. Proc Natl Acad Sci U S A 95(12):6854–6859
Woese CR (2002) On the Evolution of Cells. Proc Natl Acad Sci U S A 99(13):8742–8747

Dancing with the Urban Exaptation

Giuseppe Davide Longhi

1 Introduction

The term Exaptation refers to the adaptation random process of the elements that make up an organism, a process that Gould and Vrba define as "bricolage of nature" (Gould and Vrba 1982).

The question arises in the biological field and helps to overcome the evolutionary narratives linearity, prevalent in the twentieth century, in favor of narratives, which, taking advantage of increasingly powerful technologies, introduce unimaginable interpretative potential. Thus develops a scientific process that replaces the "great thinking of nature" with a "thinkering of opportunistic readjustments" of structures already available for new functions, which Gould and Vrba assimilate to a DIY process.

These concepts applied to the study of the city stimulate some questions:

- the city is not an asset "already available" to man, but an artifice created by man, historically subtracting goods from nature. Hence, what is the nature of the city and the structure of its narrative?
- knowing its current structure, what are its main evolutionary processes (unwilling and unable to analyze the entire urban complexity in history in a single article)?
- what is the speed of evolution of these processes?

G. D. Longhi (✉)
University IUAV-Venice, VoD ThinkTank, Venice, Italy
e-mail: longhi@community.iuav.it

C. AM. La Porta et al. (eds.), *Understanding Innovation Through Exaptation*,
The Frontiers Collection, https://doi.org/10.1007/978-3-030-45784-6_11

1.1 On the Nature of the City

Flash 1. Traditionally the evolution of the city was explained through linear illustrations of its physical-functional evolution (Duby 1980; Dethier and Guiheux 1994), in which the agents are the needs of military defense (e.g., from Palmanova to Haussmann's Paris) and the evolution of the means of production (e.g., from Karl Marx's "Countryside City Dichotomy" to Manuel Castells' "City of Communication") (Castells 1996–1998), passing through the epic of the industrial city which sees Peter Hall as a prominent narrator (Hall 1988). These approaches, which refer to the city as an expression of social and physical capital, two factors that find synthesis in Mumford's monumental work "The city in history" (Mumford 1961), are also significant for the low weight they give to the fundamental generative process: the subtraction of natural resources.
Flash 2. Nature, with its rules and its limits, is the great neglected of urban and economic stories, until Jacob Moleschott broke into the mid-1800s, offering the instruments for a circular view of urban reality based on the metabolism of ecosystems, thanks to the contributions of biology and ecology (Cosmacini 2005).

It certainly cannot be said that Moleschott's vision was at the center of the attention of the city's researchers, who will wake up a century later alarmed by the consequences of this inattention. Only in the middle of the last century, it developed the awareness that the world is a capsule with unsurpassed load limits (Kenneth Boulding's "Earth as a Spaceship," 1966, and Ian McHarg' "Design with Nature," 1969), threatened by human pressure (Paul Ehrlic's "The Population Bomb," 1968, and Paul Ehrich, with Barry Commoner and John Holdren, 1971, proposes the formula I = PxAxT). Nicholas Georgescu-Roentgen will make explicit the principle that the use of resources must not affect bioproductivity, and will support the need for a responsible relationship between economic development and the laws of thermodynamic (Georgescu-Roegen 1998). From here it is born a responsible vision of the economy (and of the development of the city), illustrated in 1973 together with Kenneth Boulding and Hermann Daly in the "Manifesto for a human economy," the foundation of the degrowth theory (Georgescu-Roegen et al. 1973).

The implications of space for these elements are critically anticipated by Jane Jacobs in the fundamental "The death and life of great american cities" (1961), where in the last chapter "The Kind of Problem a City Is" (Jacobs 1961) reflects about the interpretative 'thinkering' of the city leading it back to three stages of:

(1) *simplicity*, dominated by the linear relationship between a few variables;
(2) *disorganized complexity*, dominated by the statistical relationship between an high number of variables, studied through regression analysis, which measures the relationship between variables through the mean and the acceptable correlation error.

Jane Jacobs writes that the city is designed on the basis of average and error, so: "This is what modernist planners thought they were basing their authority on. They knew the numbers and they could accurately, if not exactly, determine how much sunlight an average man needed. They believed that through the abundant collection of punctual data they could solve all the problems of the system thanks to the averages, and their policies would be out of dispute, simply a matter of scientific facts." The myth of the data was born in this period, as an operational tool to understand and modify the city, and with it an important example of exaptation. The potential of the data is intuited by the US Air Force, which, applying Leontieff's cross-sectoral matrices to the bombing of cities, will inaugurate the practice of "precision bombing," applied to the main interchange and production nodes of European cities after the Second World War. More peacefully, Jan Tinbergen, first Nobel for economics (1969) will apply the same matrix to the Randstad Territorial Plan in the immediate post-war period, giving shape to a metropolitan vision based on interdependencies and externalities, or, rather, to a modern interpretation of the metropolis as a network and a system of networks (Leontief 1986; Tinbergen 1969).

Even the economist Robert Solow will make massive use of data to discover that the wealth of the firm is generated by its externalities (Solow 1956), a concept grasped by Jane Jacobs which understands that equally the wealth of the city is linked to the ability to internalize exogenous knowledge, from which the vitality of the metropolis, dependent on their ability to import important masses of human capital, and, thanks to them, to dynamically develop new knowledge;

(3) *organized complexity*, Jane Jacobs reconnecting to the advancements of studies in biology and computer science contained in the report of the biologist and mathematician Warren Weaver to the Rockefeller Foundation (1958), notes how the mechanical-linear rules of city development, combined with the statistical techniques, are unable to explain their nature, which, she senses, be similar to that of a neuronal network, that is, a system inspired by the functioning of neurons in a biological organism (Weaver 2003).

Thus she overcomes the linear or statistical approach of the city "as a machine for living or producing" (tipical of the modernist thinking), in favor of the city as a "learning machine" (a "machine" that learns from experience), exactly as a neuronal network learns and evolves.

These insights gave rise to the era of the archeology of cybernetics (Lynn 2013) and biology, which will provide the raw material for the global city of bits, and for inequalities and asymmetries.

Flash 3. 1946–1953, in a series of interdisciplinary seminars organized by the philanthropic foundation Macy, which promotes the search for new ideas especially in medicine, the mathematician and statistician Norbert Wiener discusses "cybernetic" ideas, then little known, because they are subject to secrecy sets up US military research, with an innovative interdisciplinary table made up of neuro-anatomists, neurophysiologists, psychologists, statisticians, ecologists, philosophers, cultural anthropologists, sociologists, physicists, and mathematicians (Montagnini 2015).

1958, Richard Feynman at California Technological Institute (CALTECH) holds his famous lesson "There's Plenty of Room at the Bottom," which will be awarded the Nobel Prize in physics, in which he theorizes the exponential availability of matter, thanks to nano-bio technologies, summarized in the famous slogan "how many

British encyclopedias are in a hair" and describes the process of self-reproduction of biological elements (Feynman 1960).

These two elements mark an epochal passage in the study of the structure of the city, in fact, to the binomial Matter—Energy proposed by Roentgen, the communication element is added (thanks to cybernetics), so the elements that make up the city are Matter-Energy-Communication. With the nano-biotechs proposed by Feynman, the replacement of the production processes by subtraction of matter with organic self-production processes begins.

The cycle evolves with the publication in 1991 of "The Computer for the 21st Century" by Mark Weiser which thus begins "The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it." The path of ubiquity begins with the connection tools directly incorporated into objects, urban infrastructures, buildings and in waiting to be incorporated into the human body (Weiser 1991).

The city intended as machine learning intuited by Jane Jacobs has become reality.

The city born as a functional machine destined to host and order the society functions, is it preparing to become a machine commanded by an elite of men who, through robots, monitor a mass of citizens whose pressure exceeds the biocapacity of nature?

It is a complex discourse that finds an important interpretation in the work led by Mohsen Mostafavi at Harvard "Ecological Urbanism," 2010 and by Shoshana Zuboff "The age of surveillance capitalism," 2019) (Mostafavi 2010; Zuboff 2019).

1.2 On the Main Evolutionary Processes of the City

The paper explains this exaptive world assuming the metaphor of the dance, a clear homage to Donella Meadows "Dancing with the systems" (Meadows 2009).

So the narrative takes as a driving force the Vitruvian man in his radical mutations and as plot the chaotic and casual "dance" of disruptive events (interpretable also in terms of exaptation) accompanying the manipulation of space evolution.

The structure of the story, therefore, is based on two great "dances:" of man searching to increase his skills in a race that sees him to compete (or to succumb?) with robots, of man in search of coexistence with nature for a development model compatible with the biocapacity of the earth.

The "dances" are developed thank disruptive events: (1) the evolution of man–machine relationships in a dematerialization process leaded by the route from Architecture Machine to Citizen-Environment Interactions, (2) the evolution of man–nature relationship, in the passage from Holocene to the Anthropocene, (3) the nano-biotechnologies world up to the bionic city.

These events bring out new multiple design alphabets (environmental, architectural, economic/social, technological, …) substantially differents, because connected to the different rules of manipulation of nature, human resources, physical space, and bits.

From the ability that man will have to create new approaches to knowledge at accelerated rates, to develop synergies between new alphabets, the success of urban communities, in harmony with man and nature, will depend.

1.3 On the Evolution Speed of Urban Processes

To interpret an exaptative process it is essential to know the nature of the materials that make up the phenomenon. In the case of the city, knowledge has advanced exponentially since the second post-war period, with Wiener and cybernetics, Feyman with nano and biotechnology and Roentgen with the bioeconomy, to make a further leap in the early years '90 with Wieser and ubiquity.

With the expansion of cognitive processes, the narration of the elements that make up the city has changed: in just over half a century, the historical narrative of the city made up of matter has changed, to the city made up of matter—energy-communication. This narrative has opened up new operational scenarios, indispensable for the survival of the earth (and with it of the mankind):

- the transition from the mechanical mode of production by subtraction of matter to the biological one of the recombination of matter;
- the transition from a "discreet" system of relationships to a "continuous" system, with the consequent revolution of the rules of social relationship and space that govern our communities.

The first point is the prerequisite for an economic revolution that has been announced, but has never been seriously addressed so far, the second for a social revolution based on "open" governance systems, thanks to continuous feedback between communities and civic representatives. But, as Henry Kissinger points out in his famous article "How the Enlightenment Ends," in "The Atlantic," man is unprepared to face such a cultural leap (and perhaps he does not have the capacity) (Kissinger 2018). So the narration of the city, starting from the second post-war period, is a synthesis of information and cultural asymmetries to which contribute: the plurimillennial culture of the nature and church, the secular culture of the merchant, the decennial culture of the man life, who barely integrates with the real time of its decisions.

In essence, it was claimed to interpret and act on the city with the knowledge and rules of the first industrial revolution, so in the last 50 years human actions, with dramatic acceleration, have annihilated the ability of many ecosystems and species to maintain themselves, as they did in the most stable conditions, that prevailed for at least 11,000 years.

The reference to exaptation is therefore useful because it reminds the world of city researchers to the complexity and times of the biological world at the origin of the urbanity, and, consequently, to the urgent need to renew our knowledge, inadequate for maintenance of such complex systems.

1.4 About the Urban Dance

The narrative of the urban structure complexity, as highlighted in the introduction, imposes the transition "from the great narration of nature (in our case of the city)" to a "thinkering" of opportunistic readjustments of heterogeneous components (environmental, social, economic, technological …) in line with the DIY model proposed by Gould and Vrba.

So, this article takes shape on the DIY model. Taking the idea of Jane Jacobs as a reference, the city is not a machine for living or working, but a machine for learning, the city cannot be explained as an intentional sequence of events but as a series of surprise, or sudden, radical shift in preferences or goals, as well as vicious cicles that may stifle its evolution (Ciborra 1991). So the evolution of the urban environment is based on a continuous adaptation and learning processes reshaping continuously the physical, natural, and social context.

Equally, for Donella Meadows "We can never fully understand our world, not in the way our reductionistic science has led us to expect. Our science itself, from quantum theory to the mathematics of chaos, leads us into irreducible uncertainty. We can't keep track of everything. We can't find a proper, sustainable relationship to nature, each other, or the institutions we create, if we try to do it from the role of omniscient conqueror."

Thinkering successfully in a world of systems requires more of us than our ability to calculate. It requires our full humanity—our rationality, our ability to sort out truth from falsehood, our intuition, our compassion, our vision, and our morality. Concepts that Donella Meadows synthesize with the metaphor of the dance, whose main elements are

- Get the beat.
- Listen to the wisdom of the system.
- Expose your mental models to the open air.
- Stay humble. Stay a learner.
- Make feedback policies for feedback systems.
- Pay attention to what is important, not just what is quantifiable.
- Expand time horizons.
- Expand thought horizons.
- Expand the boundary of caring.
- Celebrate complexity.

So, the thinkering of urban evolution is here explained with the "dances" from "Vitrouvius man" to "City Brain."

The article focuses on the topical moments of the evolution of the man-city relationship under the pressure of technological progress, especially in communications. It therefore marks the passage of man from the labor force of the industrial city to the human resource necessary for development of the city as "machine learning," up to its transformation into a robot, due to the continuous incorporation of machines, in a problematic relationship with the "smart city."

2 Urban Dance: Man, Machine, and Urban

In time the role of man changes radically, passing from the Vitruvius man enrolled in a physical environment, to his "liberation" from the walls with Le Corbusier Modulor, to his immersion in the waste of the second industrial revolution, to the supremacy of his neuronal dimension with respect to the physical one, his connection with the bits, his substitution with the robots.

These tsunami of changes, starting with the harmony between man and artifact, are today arrived to a contradictory step: with the substitution of man with robots and with the genetic manipulation of the human body. These great exaptive processes are here explained thank the technological passage from esomachines to endomachines at the origin of radical changes in the relationship man-machine-environment. In fact, we quickly passed:

- from the realization of cumbersome mechanical exomachines symbolized by the relationship Man-Cadillac (Banham 1960), outcome from mechanical technological processes, working by subtraction of matter;
- to the realization of nano biological machines, working inside the human body, thank biological self-production process thinked in 1959 by Robert Feynman. An idea developed in form of molecular machine by Sauvage, Stoddart, and Feringa (Nobel Laureates for Chemistry 2016).

In half a century we passed from the production by subtraction of matter of the industrial revolution to the generative production of the biological revolution, passing through the revolution of connectivity, between people, between things and between people and things. This is the fourth industrial revolution, or, if you want, an important step in the process of exaptive change of man and the city, which I will try to interpret, at least for the relationship among connectivity-man-environment (Fig. 1).

2.1 From Architecture to City Brain

In March 1946, organized by the philanthropic foundation Macy, which promotes the search for new ideas especially in medicine, Norman Wiener (philosopher and mathematician), together with a group of scientists composed of neuro-anatomists, neurophysiologists, psychologists, statisticians, ecologists, philosophers, anthropologists, and sociologists discuss ideas that will underpin "cybernetics," a scientific field hitherto under the hood of secrecy, imposed on military research by the US Department of Defense. A path begins to substantially evolve the knowledge of the city, which will give rise to unthinkable operational and design potential. Synthetically, that discussion will open two fields:

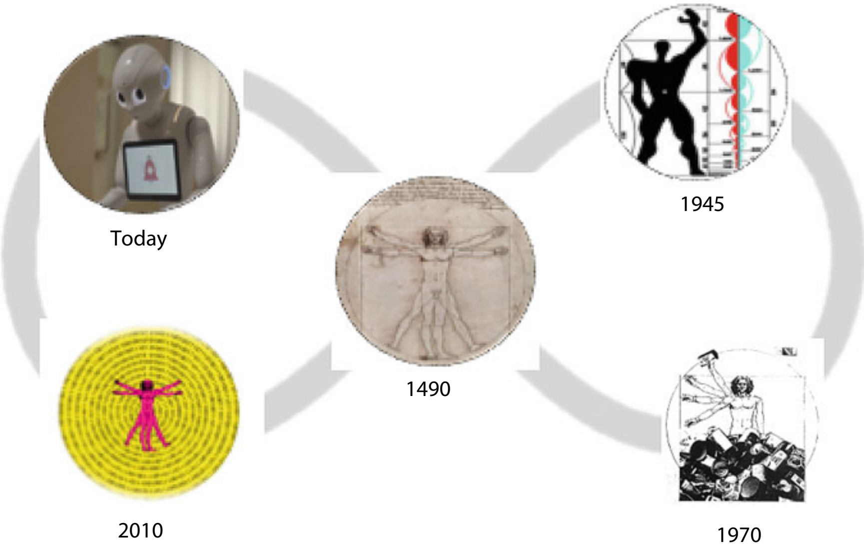


Fig. 1 From Vitruvius man to robot

- the parallelism of the computer with the human brain, which will begin, about twenty years later, starting from the experiences of Architectural Machine, to the great adventure of the augmented capabilities, which will follow:
- the concept of "ubiquity" applied to the city (late 1990s), thanks to the integration of man's increased capabilities with the network (thanks to the Internet), and subsequently to the synergy between the computer-human brain and objects;
- the current morphology of the "City Brain," capable of manipulating data and returning them in terms of services (Feng et al. 2019);
- a substantial advance in the management of governance processes, thanks to the increased cross-fertilization between technology and neurophysiology on the one hand, and, on the other, to the emergence of circular causality notion in livings and in society, with the consequent vision of the government of the city as an ecosystem, articulated in a system of interconnected circular random processes, as happens in the biosphere.

And precisely circularity and cross-fertilization require "open" governance systems (radical evolution of historical "hierarchical" governance systems) between all stakeholders, which operate on the basis of feedback (a concept developed by Jay Forrester in his proposal for Dynamic Systems which will be widely disseminated with the research "The limits to growth") (Forrester 1989).

We are therefore in the presence of a radical evolution of the first industrial revolution, the revolution of the "dark satanic factories," which represented the devaluation of human arms in the face of competition from the machine. With the advent of cybernetics, the modern industrial revolution begins, which is linked to devaluation of the human brain, at least in its simplest and most repetitive decisions.

Wiener says: "Of course, just as skilled workers somehow survived the industrial revolution, so the skilled scientist and administrator can survive the latter. However, once the second revolution has taken place, the average human being, of mediocre ability, will no longer have anything to sell that is worth buying." The competition between man and robot has begun in a city where the goods are produced at marginal cost 0 and where it's great the surveillance of people.

Furthermore, Wiener understands very early that it has to do with a technology not of "matter/energy" like in the past, but the one "of information," subject to new laws. The former had always been interested mainly in the production of a large amount of energy (e.g., steam machines, hydraulic turbines connected to dynamo etc.), its transmission (e.g., with rotating shafts or high voltage lines), its transformation into other forms of energy (such as transformers, transducers), to its use (e.g., thermal or electric motors, heating systems, etc.). On the contrary, generalized information technology is interested in:

- the production of information (by the brain of a person speaking or by a device that automatically sends a stop signal to another, such as the thermostat which switches off the refrigerator motor when the desired temperature has been reached);
- its transmission (on telephone lines, telegraphs, etc.);
- its transformation (noise filtering, coding, etc.);
- its use by a human being or a machine.

The vision of a new discipline, very influential on the development and form of urban environment, that focuses entirely on information emerges, requiring very low energy levels. It is the science to which Wiener in 1947 gives the name of "cybernetics."

Here the story (or dance) of the city becomes complex due to the cultural and cognitive asymmetries of the parties involved in the development of the city (and the strength of the conservative cultures that dominated the study and design of the city), only in 1968 the adventure of Architectural Machine starts, in 1990 the concept of ubiquity and nowadays the new vision of "City Brain" consolidate.

2.2 The Architectural Machine Adventure

The "Computer Graphics in Architecture and Design" conference at the Yale School of Art and Architecture (1968) marks the start of an important step of modern design. It is marked by the transition from Le Corbusier's "machine à habiter," based on the supremacy of the relationship between building–bulky and passive installations, developed between the first and second industrial revolution, to an architecture based on the relationship between building and computers, the miniaturized and interactive systems of IT revolution. The purpose of this new generation of architects and technologists is to initiate egalitarian design processes, aimed at overcoming the role of the designer superimposing on people, that is, overcoming the architect's "genious role" and the formal standardization of the International style, in favor of informed planning processes, led by citizens.

Gordon Pask argues in "The architectural relevance of cybernetics": "we overturn the design paradigm, focusing on the interaction between the environment and the people who inhabit it, instead of the usual interaction between the designer and the physical system he designs" (Pask 1969).

With this trend also begins a new dimension of architecture aimed at dematerialisation, marked by the relationship between atoms and bits, to say it with Nicholas Negroponte. Thus began the decline of the "Victorian" vision of architecture, based exclusively on the removal of matter, in favor of a design dialogue that exploits the opportunities of new technologies, such as nano and biotechnology, which were born in those years. The result is the start, at the beginning of the 70s, of a modern architecture, sustainable, aiming to increase human resources, thanks to the "increased intelligence, from the availability of new machines and the decrease in the load level of urban interventions, thanks to dematerialisation.

The new design process is in continuity with the thought of the metabolic movement:

- with regard to the role of the architect, who, says Kisho Kurokawa "… should not propose ideal models for society, but should conceive spatial infrastructures that the citizens themselves must make operational;"
- with regard to the synergy between physical achievements and the metabolism of natural resources, confirming the overcoming of the linear design model, typical of Western thought, in favor of the symbiosis, typical of Eastern thought, among all the elements, biotic and abiotic, which contribute to the realization of a project.

A symbiosis confirmed by Christoper Alexander, according to which the city is given by the interdependence between the fixed parts that make up the urban morphology and the variable parts made up of human resources, biodiversity (especially the animal one), the goods that circulate there, the effects of the infrastructures operation. Its development is not given by proceeding in large blocks, therefore on the idea of replacement, but on gradual growth, therefore on the idea of rehabilitation (Alexander 1966).

Shortly, The Vitruvius Man, thanks to modern computers, gets rid of the architect's demiurgical presence. This was the thought of the anarchist architects Nicholas Negroponte, Cristopher Alexander, Bob Mitchell, Alain Kay, and, in Italy, Giancarlo De Carlo. Their motto was "we are all architects" thanks to the "architectural machine" computer.

The computer use generates a new alphabet based on the deconstruction of the architectural language (Alexander, Pattern language), on its logic reconstruction and on new machine operative rules (Negroponte, Toward an Architectural Machine). The modern software (today in use) for design and geographic mapping is born.

Cedric Price is one of the great empirical interpreters of the new opportunities offered by cybernetics and information technology to architecture and the development of the city, thanks to his proposal of architecture based on improvisation. Starting from user requests, coded in constantly evolving software programs thanks to learning, anticipation, adaptability, architecture is able to adapt in real time. Price's design proposals stem from his sensitivity to the profound social and territorial transformations that began in the second half of the 1960s, which were taking shape in profound processes of deindustrialization and unemployment. The outcome is the proposal of design solutions based on provisionality, improvisation, and interactivity, highly adaptable to the volatility of economic and social conditions, with respect to time and space (Obrist 2003).

In the time of uncertainty and instability Price's work represents a new approach to design, based on a holistic process of construction, reassembly, dismantling.

To cope with the profound social and economic crisis, the buildings and the territorial planning that he proposed were aimed at increasing knowledge: his reference model was the spontaneous organization of "street theater," which was the starting point for the proposal of:

- buildings inspired by the model of the bridge crane, capable of changing in relation to changes in objectives and programs (the best known being "Fun palace"). The input of the building transformability were the citizens' preferences on how to use and occupy the spaces, who, thanks to software and computers provided the operating indications and feedback for the realtime transformation of the buildings;
- complex territorial structures, as Potteries Thinkbelt, capable of developing new systems of social, economic, and productive organization. The structures were divided into: static elements (the railway network and the logistic bases) intended to manage, thanks to an interactive network powered and controlled by computers and emerging information technologies, a system of mobile teaching units, which exploited the opportunities of the railway wagons for the transport of containers. These mobile didactic units were conceived as a quantum information system, the logistic bases were inspired by a large system of computer circuits. Potteries Thinkbelt defines a new kind of architectural monumentality, not a large static building, but an articulated field of discrete objects and diffuse events, similar to the structure of an electronic circuit;
- advanced organizational models: Price's project proposals are based on a wide agenda of opportunities, fueled by users' preferences, and on the ability of the project manager to develop an agenda capable of illustrating new projects' opportunities to unsuspecting citizens. With the "Generator" project, the modern management system for complex interventions was born, based on two roles, the "polarizers" and the "facilitators," able to catalyze on-site the interpersonal dynamics and logistical needs of users. The "polarizers" should have encouraged users to take advantage of the new opportunities of the project and stimulate their interactions, the "facilitators" should have given instructions to make the users' wishes operational, training them to use the individual systems and to sensitize them to the opportunities of the place.

Price sensed that the new ways of urban, economic, and social development required a temporary and agile architecture, capable of adapting not only to inevitable changes, but also to favor and anticipate social transformations (Fig. 2).

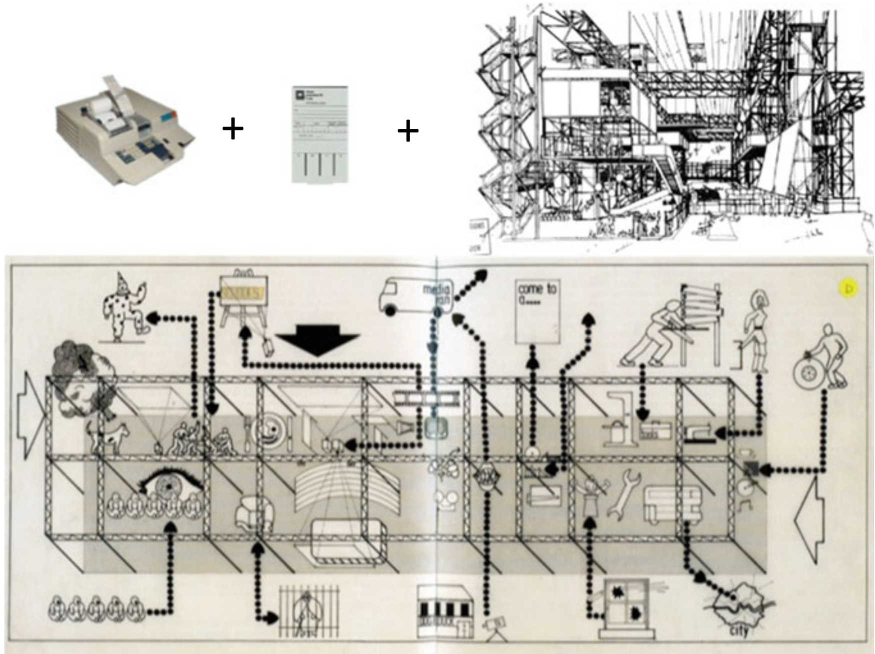


Fig. 2 Cedric Price idea of interactive building: Fun Palace, 1961

Nicholas Negroponte, founder of Architecture Machine Group first (1968) and then of MIT Media Lab (1985), develops his thinking on architecture inspired by classic models to radically renew them. His idea of "Architecture machine" is ideally linked to Le Corbusier's "Machine à habiter"—in terms of legitimizing the machine as a fundamental component of the architecture project; while from an organizational point of view its reference model is the Bauhaus, due to the presence of different disciplinary skills, whose intelligence is increased by the availability of new machines (Negroponte 1970, 1975, 1995).

Negroponte sees technology, like Alexander and Price, as a tool to develop a hypothesis of "spontaneous" architecture, in which it is not the architect with the sum of his historical and cultural experiences that impose the project on the user, but it is the latter, supported by the tools of artificial intelligence, that leads the project, thanks to the new machines that rise to the collective mind capable of recognizing the morphology, the rules of space management and solving the aesthetic data on the basis of a functionality which is cultural, custom, and urban.

Thus develops a working and design method that makes a particular use of the machine, so that it does not place itself on the plane of mimicking-emulation of man's thought, but provides his "assistance" and his skills in the IT field.

> We are simply interested in introducing and promoting machine intelligence that stimulates design for a better life and allows a whole series of self-evolutionary methods", Negroponte (1970).

ArcMac, in the idea of Negroponte, was supposed to transform the design process into a dialogue intended to alter the traditional man-machine dynamics. He wrote: “The dialogue of mutual understanding would have been so intimate, even exclusive, that it would have been impossible to realize for only one of the parties. Without doubt, in such a symbiosis, it would not have been only the human designer to decide when the contribution of the machine was relevant” In order to incorporate the project objectives and to assimilate the aims of the users, the machine should have been equipped with artificial intelligence,” because all the design procedures, together with rules or truths are tenuous, if not even subversive, if used out of context or regardless of context.” Intelligence for Negroponte is therefore not a passive quality, but an active one, expressed by behaviors and increased over time.

Negroponte also senses that the computerized processes would not be limited to helping us in the design, but, in their evolution from tools to environments, they would have merged into the physical part of the buildings.

This would open up a series of design strategies:

1. the new building materials will be aimed at creating updated forms of the past;
2. the new materials will simulate the processes present in nature, thanks to their ability to assemble and disassemble continuously;
3. the buildings will be associated with robotization processes, so they will qualify not only for their physical characteristics—technological level, industrialization processes, automation levels—but also for some subjective properties, such as autonomy and desire level. Consequently, their representation will be both material, linked to their physicality, and abstract, linked to their ability to develop random processes.

With this last observation the horizon opens to the “ubiquitous city” thanks to the fusion of material and immaterial, that is the connection of atoms and bits, which Negroponte will develop in the “City of news” research program (1975) and in the book “Being digital: atoms and bits “(1995).

These latter contributions define the structure of objects, architecture and the city as a compound of matter—atoms—and connectivity, thanks to intangible resources—bits.

Just as in the previous era of machines, designers planned following the rules of mechanics, according to the metaphor of the work chain, in current time, the global computer networks, the”time-shared” activities, the associative activities on the internet, define an environment comparable to a membrane of virtual spaces and activities. Consequently, Negroponte maintains that the organic development model of the city should be able to represent not only its physical development but also the life generated by the web, thus managing to connect operationally the relationship between atoms and bits and between representation/physical design of the city and representation of the cognitive systems expressed by its citizens.

With the fusion of computerized processes in objects (on a par with buildings and infrastructures), thanks to the rapid expansion of miniaturization, an important, probably fundamental, passage begins in the narration of the evolution of the city, in that to the history of the relationship between architecture and TLC (therefore matter-connectivity), which has been summarized so far, modern history of the energy-economy relationship will have to be added. Started in the decade from the mid-60s to the mid-70s, it has among its main exponents Kenneth Boulding, Nicolas Georgescu-Roentgen, and Hermann Daly, who will give life to the school of ecoeconomy and of degrowth movement. With these, of course, the physicist Robert Feynman (Nobel Laureate 1965), who in 1958, with his essay "There's Plenty of Room at the Bottom," opens to the knowledge of nanotechnologies and biologic production processes.

Thus, in the 1970s the founding elements of the interpretation of the modern city, which we have owed to cyberneticians since the late 1940s, became operational. At the same time Feynman "reopened the dances," marking the way for a city with exponential development opportunities, in contrast to the dominant theories of the limit of the biocapacity of the earth. This complexity of "dances" confirms that the narrative cannot be linear, because it is dominated by asymmetries. The exaptation will have to equip itself for another dance, that of the narrative of the relationship between city and resources.

2.3 The City of Ubiquity

In an innovation process whose main stages are ARPANET (1969), the WEB (1990), and the CLOUD (2010), communications infrastructures constantly change nature. From a machine to produce projects it becomes first machine to produce sociality and then machine to produce services, with the XaaS (All as a service) process: the fourth industrial revolution is started (Fig. 3).

With the enormous expansion of the potential of the computer + Internet, the fundamental question of the integration, in the construction of the city, of matter (and of the "machine") with the immaterial opens up.

The first era of the computer (from the 60s until the end of the 90s) was marked by machines designed to expand human capabilities, a phenomenon that introduced the transition from inspired organizational (physical and social) design models optimization of the production chain (see Giedion, "Mechanization take Command") and

Fig. 3 From Internet to Ubiquity

models inspired by operational research, intended for the optimization of relationship systems, thanks to the possibility of feedback (see Forrester, “Systems Dynamics”).

This scenario is destined to evolve radically with Mark Weiser’s article “The Computer of the 21st Century,” published in Scientific American in 1991, which introduces the concept of ubiquity into production and organization.

Indeed, Wieser says: “The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it.” Wieser proposes the vision of a process that from the “standard PC” was diversifying and proliferating through interconnected computer networks, introducing a series of fundamental concepts: the dematerialization of relational and production processes, organization by networks and relational platforms.

Concepts that undermine traditional morphologies, both social and physical, based on the concept of the boundary and the “finished” geometry of places, in favor of acentric processes.

With Wieser’s article, the central problem of design will become the symmetry between “closed” and acentric forms.

The evolution of Wieser thinking opens the field to three new phenomena: virtual reality, artificial intelligence, “user agents,” but Weiser opposes a strong criticism of this kind of evolution.

2.4 From Ubiquity to Citizen-Environment Interactions

In the third phase, the interactive communication system, after supporting design and sociality, becomes a complex technological system, thanks to the connectivity between objects, produced by Cloud + IoT (Internet of Things): the Smart City is born and evolves rapidly through these stages:

- *Smart City* 1.0: guided by technological companies with the objective of controlling territory and citizens (the myth of fear and security);
- *Smart City* 2.0: guided by the municipality to improve services to citizens;
- *Smart City* 3.0: guided by co-creation with citizens and experimenting forms of proactive democracy (Fig. 4).

In the Smart City, instead of dealing with individual, personal desktop computers, laptops, tablets, smartphones, etc., the experiences and interactions of humans with “computers,” will increasingly take place in the context of interacting with “smart artifacts” integrated into the environment, constituting “smart ecosystems.” This has serious implications for the research area currently called “human-computer-interaction.” It includes also a shift in terms of scale and context, ranging from individual devices for personal activities to multiple devices used in group activities and social interactions. This is followed by the progression from smart rooms to smart or cooperative buildings and their extension to smart urban environments as, e.g., smart cities and airports. The trend toward more comprehensive application contexts requires a corresponding shift from a mostly individual person-based, user-centered

Fig. 4 Smart ubiquitous city pose the classic Cedric Price question: "Technology is the answer….but what was the question?"

design approach to a multiple people and multiple devices-based, citizen-centered design approach for smart environments, we are confronted with, in the urban age. The ubiquitous and pervasive deployment of smart technology in urban environments has serious implications for privacy and security issues.

This goes along with an increasing trend of using artificial intelligence for algorithm-based automation and autonomous systems resulting in a loss of having humans in the loop and in control. Thus, the future of human-computer interaction is characterized by the challenge of addressing the corresponding design trade-offs and the need to rethink and redefine the "smart everything" paradigm in order to move beyond "smart-only" cities to Humane, Sociable and Cooperative Hybrid Cities and Societies (Streitz 2018).

The goal is to build Humane, Sociable and Cooperative Hybrid Cities reconciling people and technology. This implies to foster and enable the following actions and requirements in the town construction (Norbert Streitz, The Future of Human-Computer Interactions):

- establishing a calm technology providing ambient intelligence that supports and respects individual and social life;
- respecting the rights of citizens, especially in terms of privacy and security;
- viewing the city and its citizens as mutual cooperation partners, where a city is "smart" in the sense of being "self-aware" and "cooperative" toward its citizens by supporting them in their activities. This requires mutual trust and respect for the motives and interests of all stakeholders involved;
- acknowledging the capabilities of citizens to participate in the design of the urban environment, especially with respect to their local expertise, and stimulating their active participation;
- motivating citizens to get involved, to understand themselves as part of the urban community, to be actively engaged by contributing to the public good and welfare;

- enabling citizens to exploit their individual, creative, social, and economic potential and to live a self-determined life, and thus
- meeting some of the challenges of the urban age by enabling people to experience and enjoy a satisfying life and work.

These are some of the demanding actions and requirements that urban design has to face with for the next 20 years. Although addressing different levels of scale, many of these requirements can be generalized from Cooperative Cities to Cooperative Societies.

2.5 The City Brain

The narration of the city in its transition from physical structure to ubiquitous structure cannot be separated from the description of the system that allows its operation: the City Brain, whose key elements are

- the central nervous system: it is made up of the Cloud, which through the Cloud Computing procedures is able, as well as to collect data, to: (1) manipulate them, thanks to Big Data, AI, Machine Learning, Deep Learning, (2) organize them, thanks to the Infrastructure as a Service (IaaS), Platform as a Service (PaaS), Software as a Service (SaaS), (3) socialize them, thanks to SNS (Social Network Systems);
- the nervous motor system: made up of the Internet with its stages of evolution (IoT, Mobile and the related technological passages G4, G5, …);
- the peripheral nervous system: constituted by Edge Computing with its property, thanks to the "reflex arcs" which don't depend on the central urban brain.

The City Brain infrastructures allow the "neuronal" interactions between the different physical and social elements that make up the city and its environment, from this point of view, the Smart city poses severe problems of social organization, as it obliges to rethink:

1. the neuronal organization of the community: Smart community, Smart Citizenship, Smart Government …;
2. the neuronal organization of the city's functions: Industry 4.0, Smart building, Smart traffic, Smart Health, …;
3. the governance of relationship between human resources and robots, with regard to employment and ethical problems;
4. the governance of human activities—environment interactions (Fig. 5).

This rethinking cannot ignore in the city design the role of the Public Administration Social Net infrastructure is substantially different from that of the private social networks, organized by the communication majors (Google, Facebook, Instagram, …).

These Majors collect data, that are a private and collective good of citizens, essentially by not paying them, generating surplus value through their "manufacturing"

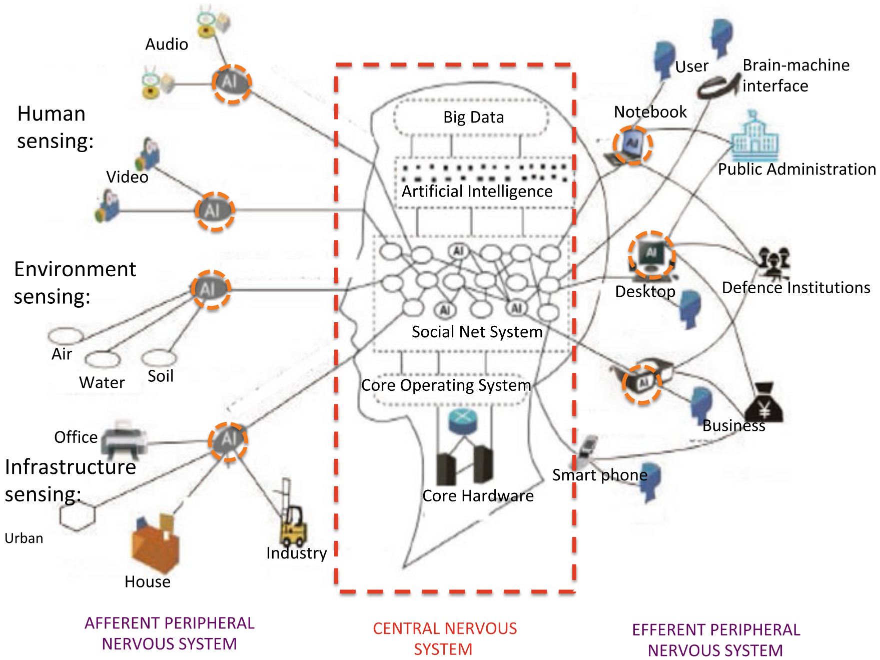


Fig. 5 The urban information system clone of the human nervous system: to increase human capacity or to replace them with robot?

(A.I phase and related operations) and their marketing (through Social Net). The municipality that has a primary asset, both individual and common (the data of citizens, public organizations, nature, historical heritage …), instead is called to initiate social enhancement processes, through the same activities of "manufacturing" and distributing data.

Therefore, through the organization of the social net, the public administration should re-appropriate the role of producer with the aim of generating social added value (Maistrello 2006).

To achieve this step, a process of up-to-date culture of Public Administration must be started, as it must be able to manage the difficult transition from governing discrete systems in a linear way, to governing complex systems of "open" flows.

In fact, social networks operate according to the emergency rule: that is, starting from simple rules (or elements) they are able to self-generate complex schemes (or structures), which the mere sum of the parts would not have left to imagine. So if the complex system is managed with the rules of the linear, unforeseen situations are generated, which the administrators are not able to govern.

This matter proceeds at accelerated way because the number of social interactions "out of control" increases exponentially in relation to the number of components (according to Moore's law), generating a system of unpredictable/uncontrolled social behavior.

The design of the Municipal Social Net (s) consequently consists in the design of open and networked cooperation systems, producing value from every element of the urban environment (citizens, natural capital and physical capital) thanks to the detection of any type of behavior and expectation.

This is possible by overcoming the social network, intended exclusively for man-man interaction, thanks to the new “ubiquitous” infrastructures, that is, made up of material elements (buildings, offices, shopping centers, roads, urban systems, …) which incorporate intangible services through the Cloud-Big Data-IoT processes.

So every building, every car, every shopping center, every plant, every citizen will have a connection code to the social network, managing automatically information in real time and also interacting with other people or things, involving human-human, human-things, and things-things interactions.

This implies overcoming the idea of the social net as an increasingly costly and conflicting structure of power centralization, in favor of a “neuronal” infrastructure, “listening” to the city, producing new social value.

This is an operation of the society redefinition comparable to the advent of writing.

2.6 Dilation of the Idea of Space and Dilation of the Idea of Wealth

The process of continuous expansion of the idea of space, thanks to the integration of connectivity tools in physical structures, generates an important change in the process of accumulation and distribution of wealth among citizens.

Thus began a “dance” fueled by the revision of the neoclassical theories on economic development asserted first by Robert Solow and after by Robert Lucas, in synergy with Jane Jacobs, ending with Paul Romer (from 1956 to 1990). This path is of fundamental importance for the explanation of the city evolution, as it is marked by the passage from the supremacy of physical capital (expressed in artifacts, plants and infrastructures and financial resources) to that of a holistic system in which interact four driving forces: ideas, institutions, population, human capital (expressed by education, research, and development).

The main growth factor of these driving forces regarding the economy, according to Solow, is the exogenous factor of technological progress. An intuition that is completed by Lucas and Jacobs, who underline the role of the city (and, in particular, of its size and dynamism) in development, because human capital, generator of technological progress, is concentrated in it.

A concept sustained also by Romer (1986), who maintains that development is in relation to an unlimitedly available good, consisting of ideas, which are introducing a series of changes in our way of thinking about development, as follows:

- they are non-rival goods, as they can be used simultaneously by a large number of people without generating congestion or exhaustion;

- develop new technologies, such as biotechnology, which help demolish the fair of diminishing returns, which has obsessed the economic thinking from Ricardo to Keynes. On the contrary, new technologies create increasing returns, because new knowledge, thanks to research, starts new products. Furthermore, in the design and construction, the new technological frontiers, based on dematerialisation and biotechnology, allow to create products by drastically lowering the withdrawal of resources from nature, thus minimizing the impact on the load capacity of the earth—they generate the fall in production costs, the centrality of investments thus shifts from production to research;
- the production of ideas is inseparable from the effects of scale, and therefore confirms the fundamental role of urban concentration and with it the positive reading of the phenomenon of megacities and globalization;
- they are based on organizational models (also of the city) not competitive but linked to the symmetry of relationships, thus collaborative;
- the latter two factors (effects of scale and organization) are often considered together, but are logically distinct; the organizational effects have attracted more attention but the scale effects are more important to understand the great change in human history that we are living.

This path inspires an urban design model in which the driving force is human capital, so the primary development infrastructures of the city are those that feed knowledge (formal and informal), research, and development activities, to which must be added the infrastructures to protect human capital, such as healthcare. Hence, according to Paul Romer, the purpose of urban planning is to "identify additional units of public good, in order to prevent the decrease in the productivity of human capital". On the contrary, if the city is conceived as a simple agglomeration of productive factors (in our case manufactured goods or physical spaces anyway), as happens in current urban planning practices, the centrifugal forces linked to rent will prevail.

Furthermore, a design based mainly on the increase in physical capital (e.g., through the construction business), according to Solow, does not produce long-term effects, because what can affect growth is, ultimately, only the rate of introduction of new technologies, which affect 80 % of the development processes. The purpose of urban planning is therefore not to exclusively satisfy the needs of resident citizens (to satisfy endogenous needs), but to capture the innovative flows of knowledge (the exogenous flows of human resources), internalize them in the development processes of the city, to generate export flows of goods and knowledge and to favor the integration in the city network.

The wealth of the city is thus determined by the quality of its infrastructures and places, that favor the accumulation of knowledge, the development of skills and empathy.

3 Conclusions

As mentioned in the introduction, the adaptation of the concept of exaptation, born in the biological field, to a multidisciplinary field such as the city is not easy. It is true, as Andriani argues, that the effort to adapt this concept to areas different than that of the living is consolidated, however these efforts mainly concern a sectoral "expansion" (exaptation and technology, economics, physics, social sciences, …), in the case of the city we are faced with a system with an infinite number of variables, the aggregate trend of which cannot be determined a priori, hence it could be said that the nature of the city itself is exaptative (Andriani and Carignani 2014; Andriani and Cattani 2016; Andriani et al. 2017).

The article illustrates the complexity of the urban structure by referring to Jane Jakobs' question "The Kind of Problem a City Is."

From the narrative it appears that the dynamics of the components of this vision take on an exponential acceleration in relation to the development of the "augmented capabilities" of man, but also an exponential confusion for the inability of man to manage this structure, changing in a way unpredictable due to the different forms of exaptation activated by the context elements that are proposed according to the Donella Meadows metaphor of the dance, to mark the improvisation and creativity of the variations, from which the emergence of unpredictable (perhaps one might say disruptive) phenomena. The vision of the structure of the city and its non-linear variability is traced back to a series of questions:

1. whom is the city made? Over time, the construction of the city has gone from the supremacy of the land factor to that of human resources, as its vitality depends on the quality and quantity of knowledge and innovation processes. So to the rational space of the city, with its figures inscribed in precise geometric shapes, is added an idea of "delirante" space (from lira = border, therefore de-lirare means to go beyond the border), says the philosopher Cacciari (2004). But for the the city "delirare" is essential its empathy in welcoming the different. So, over time, the shape of the city does not depend on top-down relationships between the prince and the designer, but tends to be shaped on the basis of collaborative practices fueled by feedback. This raises a question: if the web is the new arena in which civitas is practiced (a topic dear to Paul Virilio), who will govern the thinkering developing in this arena?;
2. what is the city made of? Over time we have gone from a city explained through its matter to a city composed of matter, energy, connectivity, with an unscheduled process, in search of saving limited resources such as matter and energy, in favor of the use of unlimited resources (connectivity), in the hope of decreasing impact, costs and increasing the knowledge rate. The largely random result is the transition from a city composed of "passive" elements to a proactive city, in which the idea of the border is replaced by that of ubiquity, where the machines that man uses are always more miniaturized, until they are incorporated into the human body.

The chips, the computer technological components, the net, at first was incorporated in the machine, to develop urban ubiquitous infrastructures, connecting people, community and things, with the aim of encouraging more democratic relationship in the process of urban evolution.

Today man is becoming a complex artifact, resulting for the symbiosis between its original natural dimension and the incorporation of bio and nanotools. This is a transitory state of the project of massive replacement of men with robots, which, led by a small number of large companies, distorts the meaning of human beings, putting the values of our civilization in discussion at the root. The long time of evolution seems to have produced the overcoming of the human value in favor of the robotic machine in the service of a restricted economic élites;

3. who “idea” the city? The route goes from the city of the medieval “maestri comacini” (magisters “cum machina”), to the engineers and architects of the industrial revolution era, to which are added the biologists and statisticians (in the second industrial revolution), now integrated by philosophers, mathematicians, neuro-anatomists, neurophysiologists, psychologists, ecologists, anthropologists, and cyberneticians. The expected result of this great panel of knowledge was the “city of convergences,” but on the contrary we see the emergence of a “City Brain“ aimed at citizen surveillance (Zuboff), or a babelic confusion of languages and tools due to the cognitive asymmetries generated by the expansion of the urban “thinkering;”
4. what are the driving forces? The dance of the city was guided by the war that marked its morphology, with the walls, the segmentation of space from the era of the nations, the control of the relational flows of the Smart City. Over time, this force has been accompanied by an “angelic” vision, advocated by cyberneticians, according to which citizens’ relations are absolutely immaterial regardless of the needs of the body and physical relationships.

History has taught us how the evolution of the relationship between man, machine, and space is unpredictable.

The example of the nanomolecular machine intuited by Richard Feynman at the end of the 1950s is worth asking: what will this machine be for? His witty answer is: perhaps to make mites travel in human arteries.

About 60 years later in 2016, the chemists Sauvage, Stoddart and Feringa were awarded the Nobel Prize for their research on nanomachines, inspired by Feynman’s intuition. It will serve to transport nano instruments (for example medical) inside the human body (Fig. 6).

In the same 60 years the issue was first studied by the US Department of Defense then by large companies such as Amazon and Tesla, to develop tools for a migration to Mars. Who will choose whether this innovation will be directed toward human care, space tourism, or forced extraterrestrial mass migration?

Rifkin maintains that rather than being directed toward processes of domination, be they economic or military, the technique should be directed toward the development of empathy, therefore the current exponential growth of technology, accompanied by the delirium of the current Babelic city, should be compensated by the

Fig. 6 Winy Maas robotic city: man incorporating a multiplicity of machines

return to the pax romana, in which the urbs (be it material or immaterial) will be accompanied to a civitas based on the value of welcome.

References

Alexander C (1966) A city is not a tree. In: Design 206/1966. London

Andriani P, Carignani G (2014) Modular exaptation: a missing link in the synthesis of artificial forms. Res Policy 43(8):1608–1620

Andriani P, Cattani G (2016) Exaptation as source of creativity, innovation, and diversity: introduction to the special section. Ind Corp Change 25(1):115–131

Andriani P, Ali A, Mastrogiorgio M (2017) Measuring exaptation and its impact on innovation, search, and problem solving. Organ Sci 28(2):320–338

Banham R (1960) Theory and design in the first age machine. Prayer Paperbacks, New York

Boulding, K. E. (1966, March 8). The economic of the coming spaceship earth. In First presented at the sixth resources for the future forum on environmental quality in a growing economy in Washington, DC. http://arachnid.biosci.utexas.edu/courses/THOC/Readings/Boulding_SpaceshipEarth.pdf. Accessed Feb 14 2020

Cacciari M (2004) La città. Pazzini, Villa Verrucchio

Castells M (1996–1998) The information age trilology

Castells M (1996b) The rise of the network society, the information age: economy, society and culture, vol I. Blackwell, Cambridge

Castells M (1997) The power of identity, the information age: economy, society and culture, vol II. Blackwell, Cambridge
Castells M (1998) End of millennium, the information age: economy, society and culture, vol III. Blackwell, Cambridge
Ciborra C (1991) From thinking to tinkering: the grassroots of strategic information systems. In Bricolage, care and information. Technology, work and globalization. Palgrave Macmillan, London
Cosmacini G (2005) Il medico materialista. Vita e pensiero di Jakob Moleschott. Laterza, Bari
Dethier J, Guiheux A (1994) La Ville, art et architecture in Europe, 1870–1993. Ed. du Centre Pompidou, Paris
Duby G (ed) (1980) Histoire del la France Urbaine. Seuil, Paris
Ehrich PR (1969) The population bomb. SierraClub/Ballantine Book, New York
Ehrlich PR, Holdren JP (1971) Impact of population growth. Science 171:1212–1217
Feng L and other (2019) A "city brain" for the smart city. Research Center on Fictitious Economy & Data Science, CAS, Beijing
Feynman, R. (1960, February). There's plenty of room at the bottom. In Caltech's engineering and science. Pasadena
Forrester J (1989) The beginning of system dynamics. Talk at the international meeting of the system dynamics society, Stuttgart
Georgescu-Roegen N (1998) Energia e miti economici. Boringhieri, Torino
Georgescu-Roegen N, Boulding K, Daly E (1973) Manifesto per una economia umana. http://www.decrescita.it/old/stampa.php?ID=30. Accessed Feb 14 2020
Gould S, Vrba E (1982) Exaptation—a missing term in the science of form. Paleobiology 8:4–15
Hall P (1988) Cities of tomorrow: an intellectual history of urban planning and design in the twentieth century. Blackwell, Oxford
Jacobs J (1961) The death and life of great American cities. Random House, New York
Kissinger, H. (2018). How the enlightenment ends: philosophically, intellectually—in every way—human society is unprepared for the rise of artificial intelligence. Atlantic, New York
Leontief W (1986) Input-output. Oxford University Press, New York
Lynn G (ed) (2013) Archaeology of the digital. Canadian Center of Architecture and Sternberg press, Montreal-Berlin
Maistrello S (2006) Internet, la città, la rete sociale. https://www.apogeonline.com/articoli/internet-la-citta-la-rete-sociale-sergio-maistrello/. Accessed Feb 14 2020
McHarg I (1969) Design with nature. The Falcon Press, Philadelphia
Meadows D (2009) Dancing in systems. Earthscan, London
Montagnini L (2015) Information versus Matter and Energy: la concezione dell'informazione in Wiener e le sue conseguenze sull'oggi. Biblioteche oggi, Roma
Mostafavi M (ed) (2010) Ecological urbanism. Harvard Press, Lars Muller, Baden
Mumford L (1961) The city in history: its origin, its transformations, and its prospects. Harcourt, Brace & World, New York
Negroponte N (1970) The architecture machine. MIT Press, Cambridge
Negroponte N (1975) The soft architecture machine. MIT Press, Cambridge
Negroponte N (1995) Being digital: atoms and bits. Knopf, New York
Obrist U (ed) (2003) Re:CP Cedric Price. Birkhauser, Basel
Pask G (1969) The architectural relevance of cybernetics. In: Architectural design
Romer P (1986) Increasing retourns and long run growth. J Polit Econ 94(5)
Solow R (1956) A contribution to the theory of economic growth. Q J Econ 70(1):65–94
Streitz N (2018) The future of human-computer interaction: From HCI to Citizen-Environment Interaction (CEI) in cooperative cities and societies. In: Proceedings of the 2nd international conference on computer-human interaction research and applications (CHIRA 2018), SCITEPRESS—Science and Technology Publications, pp 7–13
Tinbergen J (1969) Nobel Prize lecture. https://www.nobelprize.org/prizes/economic-sciences/1969/tinbergen/lecture/. Accessed Feb 14 2020

Weaver W (2003) A quarter century in the natural science. In: The Rockefeller foundation annual report, 1958. The Rockefeller Foundation, New York
Weiser M (1991) The computer for the 21st century. In: Scientific American. New York, pp 9–91
Zuboff S (2019) The age of surveillance capitalism. Public Affairs, New York

Exaptative Thinking as What Makes Us Human

Liane Gabora and Kirthana Ganesh

1 Introduction

The term *exaptation* was coined by Gould and Vrba (1982) to denote what Darwin referred to as *preadaptation*: the exploitation, or cooption, of an existing trait to carry out a new and different purpose. The exapted trait must be both necessary and sufficient to carry out the new purpose. A good example of biological exaptation is feathers. Although feathers originally evolved to provide insulation and improve temperature regulation, they were later co-opted to facilitate flight (Gould and Vrba 1982). Exaptation involves what has been referred to as the adjacent possible (Beckage et al. 2011), or the realm of *near potentiality* (Gabora and Aerts 2009), because it involves the modification of existing structure or dynamics in a way that is neither *presently actual*, nor *impossible* (Fig. 1).

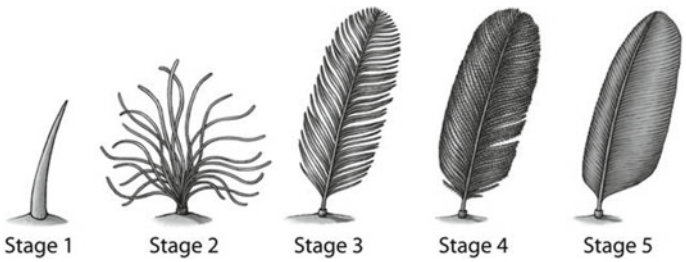


Fig. 1 The biological exaptation of a feather, from developing filaments for insulation, to eventually facilitate flight Adapted from "Novelty and innovation through exaptation" by Silvia Rita Sedita, 2018

L. Gabora (✉) · K. Ganesh
Department of Psychology, University of British Columbia, Kelowna, BC, Canada
e-mail: liane.gabora@ubc.ca

C. AM. La Porta et al. (eds.), *Understanding Innovation Through Exaptation*,
The Frontiers Collection, https://doi.org/10.1007/978-3-030-45784-6_12

Biological exaptation occurs when selective pressure causes potentiality to be exploited. Like other kinds of evolutionary change, exaptation is observed across all levels of biological organization, i.e., at the level of genes, tissue, organs, limbs, and behavior. Exaptation is also present in the cognitive processes that underlie cultural (Gabora et al. 2013), cognitive (Gabora and Carbert 2015), and economic (Dew et al. 2004) change. Indeed, to explain the concept, Gould and Lewontin (1979) originally used the notion of a spandrel. The term *spandrel* refers to the roughly triangular space between the tops of two adjacent arches and the ceiling. Such spaces were originally nothing more than a by-product, until artists realized they could paint designs in these areas, thereby enhancing the aesthetic quality of the building. Such designs soon became the preeminent aspect of these spaces, much as swim bladders, which originally evolved to facilitate vertical movement in the water column, eventually turned into lungs, and thereby acquired what is (for, us at least) its most important function of enabling survival on land. Thus, a spandrel is a cultural artifact as opposed to a biological trait (Fig. 2).

Exaptation in the cultural and economic domains is the result of a certain form of cognition, which can be referred to as exaptive thinking, or *psychological exaptation:* the capacity to adapt a particular pattern of thought or behavior from its original application to a new one, or the re-purposing of an object designed for one use for use in another context (Gabora et al. 2013). Psychological exaptation is related to what Rothenberg (1971, 2015) calls Janusian thinking, which involves achieving a new outcome by looking at something from a different perspective.

As an example of psychological exaptation, consider the invention of the tire swing. It came into existence when someone re-conceived of a tire as an object that could form the part of a swing that one sits on. Much as the current structural and material properties of an organ or appendage constrain possible re-uses of it, the

Fig. 2 The arch on the top depicts a plain spandrel, which was later used as a space to create aesthetically appealing designs (the arch at the bottom); an example of cultural exaptation

current structural and material properties of a cultural artifact (or language, or art form, etc.) constrain possible re-uses of it. Incongruity humor constitutes another form of psychological exaptation; an ambiguous word, phrase, or situation, that was initially interpreted one way is revealed to have a second, incongruous interpretation. Exaptation of representations and ideas dramatically enhance the ability to not just cope with the technological and social spheres of life, but develop individualized perspectives and unique worldviews conducive to fulfilling complementary social roles (Gabora and Smith 2018). This increase in cognitive variation provides the raw material for better adaptive fit to selective pressures.

Waste recycling is a particularly interesting example of exaptation in the cultural domain because of its applications to sustainability efforts. In waste recycling, an item that is a wasteful by-product in one context is found to be useful in a different context. Yet another example is data transformation, in which data in one format is changed to a different format while preserving the content so that it can be put to a different purpose or made easier to interpret or understand (as in the visualization of astronomical data).

This chapter proposes that while biological exaptation results in novelties that have adaptive value for a perpetuation of the kind of self-sustaining structure to which we refer to as "alive," psychological exaptation results in novelties that have adaptive value for a second kind of complex, self-perpetuating structure, a *worldview,* i.e., an integrated network of understandings that collectively provide a way of *seeing* the world and *being in* the world (Gabora 1999, 2012). We will look at how this form of psychological exaptation differs from both the kind that animals engage in, and from biological exaptation, and how it makes possible a second kind of evolutionary process: the evolution of culture.

2 Psychological Versus Biological Exaptation

Although biological and psychological exaptation are similar in their outcome, the underlying mechanisms are different. In biological evolution through natural selection, exaptation occurs through a *breadth-first process* involving the random generation of numerous variants and selective retention of the fittest. Millions of possibilities may be tried in parallel, the vast majority of which are either neutral or deleterious, but the occasional one is beneficial, and thus more likely to be inherited by the next generation. In other words, natural selection relies on the capacity to try out multiple possibilities simultaneously and select the fittest. Psychological exaptation, in contrast, is more *depth-first;* as few as a single possibility is brought to mind and progressively modified until the goal state is achieved.

This depth-first process is not random but strategic and capitalizes on the architecture of associative memory to make educated guesses about how previously acquired knowledge could be put to new uses. More specifically, memory is distributed (i.e., encoded items are spread out across multiple neurons) and content-addressable (i.e., there is a systematic relationship between the content of an item, and the location of the neurons involved in its encoding). This cognitive architecture enables knowledge and ideas that are relevant to the task at hand to come to mind naturally without systematic search (Gabora 2017).

3 Exaptive Thinking in Humans Versus Other Species

It is said that many species can be *creative,* i.e., they can come up with new ways of foraging or escaping predation, and some even use tools. According to the animal behavior literature, the innovation process consists of four stages in: *sampling, exploring, problem solving,* and *learning*, the last of which includes incorporating the solution into a behavioral repertoire (Sol 2015). These four stages bear some resemblance to Wallas' (1926) four stages of the creative process: preparation, incubation, illumination, and verification. The notion of "sampling" appears to be related to the notion of "problem finding" (Getzels and Csikszentmihalyi 1976; Mumford et al. 1994; Runco and Chand 1994), and the first two of Sol's stages map onto the "generate" and "explore" stages of creative cognition (Ward 1995). Moreover, the trait referred to in the animal behavior literature as *neophilia* (Sol 2015) appears to be close in meaning to the human personality trait of "open to experience;" both entail risk-taking, going new places, and trying new things.

These similarities might suggest that psychological exaptation in humans differs from that of other species only in degree, not in kind. However, while animals are capable of problem-solving—e.g., opening a lid to find hidden food—they are incapable of art-making and scientific theorizing. Their exaptive thought processes appear to be the result of trial and error, as opposed to strategy and intuition. We can refer to exaptation through trial and error as *generic exaptation:* it comes about through chance processes and just happens to be beneficial. It is proposed that both biological exaptation and the psychological exaptation of animals, is of this form.

When innovations are essential for survival, the nexus of traits underlying innovative capacity become canalized. A phenotypic response to an environmental condition, such as a learned innovative behavior, can over time be *genetically assimilated*, and thus innate. Some limitations of innate behavior are (1) it is rather inflexible, and (2) it operates over the course of biological generations. Thus, while some kinds of innovation may be genetically assimilated, it is unlikely that the innovations that fuel human cultural evolution are, given that they can unfold spontaneously over timeframes of hours or minutes (e.g., humorous internet banter).

This leads to another significant difference between human innovation and that of other species. Their innovations do not *evolve;* i.e., it is only humans whose innovations exhibit change that is adaptive (enhances the survival, well-being, or reproductive capacity of its bearers), open-ended (i.e., the space of possibilities is not limited), and cumulative (i.e., one modification builds on another in such a way as to improve utility or bring aesthetic pleasure). There may be random variations in the way the action is implemented from one individual to the other due to copying error, differences in size, or shape, or the presence of injuries, resulting in individual differences in how a particular idea is implemented behaviorally. However, such accidental differences do not form the basis of a process of cumulative change such that cultural outcomes become increasingly useful, specialized, psychologically therapeutic, and artistically expressive.

The inability of other species' innovations to evolve is not due to their incapacity to spread innovations from one individual to another. Many species can imitate, i.e., copy what their neighbors are doing, and thereby benefit from an action without inventing it from scratch; however, their imitation does not result in a process of adaptive, open-ended, cumulative change as is observed among humans.

We said above that what differentiates psychological creativity from biological creativity is that it is depth-first, and that this was made possible by a cognitive architecture that was distributed and content-addressable. Other species' cognitive architecture is, like that of humans, distributed and content-addressable, and as in humans, this endows them with a higher than chance probability of stumbling upon relevant, workable solutions. However, they encode situations in less detail, which makes their mental representations less distributed than those of humans; in other words, fewer neurons participate in the encoding of any particular experience. Thus, for example, say you had been tasked with the task of an informal chair that conformed to the sitter's shape. If your mental representation of the experience of throwing a beanbag omitted the detail that the beanbag conformed to the shape of your hand, then any neurons that are tuned to respond to experiences involving "conform to shape" would not be activated. These neurons would therefore not make the connection between a beanbag experience and the need to make a chair that conforms to shape, and therefore you would not be able to invent the beanbag chair. The human brain encodes experiences in sufficient detail that neurons that were activated in one context are re-activated in other contexts, allowing associations to forge more readily between experiences that are connected in different ways, and enabling unusual ideas to come to mind.

Generic exaptation can be contrasted with *strategic exaptation,* in which knowledge, past experience, and/or intuition are involved in the transformation of an old idea into a new one, to the point where it may be difficult to detect traces of the original source of inspiration in the innovation that eventually resulted. It is proposed that this is what differentiates psychological exaptation in humans.

Because an innovator's repertoire of knowledge and experience is continuously updated, psychological exaptation is not just strategic; it is flexible and dynamically responsive to current needs, trends, or tastes, and can improve over time as new knowledge and experience are obtained. Humans exhibit individual differences in the extent to which they dynamically modulate their innovations in response to changing environmental conditions. Such differences can also be found at the organizational level, and perhaps the cultural level as well.

The upshot is that although other species can engage in psychological exaptation, it is our capacity for a particular kind of exaptive thought that differentiates us: the capacity for recursive exaptive thought, such that the output of one exaptive thought is the input to the next, and to do so drawing upon the collective contents of one's worldview, until a perceived need is met, a question has been answered, or an inviting aesthetic possibility has been explored. This process has been called *representational redescription* because the contents of working memory are recursively redescribed, or restructured by drawing upon similar or related ideas (Karmiloff-Smith 1992). The process may involve looking at something from different real and imagined perspectives, at different levels of granularity (from fine details to big picture), and different kinds of thought processes, bits, and pieces fall into place (Gabora 2010, 2017, 2019; Sowden et al. 2015). This, in turn, has enabled us (for better or worse) to collectively transform the planet we live on.

4 Exaptation in the Service of Self-sustaining Organization

Human exaptation is not just strategic and dynamic; it is carried out in the service of a structure that is self-organization and self-mending. Such a structure is very different from that of a database. Like some neural networks, this structure is hierarchical and modular, and capable of learning through local interactions among its parts. However, unlike a neural network, it uses emotions as signposts in the effort to *preserve* a higher-level pattern of global interconnectedness. More formally, human psychological exaptation arises in virtue of the goal of maintaining an organizational structure that is Reflexive, Autocatalysis, and F-generated, sometimes referred to as a RAF (Gabora and Steel 2017; Hordijk et al. 2011; Hordijk and Steel 2004, 2016; Steel et al. 2019). The term *reflexive* is used here in its mathematical sense, meaning that every element is related to the whole. In a biological context, the term *food set* refers to the reactants that are initially present, as opposed to those that are the products of catalytic reactions. In a psychological context, the term food set refers to knowledge and experience that comes from direct sensory experience in the world, including socially transmitted information; thus, non-foodset items consist of thoughts and ideas that are the result of reflection, imagination, or creative thinking. In its biological context, the term autocatalysis refers to a set of catalytic molecules in which each molecule is either part of the foodset or can be generated through a sequence of reactions starting from the foodset, such that as a whole they can be reconstituted. A human mind is *autocatalysis* when it contains a network of memories and/or knowledge items that are (similar to the biological situation) inter-accessible by way of sequences of mental operations such as reminding events. Be they biological or cognitive in nature, structures that are reflexive, autocatalysis, and foodset-generated (sometimes called *f-generated*) are referred to as RAFS.

The RAF framework has been used to model the transition toward the kind of cognitive organization capable of evolving culture (Gabora and Steel 2017, under review). This model followed up on the proposal that the increased complexity of Homo erectus culture compared with other species such as Homo habilis reflected the onset of the capacity for representational redescription (Corballis 2011; Donald 1991; Gabora and Smith 2018; Hauser et al. 2002; Penn et al. 2008). Representational redescription would have enabled the forging of associations between mental representations, thereby constituting a key step toward autocatalysis structure. Representational redescription enabled the emergence of hierarchically structured concepts, making it possible to shift between levels of abstraction as needed to carry out tasks composed of multiple subgoals. A computational model of cultural evolution that showed that the mean fitness of ideas across a society of artificial agents increases with the introduction of two innovation enhancing abilities: (1) *chaining*, the ability to combine simple ideas into complex ones, and (2) *contextual focus*, the ability to shift from a convergent to a divergent processing mode when the fitness of one's current actions is low (Gabora and Saberi 2011; Gabora and DiPaola 2012). Moreover, both factors—chaining and contextual focus—proved most useful in times of environmental fluctuation (Gabora et al. 2013). Of course, care must be taken in extrapolating from a simple computational model to the real world. However, the computer experiments are not the only source of support; Chrusch and Gabora (2014) synthesized these computational modeling results with findings from behavioral genetics, psychology, and anthropology to produce an integrated multi-level account of how chaining, contextual focus, and thereby human creative abilities could have evolved.

5 Exaptation in the Clinical Context

The human worldview has been shown to be self-organization, self-healing, and autopoietic (Gabora and Merrifield 2012). Psychopathology, or mental illness, is characterized by significant distress in an individual, in a variety of contexts (American Psychiatric Association 2013). There is a sense of fragmentation, disorientation, or disordered processing of one's experiences. It can be conceptualized as difficulty engaging in the aforementioned processes to organize one's worldview. Psychological exaptation then, can be seen as a skill that can be developed in individuals to help organize their worldviews, to accommodate distressing events and experiences such that they become productive, and more meaningful to them. In other words, an exaptive thought process can enable a negative life event to be recontextualized, such that it is framed in a manner that aids in psychological well-being. Indeed, several psychotherapeutic approaches, such as cognitive reframing in CBT (Beck 2011), and trauma processing in EMDR (Shapiro 1997), although they do not explicitly frame it as such, involve psychological exaptation.

6 A Quantum Framework for Exaptation

A mathematical framework for exaptation has been developed (Gabora et al. 2013), which could in fact be said to be a quantum model, not in the sense of Penrose, but in the sense that it uses a generalization of the quantum formalism that was developed to model situations involving extreme contextuality in the macroworld. The state of a trait (or the starting point for an idea) is written as a linear superposition of a set of basis states, or possible forms the trait (or idea) could evolve into, in a complex Hilbert space. (For example, the basis states might represent possible ways of using a tire). These basis states are represented by mutually orthogonal unit vectors, each weighted by an amplitude term. The choice of possible forms (basis states) depends on the context-specific goal or adaptive function of interest, which plays the role of an observable. (For example, in the context of wanting to create a playground someone turned a useless tire into a tire swing). Observables are represented by self-adjoint operators on the Hilbert space. The possible forms (basis states) corresponding to this adaptive function (observable) are called eigenstates. In this model, innovative capacity did not evolve as an exaptation from some other, selected-for adaptive trait. Rather, innovation itself—or at least the retooling of an object or idea by considering it from a new point of view—is modeled as exaptation.

Examples from both biological evolution and the evolution of cultural novelty through innovation have been worked out using the quantum model of exaptation. The approach has also been used to model cross-domain creativity, i.e., the restructuring of an idea by considering it from the perspective of another discipline or incorporating an inspirational source from another subject area (Gabora and Carbert 2015).

7 Summary and Conclusions

This chapter summarized ongoing research comparing and contrasting biological and psychological exaptation. Psychological exaptation—the capacity to adapt a particular pattern of thought or behavior from its original application or context to a new one—differs from biological exaptation in arising out of structural change at the neural level as opposed to the genetic level, and in being strategic, as opposed to a matter of trial and error.

It is likely that at least some of the behavioral innovations of animals qualify as psychological exaptation. However, their innovations do not build cumulatively on one another, and thus do not evolve. Psychological exaptation plays a key role in creativity, though they are not quite the same thing. Creativity often involves reiterated change to a concept or idea by looking at it from different perspectives until there is an internal sense of completion, and the external creative output feels finished. Creativity contributes to the evolution of a second kind of self-organization, essentially "autocatalysis" structure: an integrated, self-sustaining internal model of the world, or worldview.

Both biological and psychological exaptation have been mathematically modeled using a generalization of the quantum formalism, which is specifically suited to modeling change under the influence of a context.

Acknowledgements This research was supported in part by a grant (62R06523) from the Natural Sciences and Engineering Research Council of Canada.

References

American Psychiatric Association (2013) Diagnostic and statistical manual of mental disorders, 5th edn. American Psychiatric Association, Arlington, VA

Beck J (2011) Cognitive behavior therapy: basics and beyond. The Guilford Press, New York, NY

Beckage B, Gross LJ, Kauffman S (2011) The limits to prediction in ecological systems. Ecosphere 2(11):1–12

Corballis MC (2011) The recursive mind. Princeton University Press, Princeton, NJ

Chrusch C, Gabora L (2014) A tentative role for FOXP2 in the evolution of dual processing modes and generative abilities. In: Bello P, Guarini M, McShane M, Scassellati B (eds) Proceedings of the 36th annual meeting of the cognitive science society. Austin TX: Cognitive Science Society. (Held July 23–26, Quebec City), pp 499–504

Dew N, Sarasvathy S, Ventakaraman S (2004) The economic implications of exaptation. J Evolut Econ 14:69–84

Donald M (1991) Origins of the modern mind: three stages in the evolution of culture and cognition. Harvard University Press, Cambridge, MA

Gabora L (1999) Weaving, bending, patching, mending the fabric of reality: a cognitive science perspective on worldview inconsistency. Found Sci 3(2):395–428

Gabora L (2010) Revenge of the 'neurds': characterizing creative thought in terms of the structure and dynamics of human memory. Creat Res J 22(1):1–13

Gabora L (2012) Dynamical disequilibrium, self-transformation, and the evolution of a sustainable worldview. Chaos Complex Lett 6(1–2):37–44

Gabora L (2015). A communal exchange-based framework for cultural evolution. In R. Dale, C. Jennings, P. Maglio, T. Matlock, D. Noelle, A. Warlaumont & J. Yashimi (Eds.), Proceedings of the 37th annual meeting of the Cognitive Science Society. Austin TX: Cognitive Science Society. (Held July 22–25, Pasadena), pp 2835–2836

Gabora L (2017) Honing theory: a complex systems framework for creativity. Nonlinear Dyn Psychol Life Sci 21(1):35–88

Gabora L (2019) Reframing convergent and divergent thought for the 21st century. In: Goel A, Seifert C, Freska C (eds) Proceedings of the 2019 annual meeting of the cognitive science society. Cognitive Science Society, Austin TX, pp 1794–1800

Gabora L, Aerts D (2009) A model of the emergence and evolution of integrated worldviews. J Math Psychol, 53: 434–451

Gabora L, Carbert N (2015) Cross-domain influences on creative innovation: preliminary investigations. In: Proceedings of the 37th annual meeting of the cognitive science society, pp 758–763

Gabora L, DiPaola S (2012) How did humans become so creative? In: Proceedings of the international conference on computational creativity. Palo Alto: association for the advancement of artificial intelligence. ISBN: 978-1-905254668. (Held May 31–June 1, Dublin, Ireland), pp 203–210

Gabora L, Merrifield M (2012) Dynamical disequilibrium, transformation, and the evolution and development of sustainable worldviews. In: Orsucci F, Sala N (eds) Complexity science, living systems, and reflexing interfaces: new models and perspectives. IGI Global, Hershey, PA, pp 69–77

Gabora L, Saberi M (2011) An agent-based model of the cognitive mechanisms underlying the origins of creative cultural evolution. In: Goel A, Harrell F, Magerko B, Prophet J (eds) Proceedings of the 8th ACM conference on cognition & creativity. New York: ACM Press. (Held Nov 3–6, Atlanta, GA), pp 299–306

Gabora L, Scott E, Kauffman S (2013) A quantum model of exaptation: incorporating potentiality into biological theory. Prog Biophys Mol Biol 113(1):108–116. [http://arxiv.org/abs/1310.0558]

Gabora L, Smith C (2018) Two cognitive transitions underlying the capacity for cultural evolution. J Anthropol Sci 96:27–52

Gabora L, Steel M (2017) Autocatalytic networks in cognition and the origin of culture. J Theor Biol 431:87–95
Getzels JW, Csikszentmihalyi M (1976) The creative vision: a longitudinal study of problem finding in art. Wiley, New York
Gould SJ, Lewontin R (1979) The spandrels of San Marco and the panglossian paradigm: a critique of the adaptationist programme. Proc R Soc Lond B 205(1161):581–598
Gould SJ, Vrba ES (1982) Exaptation–a missing term in the science of form. Paleobiology 8:4–15. https://doi.org/10.1017/S0094837300004310
Hauser MD, Chomsky N, Fitch WT (2002) The faculty of language: what is it, who has it and how did it evolve? Science 298:1569–1579
Hordijk W, Kauffman SA, Steel M (2011) Required levels of catalysis for emergence of autocatalytic sets in models of chemical reaction systems. Int J Mol Sci 12(5):3085–3101
Hordijk W, Steel M (2004) Detecting autocatalytic, self-sustaining sets in chemical reaction systems. J Theor Biol 227(4):451–461
Hordijk W, Steel M (2016) Chasing the tail: the emergence of autocatalytic networks. Biosystems 152:1–10
Karmiloff-Smith, A. (1992). Learning, development, and conceptual change. Beyond modularity: A developmental perspective on cognitive science. The MIT Press.
Mumford MD, Reiter-Palmon R, Redmond MR (1994) Problem construction and cognition: applying problem representation in ill-defined domains. In: Runco MA (ed) Problem finding, problem solving, and creativity. Ablex Publishing Corporation, Norwood, NJ
Penn DC, Holyoak KJ, Povinelli DJ (2008) Darwin's mistake: explaining the discontinuity between human and nonhuman minds. Behav Brain Sci 31:109–178
Rothenberg A (1971) The process of Janusian thinking in creativity. Arch Gen Psychiatr 24:195–205
Rothenberg A (2015) Flight from wonder: an investigation of scientific creativity. Oxford: Oxford University Press
Runco M, Chand I (1994) Problem finding, evaluative thinking, and creativity. In: Runco M (ed) Problem finding, problem solving, and creativity. Hampton, Norwood, NJ, pp 40–76
Shapiro F (1997) EMDR: eye movement desensitization & reprocessing. Harper Collins Publishers, New York, NY
Sol, D. (2015). The evolution of innovativeness: exaptation or specialized adaptation? In: Animal creativity and innovation. Academic Press, pp 163–187
Sowden PT, Clements L, Redlich C, Lewis C (2015) Improvisation facilitates divergent thinking and creativity: realizing a benefit of primary school arts education. Psychol Aesthetics Creativity Arts 9(2):128–138
Steel M, Hordijk W, Xavier JC (2019) Autocatalytic networks in biology: structural theory and algorithms. J R Soc Interface, 16(151), rsif.2018.0808
Wallas G (1926) The art of thought. Cape, London
Ward TB (1995) What's old about new ideas? In: Smith SM, Ward TB, Finke RA (eds) The creative cognition approach. The MIT Press, pp 157–178

Index

C. AM. La Porta et al. (eds.), *Understanding Innovation Through Exaptation*,
The Frontiers Collection, https://doi.org/10.1007/978-3-030-45784-6