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An Evolutionary Perspective of Radical Innovation and its implications for Management and Organizations

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Extended Abstract

This thesis develops an evolutionary perspective of technological change based on a complex analogy between biological and technological evolution. The research is built on the extensive background of evolutionary economics and some seminal interdisciplinary research, including Herbert Simon's work on modular complex systems, and the artifact-centered evolutionary models of innovation. Marking a radical departure from this rich tradition, the base (biological) domain of the analogy is not eukaryotic evolution, whose driving process is vertical transmission, but bacterial evolution, based instead on Horizontal Gene Transfer. The new perspective highlights the key role of the horizontal transfer of Functional Modules in generating radical innovation, and unveils the striking similarities between biological and technological evolution, solving some extant critical disanalogies.

The thesis is made of three papers, framed between an introductory chapter and a conclusion. The introduction to the thesis is aimed at presenting and discussing the rationale of the research work: beyond the research gaps, there are compelling reasons why a novel theory aimed at shedding some more light on the origin and dynamics of radical innovation should interest managers and have not only descriptive, but also normative implications.

The introduction is also aimed at providing cohesion and connectivity between the three papers cross-referencing them within the coherent research design that originated them in the first place.

Paper 1 (co-authored with Pierpaolo Andriani) is a methodological book chapter focused on the study of complex systems in economics. It was originally intended as a general methodological contribution to the study of evolutionary systems through complex analogies – providing also an epistemological clarification to the fundamental concepts and constructs used in the following papers.

Paper 2 presents the novel evolutionary theory of technological change and applies it to a case of lithic radical innovation: the invention of Bow and Arrow. The origins of radical innovation is the central issue here, but some general implications for management have been proposed. The role of technology as part of the culture is especially emphasized.

Paper 3 (co-authored with Gino Cattani and Giusi Zaina) is more comprehensive and management-oriented: it presents the theory, reconsiders a quintessential case of radical innovation (the Turbojet Revolution) through the new perspective, taking into account some new historical discoveries, and develops some managerial implications, including the new construct of *replicative/integrative capability*.

Closing the thesis, the conclusion summarizes the theoretical framework and the contributions, also proposing some promising albeit uncertain potential implications of the theory and research avenues underdeveloped in the papers.

Keywords: Horizontal Gene Transfer; Functional Module; Modularization; Technological Evolution; Radical Innovation; Mirroring Hypothesis; Turbojet Revolution.

Introduction

The semiconductors industry is facing a radical crisis. The rapidly approaching end of the Moore's Law (Moore 1965) heralds a technological discontinuity that is presumed to interrupt the industry's past 40 years of extraordinary success.

Significant research efforts at firm, industry, university and institutional level are confronting the challenge with incremental successes, (e.g. the Nanoelectronics Research Initiative, NRI (https://www.src.org/)); all the same the search for a radically new technology that could propel computing beyond the limitations of current technology while maintaining the industry growth rate has been essentially unsuccessful.

This new technology has not yet surfaced.

The end of the Moore's law is *"arguably the most significant presumptive anomaly of our time"* (Khan et al. 2014), but by no means the only one: the automotive industry, the aviation industry, the publishing industry - just to name a few - are facing similar incipient crises.

A better understanding of this radical uncertainty through a theoretical approach supporting managerial and technical decisions at firm, industry and institutional level could hardly be more urgent.

Background & Research Gaps

Presumptive Anomaly

The concept of *presumptive anomaly*, a powerful theoretical construct that describes so clearly the period of radical uncertainty marked by end of the Moore's law (Khan et al. 2014), was first introduced by historian of technology Edward Constant in his seminal book on the Turbojet Revolution (Constant 1980)[1]. According to Constant, a technological presumptive anomaly occurs *"not when the conventional system fails in any absolute or objective sense, but when*

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[1] Reconsidering the origins of the Turbojet revolution is the key case studied in Paper 3 of this thesis

assumptions derived from science indicate either than under some future conditions the conventional system will fail (or function badly) or that a radically different system will do a better job" (Constant, 1980: 15). Constant's theory ostensibly draws from Kuhn (1970) as he adopts the Kuhnian concept of anomaly as the origin of scientific revolutions. [2]

The resemblance between the 'presumptive anomaly' preceding the Turbojet Revolution (circa 1921-1937) and the current state of the semiconductors industry is so striking that justifies 'per se' the reconsideration of the Turbojet Revolution, whose origin is still controversial among historians (Giffard 2016).

Technological Paradigms

The concept of '*presumptive anomaly*' describes a state rather than a process, and has therefore a limited – if any - guidance power for managers and decision-makers. Much more promising is the concept of *'technological paradigm'* (Dosi 1982) derived by Kuhn's concept of 'scientific paradigm'. A technological paradigm is a 'model' and a 'pattern' of solution of selected technological problems – the reciprocating aero-engines at the beginning of the Turbojet Revolution, for example, or the silicon-based current microchip technology. A *technological paradigm* – at industry level - includes therefore *design rules* for the 'dominant design' artifact, rules of practice, and a knowledge base shared among scientists and professionals of the

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[2] besides Constant, other important theories of technological change share a general Kuhnian vision hypothesizing technological change developing through successive cycles separated by crises. Indeed, both the Abernathy-Utterback model (Abernathy and Utterback 1978) and the Anderson-Tushman theory (Anderson and Tushman 1991) imply a cyclic pattern tuned by periods of incremental innovation and punctuated by radical innovation bursts. Abernathy and Clark (1985) actually cite Kuhn (1972), but they only refer to the general cyclic pattern, while Constant goes as far as to proposing the new construct of 'presumptive anomaly', explicitly assuming a Kuhnian causal analogy in opposition to a more descriptive one.

industry. Best practices, a deep understanding of the theoretical and operational constraints and problem-solving heuristics contribute to suggest what can be done to improve the technology, propelling incremental innovation. Unfortunately, the consensus also contributes to constrain the research, since both practitioners and theorists understand not only what they *can* and *should* do (Dosi & Nelson 2013:7), but also (even too well) what they *cannot* or *should not* do. Consistently, the historical record often shows that the right development often lies outside the paths considered viable by the experts. This is the case of the turbojet revolution, and could well be today one of the reasons undermining the institutional effort for a new semiconductors' technology.

Technological Trajectories

The existence of a technological paradigm – in seamless analogy with Kuhnian thinking – calls for the definition of processes changing it when a presumptive anomaly is recognized: *"the emergence of new technological paradigms (…) stems from the interplay between scientific advances, economic factors, institutional variables, and unsolved difficulties on established technological paths"* (Dosi 1982:147). The path leading from the current paradigm to the next one is part of the theoretical model proposed by Dosi in his landmark paper of 1982. Indeed, from the very beginning Dosi stated that his model *"tries to account for both continuous changes and discontinuities in technological innovation… continuous changes are often related to progress along a technological trajectory defined by a technological paradigm, while discontinuities are associated with the emergence of a new paradigm"* (Dosi 1982:147 (abstract)).

However, while the continuous 'incremental' changes - within the same paradigm and dominant design - have been extensively researched and significant managerial advice has been derived, the emergence of a new paradigm, especially in its initial phases, are still obscure, signaling an interesting research gap: *trajectories in the space of processes and related input intensities have been studied much less than trajectories in the output characteristic space, and this is indeed a challenging research area ahead).* (Dosi & Nelson, 2013:).

Trajectories, Modularity and the emergence of a new Dominant Design

The technological trajectories leading to a new dominant design “appear to be driven by ‘hierarchically nested technological cycles’ entailing both relatively invariant core components improving over time and a series of bottlenecks and ‘technological imbalances’ (Rosenberg, 1976) regarding the consistency among all the components of the systems (cf. Murmann and Frenken, 2006). (Dosi & Nelson 2013:9)

Indeed, the modularity of technological systems is central in understanding the processes leading to a new dominant design – and of the model proposed in this thesis. All the same, the key theoretical and managerial issue (and research gap) is the identification of which one of the ‘hierarchically nested’ artifacts (functional modules, in the terminology used within this thesis) is about to trigger the radical innovation phase. In fact, the community of firms, engineers and practitioners working in any industry try relentlessly to ‘extrapolate forward’. All the same, the historical records[3] often shows that they seldom succeed, while certain ‘focused naïve’[4] outsiders are unexpectedly able to put forward the right solution. The Turbojet Revolution (paper 3), the Bow and Arrow invention (Paper 2), the Microwave Oven (Paper 1; Andriani & Carignani 2014) – and many other radical innovations as well – confirm that trajectories are not means to reduce Knightian uncertainty into probabilizable risk (Dosi & Nelson 2013:10)

Evolutionary Technology

The concept of technological trajectory is consistent with an evolutionary vision of technological change: indeed, there is consensus on a generalized concept of evolutionary technology: *“Scholars from a wide variety of disciplines have converged on the proposition that technological advance needs to be understood as proceeding through an evolutionary process characterized by multiple search efforts”* (Dosi and Nelson 2013)

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[3] E.g. the Turbojet case discussed in Paper 3

[4] focused naïveté: a useful ignorance of prevailing assumptions and theories,” (Gieryn and Hirsh 1983:91)

The foundational basis of the broad consensus is necessarily general, limited to the recognition that *'at any time there generally are a wide variety of efforts going on to advance the technology, which to some extent are in competition with each other, as well as with the prevailing practices'* (Dosi & Nelson 2013:3-4)

Deepening this 'weak' vision of evolutionary technology into a more robust complex analogy between technological and biological innovation could open significant avenues of research and implications for management. Unfortunately, critical disanalogies have haunted biological analogies, raising concerns about their usefulness in generating novel ideas that are then built into new theories. Since Edith Penrose's classic critique of the tendency to adopt imposing biological models upon economic processes (Penrose 1952) – and even before - many scholars take for granted the assumption that the structures and processes underlying organic and cultural evolution are substantively different. Penrose (1952) criticized the adoption of biological analogies in economics and, in general, social sciences:

> "To treat innovations as chance mutations not only obscures their significance but leaves them essentially unexplained, while to treat them directly as purposive attempts of men to *do* something makes them far more understandable. To draw an analogy between genetic heredity and purposive imitation of success is to imply that in biology the characteristics acquired by one generation in adapting to its environment will be transmitted to future generations. This is precisely what does *not* happen in biological evolution. Even as a metaphor it is badly chosen although in principle metaphorical illustrations are legitimate and useful. But in seeking the fundamental explanations of economic and social phenomena in human affairs the economist, and the social scientist in general, 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, p. 819).

Penrose's critique suggests that despite some surface similarity between organic and cultural evolution the underlying structures and processes are different, and this difference is not a matter of degree but of substance.

According to Darwin (1859), biological evolution follows a bifurcating evolutionary process whose branches are the result of descent with modification—through vertical gene transmission or inheritance—from a common root or ancestor, as represented by the so-called 'Tree of Life.' Yet the evolution of many cultural phenomena, including technology, does not neatly fit this pattern, exhibiting instead a reticular structure (Ziman 2000).

Recent results in biology - and in particular in bacterial evolution – give us the opportunity of overcoming all these critiques and build a deep, *complex analogy* (Paper 1), recasting the old debate on a novel sound scientific and epistemological bases.

Indeed, it is today recognized that descent with modification is but one of the possible transmission mechanisms, and a tree-like evolutionary pattern is an incomplete representation of biological evolution, which itself exhibits a reticular structure (Bapteste et al. 2004). This thesis proposes a novel analogy based on the 'Woesian' model of cell evolution (Woese 2002, 2004), opening a promising path for understanding technological change and, in general, cultural evolution. As we shall see, this model complements the Darwinian evolutionary theory by proposing horizontal gene transfer (HGT) as a fundamental force driving cellular evolution. The model describes the evolutionary phase preceding a critical discontinuity in which the origin of species is located, which Woese called the 'Darwinian Threshold.' Before this event, a modern type of genome replication mechanism did not yet exist, species had not yet emerged, and HGT was the main force driving evolution. Recent findings in comparative genomics (e.g. Gogarten & Townsend, 2005) have further corroborated this model by showing how both HGT and vertical inheritance are at work among bacteria lineages and more complex organisms, even after the Darwinian Threshold. By revealing the coexistence of horizontal transfer and vertical inheritance, and showing how biological evolution is inherently reticulate (i.e., it has a network-like structure), the Woesian model unveils striking similarities in structures and processes between biological and cultural evolution—thereby recasting the old debate about the usefulness of building biological analogies.

A recurrent problem with previous evolutionary analogies is their metaphorical use of Darwinian principles, which inevitably conceals the actual mechanisms driving cultural evolution. An important implication of adopting a Woesian model of (cell) evolution is that it is now possible to advance a more general conceptual framework in which gradualist and discontinuous perspectives of change can be reconciled. Horizontal (gene) transfer can in fact account for a seemingly discontinuous change. Also, biological analogies have typically triggered mixed reactions. Critics tend to highlight that cultural evolution is inherently Lamarckian and discourage attempts to transfer terms, concepts, or mechanisms from biology into other fields. But a Woesian model can explain why horizontal transfer of genetic material might explain deceptively Lamarckian processes. Indeed, what can appear as a Lamarkian or epigenetic phenomenon can now be recognized as the *horizontal transfer* of an existing *functional module*. The transfer of functional modules from an industry to another often implies a functional shift, an evolutionary event called *modular exaptation* (Andriani & Carignani, 2014; see also Paper 1 for a methodological and epistemological discussion). Originally developed for specific applications, certain modules may later prove to be valuable not only for other, yet unanticipated applications, but even for unorthodox, holistic re-combinations that offer unexpected performances (e.g., Constant, 1980).

These evolutionary constructs and phenomena (*functional module, modular exaptation*) are viable not only at a general macro-economic level, but even more at industry and product (artifact) level. They can become therefore robust building blocks not only for theory building, but also for deriving managerial propositions.

Radical Innovation

The inception of radical innovations has been hardly understood, and is therefore so difficult to manage. An important contemporary case of incipient radical innovation – mirroring the initial phases of the *turbojet revolution* in aero-engines (Constant 1980) – is the radical uncertainty affecting the semiconductors' industry effort in recognizing the technological trajectory leading to the new paradigm and dominant design, discussed in this introduction.

The turbojet revolution could be described as a case of *recombinant innovation* – since the recombination of components was clearly the mechanism of the invention, but the recombination process is just a description of what took place, falling short of explaining the reasons of the success of a specific architecture over the hundreds designed and prototyped by the aero-engine industry and by external individuals - and start-up firms as well - during the long inception of the revolution. Indeed, Constant in his seminal book felt the necessity of proposing a different model. Unfortunately, his model is not supported by recently discovered historical evidence (Giffard 2016; Paper 3).

Several studies have examined the consequences of radical innovations and elucidated conditions under which incumbents are more or less likely to retain their competitive advantage vis-à-vis new entrants (Abernathy & Utterback, 1978; Anderson & Tushman, 1991; Cattani, 2005; Henderson & Clark, 1990). A recurrent finding of these studies is the declining performance of incumbents in the face of radical innovation (Hill and Rothaermel 2003).

However, and in partial disagreement with these results, the 'incumbent curse' is not a pattern always accepted in academia (Chandy and Tellis 2000). Moreover, there is little - if any - consensus among innovation scholars on the origins of radical innovations, especially the micro processes and evolutionary forces responsible for their emergence in a specific industry. Indeed, extant evolutionary models of technological change that have discussed radical innovation – e.g., the punctuated equilibrium model (e.g Abernathy & Utterback, 1978; Anderson & Tushman, 1991; Mokyr, 1990; Tushman & Romanelli, 1994) or the model of technological speciation – provide only an incomplete synopsis of those processes and forces. This in turn further complicates any attempt to draw precise implications for how organizations should search and organize for radical innovation.

To get around some of these issues, this thesis describes a novel model for understanding technological change, and particularly radical innovation[5], which could also integrate the process of *modular exaptation* (Andriani and Carignani 2014) within the 'Woesian' model of cell evolution (Woese, 2002, 2004). The model complements the Darwinian evolutionary theory by proposing horizontal gene transfer (HGT) as a fundamental process driving cellular evolution.

Thesis outline

The first paper (Andriani and Carignani, forthcoming) discusses some critical epistemological and methodological issues on which the following papers are founded, introducing the structure

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[5] In accordance with Henderson & Clark, (1990), by 'radical' innovation in this thesis I mean an innovation that "establishes a new dominant design and, hence, a new set of core design concepts embodied in components that are linked together in a new architecture" (p. 11). This innovation often results in the creation of a new market or industry (e.g. Garcia & Calantone, 2002)

mapping between base domain (bacterial evolution) and target domain (technological change), defining the building blocks, and focusing on the central concept of functional module.

The second paper (Carignani 2016) applies the 'Woesian' model to an important albeit remote case of radical innovation (the invention and evolution of the Bow and Arrow). It is highly unusual to present a paleo-lithic single case to illustrate a theory of innovation whose aim is to generate useful implications for management and organization. However, the author believes that choosing a case of prehistoric radical innovation has the merit of generalizing the model, showing how technology evolved in a context in which nor science nor economics nor even 'humans' in the modern sense existed.

In the third paper (Carignani, G; Cattani, G; Zaina 2017), we rethink the Turbojet Revolution – a quintessential case of radical innovation- to elucidate the key features of the Woesian' model showing how horizontal transfer is a crucial evolutionary process in the early phases of radical innovation. We then elaborate some implications of the model discussing how organizations should search for radical innovation and emphasize the role of a firm's *replicative/integrative capability*, i.e., the ability to 'replicate with modifications' existing functional modules integrating them into a novel architecture.

Author Contribution Statements

Paper 1 and Paper 3 are co-authored. As required by a reviewer, I provide hereby a contribution statement.

Paper 1: The power of Complex Analogy: seeking Evolutionary Patterns in Technological Radical Innovation

Both authors contributed to this work: the overall vision is shared, the introduction and the conclusions have been written jointly, and all the other sections and paragraphs have been thoroughly discussed. The parts originally conceived and written by the author of this PhD Thesis are the idea and development of the 'complex analogy', built on Gentner's theory and the technological cases and examples.

Paper 3: Evolutionary Chimeras: a Woesian perspective of Technological Change

All three authors contributed to this work: the overall vision is shared, the introduction and the conclusions have been written jointly, and all the other sections and paragraphs have been thoroughly discussed. Given the interdisciplinary nature of this paper each of the authors contributed in accordance to his or her specific expertise: economics and social sciences (Gino Cattani), biology and bacterial genetics (Giusi Zaina), technology and engineering (Giuseppe Carignani). The parts originally conceived and written by the author of this PhD Thesis are the original idea of Horizontal Gene Transfer as the core of a novel analogy, building on Woesian concepts and the detailed micro-historical technical analysis of the core case (the turbojet revolution) and other technological cases presented.

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The power of Complex Analogy: seeking Evolutionary Patterns in Technological Radical Innovation

Working Paper

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Please refer to the published book to reference this paper

Introduction

Charles Darwin took very seriously the problem of the origin of organs of extreme perfection and complication.[6] It is a major difficulty of his gradualist evolutionary theory of ‘descent with modification’. The objection, convincingly proposed by St. George Mivart (an English Catholic biologist) is based on the fact that natural selection can hardly explain the incipient stages of organs because they can improve the fitness of an organism only when they are completely developed and functional (Mivart 1871).[7]

Darwin cautiously advanced a hypothesis that was actually a brilliant insight into later research: he suggested the possibility of functional shift, an evolutionary process later redefined ‘exaptation’. This first Darwinian example of functional shift is quite clear:

> *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*

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[6] ‘Difficulties on theory’ is the title of Chapter VI of Origin (Darwin 1859), while ‘Organs of extreme complexity and perfection’ is the paragraph in which the swimbladder case is presented.

[7] “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, p.24).

> *natural selection has actually converted a swimbladder into a lung, an organ used exclusively for respiration. (Darwin 1859, p.190)*

The same process described by Darwin can be recognized in technological change: for example, in early agricultural tractors equipped with internal combustion propulsion plants the engine/gearbox case was “so huge and so rigid” (Dew et al. 2004, p.78) that it could be ‘exapted’ into a chassis (the structural frame of the vehicle). The engine/gearbox assumed the structural function, reducing the tractor’s overall weight and cost and ultimately contributing to its success (Dew et al. 2004). Clearly, the breakthrough was enabled by the fact that the engine was *‘ideally similar in position and structure’* to the necessary structural component: the very words used by Darwin apply perfectly to technological innovation. The case is not unique: several scholars have discussed dozens of significant cases of ‘functional shift’ in technological change (Dew et al. 2004; Cattani 2005, 2006; Andriani and Carignani 2014).

We can easily recognize these cases of ‘functional shift’ as a similar process shared by two ostensibly very different complex systems (biological evolution and technological change). The similarities between the technological and the biological domains, however, are not limited to exaptation: Wagner and Rosen propose nine ‘commonalities’ between ‘nature’ and ‘technology and science’, showing that technological innovation “reflects almost everything we have learned about biological evolution in the two centuries since Darwin”, so that “innovations in biological evolution and in technology have many common features” (Wagner and Rosen 2014, p.1).

One may wonder why two complex systems as different as technological change and biological evolution share such an impressive number of similar processes. This chapter argues that the similarity between these two domains is not just a nice coincidence, but is based on structural reasons: it is a ‘complex analogy’ that legitimizes the transfer of concepts across the two domains. This is clearly an interesting methodological approach to the study of complex systems, because it suggests that the knowledge acquired in one of the systems (the ‘base’ domain) can be applied to the other (the ‘target’ domain). But under what conditions can concepts developed in one discipline, and resting on an accepted and historically well-tested base of related concepts, definitions and operational methods be transferred to a new domain? A key point: can the concept of exaptation, steeped in evolutionary biology, and anchored on the related evolutionary concepts of functions, selection and fitness, be legitimately used to analyse technological change? This is the question we tackle in this chapter. Building on the concept of *complex analogy* (Gentner 1983) we assert is that the transfer of concepts across domains is possible if the domains share not just generic similarities, but a coherent set of *relations* between analogous concepts (structure mapping).

The chapter is organized as follows: after discussing some properties of complex systems, Section One introduces the concept of exaptation, briefly describes the literature associated with it and highlights a few critical issues related to the validity of the exaptation concept in innovation studies. Section Two deals with the foundational concepts underlying exaptation: in particular, we discuss function and functional modules in biology and technology, and derive the concept of modular exaptation on which this chapter is focused. In Section Three, we present an overview discussing the role of analogy in scientific (and philosophic) thinking and introduce the concepts of *structure mapping* and *complex analogy* (Gentner 1983). We show that analogic thinking across the coupled field of evolutionary biology and technological change is legitimate provided that a certain number of conditions are in place. We apply this approach to the case of exaptive evolution in technological change, thereby providing one of the first building blocks in methodological terms to the effective study of exaptation. At the core of the theoretical argument there is an artefact-centred technological-biological evolutionary analogy. In Section Four we summarize our methodological contributions and discuss implications and possible avenues of research.

Exaptation in Complex Systems

Complex systems science focus on the study of emergent properties in systems composed of multiple heterogeneous agents interacting over mostly non-regular and time-dependent network configurations often nested within one another. The astronomical number of configurations of complex systems' agents occasionally gives rise to emergent properties that are evolutionary novel, thereby increasing the complexity of the system and in some cases conferring some kind of evolutionary advantage to a system that expresses such properties.

Complex systems theory stresses the ontological unpredictability of such properties. Unpredictability goes beyond quantum mechanics unpredictability (Prigogine and Stengers 1997). It is steeped in the multiple phenomena related to:

(a) The huge number of configurations of many complex systems that will eschew any type of information processability even by the most powerful information-processing machines designable in the foreseeable future. Wagner (2011) has calculated that for typical metabolic systems, protein and genetic systems (both at the genotypic and phenotypic level) the number of configurations of even simple systems extends to numbers of the order of (or bigger of) 10^{100}. Similar numbers characterize technological systems as well; and

(b) 'Butterfly-effect'[8] dynamic that may activate self-sustaining information cascades that may lead to the emergence of radical different behaviour in existing systems. As bifurcations between dynamical trajectories may be triggered by noise or apparently inconsequential events, predictability is inherently impossible.

Complexity is both inter-disciplinary and cross-disciplinary. Inter-disciplinarity derives from the fact that solutions of complex problems demand high cognitive diversity, whereas cross-disciplinarity refers to the fact that solutions or frameworks are often transferrable across disciplines.

Exaptation

One emergent property of complex systems is exaptation. Exaptation, the co-opting of a technology or biological trait or module for a function for which it was not designed or selected, is a major but overlooked evolutionary force (Gould and Vrba 1982; Dew et al. 2004; Kauffman 2000; Cattani 2006; Wagner 2011; Andriani and Carignani 2014). Exaptations result from novel associations between artefacts and domains of applications. The association is mediated through an historical context. For instance, the emergence of the modern trumpet and horn is due to the

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[8] The Buttefly Effect indicates a particular dynamic in which a system becomes extremely sensitive to initial conditions. The sensitivity may cause the onset of a chaotic behaviour whereby tiny inconsequential factors trigger an explosive divergence from the previous state of the system.

exaptation (and subsequent adaptation) of mechanical valves,[9] originally used to control airflow in blast furnaces. Friedrich Blühmel, a horn player who worked in a mining company (context), transferred a technology well known in the mining industry to the music industry (Tappi 2005). 'The wonderful metamorphoses in function' hypothesized by Darwin (1859, summary of Chapter 6) was later reframed and defined 'preadaptation' by the French naturalist Lucien Cuénot (1914). Cuénot's 'preadaptation' refers to traits whose functional shift increases the fitness of an organism. The concept was reframed by Gould and Vrba (1982), in which they coined the term 'exaptation' to describe the process (rather than the effect) of functional shift. Gould and Vrba contrasted exaptation, or the discovery of a new function for an existing trait, with adaptation, defined as the improvement of a trait through natural selection. Exaptation is intrinsically non-adaptive. In an evolutionary fitness landscape, adaptation is akin to peak-climbing, driven by increase in a well-defined fitness function; as exaptation (especially the most radical ones) is inherently about the emergence of new functions, that is, exaptation entails a structural modification of the fitness landscape and corresponds to the introduction of a new peak.

To qualify as an exaptation, a feature cannot have arisen "as an adaptation for its present role" (Gould 1991, p.43) but instead must have been coopted for its current function and enhance fitness (Gould 1991). Exaptations appear ubiquitous in the history of technology and markets. Mokyr claims (2000) that exaptation is frequently encountered in the history of technology".

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[9] "The numerous uses of the mechanical forces, which I had an opportunity of seeing during my presence in Upper Silesia, particularly the various air pipes used in the blast apparatus of the high and low furnaces which always led me back to the basic idea of executing an improvement on these instruments, I believe I could use to reach my goal and therefore sought the company of the keepers of the machines and other experts in order to comprehend the closing and opening of the wind pipes, whilst I started out with the idea of which way the air must pass through the tubes of the instrument, to lengthen or shorten according to certain dimensions, in order to make up the missing notes of the compass" (Heyde, 1978, p.21) .

Several authors have shown the ubiquity of exaptation in technological evolution (Lane 2011; Kauffman 2000; Andriani and Carignani 2014; Cattani 2006; Dew et al. 2004), in biological evolution (Barve and Wagner 2013; Gould 1985; Andriani and Cohen 2013; Wagner 2011) and in other disciplines, such as anthropology, psychology, and language (Buss et al. 1998; Brown and Feldman 2009; Fitch 2005). Exaptations can be conceptualized as *jumps* of technologies across different application domains.

Transferring technologies across domains is one way to reduce the cognitive complexity associated with radical innovation, which involves the parallel creation of technologies and markets. Another way of dealing with the burden of cognitive complexity is to transfer ideas from one domain (or discipline) to another. For instance, the origin of the events that would lead more than a century later to the discovery of the most successful drug in history, that is, the aspirin, lie in a curious event that happened in England in 1758. The Reverend Stone tells the story in a letter to the Royal Society:

> There is a bark of an English tree, which I have found by experience to be a powerful astringent, and very efficacious in curing agues and intermitting disorders.[10] About six years ago, I accidentally tasted it, and was surprised at its extraordinary bitterness; which immediately raised in me a suspicion of its having the properties of the Peruvian bark.[11] As this tree delights in a moist or wet soil, where agues chiefly abound, the general maxim, that many natural remedies lie not far from their causes, was so very opposite to this particular case, that I could not help applying it; and that this might be the intention of Providence here I must own I had little weight on me. (Jeffreys 2008, p.17)

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[10] Agues stands for malaria. Malaria was at the time found all over Europe including the South of England and the Netherlands.

[11] The Peruvian bark was so well known as the only treatment and prophylaxis against malaria, that the author doesn't find necessary to use its proper name, the Chinchona tree from which bark quinine was extracted.

Reverend Stone discovered that the bark of the willow was an effective treatment for a symptom of malaria, that is, high fever. The letter contains several interesting points for the historian of technology but one in particular is important for this chapter. The first concerns the logic used by Stone. Stone assumes that as the bitterness of the willow reminded him of the Chinchona tree, then, the therapeutic action of the Chinchona may be shared by the willow. In other terms, a shared attribute stands as an indicator for a shared causal relationship between the attribute and the action on the organism. Although Reverend Stone's hypothesis was revealed to be entirely wrong, Stone's analogical thinking led via unintended routes to a major technological revolution. Stone's hypothesis was rooted in a popular folk theory, promoted by Paracelsus, known as *Doctrine of Signatures*. This doctrine predicated an early form of analogic thinking based on shared attributes, rather than shared relations. The doctrine asserted that Nature gave away signs about the functions of natural things. So a flower shaped as an eye could cure eye problems. The bitterness of the willow bark thriving in stagnant water, hence related to the then reputed cause of malaria ('bad air'), was a sign that revealed its healing property, that is, an unexpected function.

Source of Selectable Variation in the Technosphere

According to a generalized Campbellian *variation-retention-selection* epistemology (Bickhard and Campbell 2003), the expansion of the technosphere requires a wealth of variations, on which selection can act. Along with traditional channels of production for variations, such as random mutations and purposeful design, an additional channel is provided by exaptation. The emergence of exaptive variations reflects a fundamental property of technologies, that is, the non-prestateability of technological applications (Kauffman 2000). The term non-prestateability indicates that the full set functions (current and potential) of any technology cannot be listed at any moment in time. This is due the fact that the number of applications of any technology depends on the interaction technology-context. Because such interaction is inherently unlimited and subject to combinatorial explosion, the number of potential applications of existing artefacts must inherently be larger than what designers or inventors can conceive. The exaptive channels thus feeds on the heterogeneity of the economy (Jacobs 1969; Mokyr 2002, 1990). Drawing on Gibson's (1950) idea of artefacts as affordances, Tuomi (2002) also extends the non-prestateability argument by noting:

Technologies and technical products have 'Interpretative flexibility'… Different user groups and stakeholders impute different meaning to a given technological artefact … Instead of being a 'well defined' objective artefact, with characteristics that could be described without reference to social practice, the artefact in question has many, and possibly incompatible, articulations. These 'meaningful products' may develop independently of each other, and one technological artefact can embed several meaningful products simultaneously. Exaptation, therefore, provides an inexhaustible source of variations in the economy, complementing random and purpose-driven inventions and innovations.

Non-prestateability extends from artefacts to capabilities. Whence do capabilities that sustain competitive advantage come? The traditional answer is that they are designed to fill an identified market opportunity. Yet Cattani (2005, 2006) shows that Corning's supremacy in the fibre optic industry is due to capabilities it developed prior to the emergence of the fibre optic industry. Cattani thus extends the discussion of exaptation[12] from artefacts to capabilities. Using the notion of *transformative capability* (Garud and Nayyar 1993), Cattani also shows that the value of proprietary capabilities is similar to that of shadow options, so the role of foresight depends on the redeployment of capabilities in new domains.

Radical Innovation

Exaptation is linked to radical innovation via the concept of speciation. Levinthal (1998)[13] explains the sudden rise of market-changing innovations in terms of speciation. He notes that in several instances, technological change associated with the emergence of new market-defining applications is minimal or non-existent. A new market speciation results from technology-

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[12] Cattani prefers the term preadaptation. We consider preadaptation and exaptation synonyms.

[13] Levinthal (1998) does not use the term exaptation, but his definition of speciation depends on the cooption of technologies mechanism of exaptation described above.

domain changes (Adner and Levinthal 2002), not a Schumpeterian technology–technology combination. A speciation process thus leads to branching of industries and the emergence of new market lineages (Dew et al. 2008).

Another line of inquiry focuses on the interaction between exaptive and adaptive processes. Exaptation as a fundamental micro-process of innovation (Cattani 2006) that usually triggers adaptive technology market responses, which, as Jacobs (Jacobs 1969, 1985, 2000) shows, may become self-reinforcing and assume the character of avalanches. Levinthal (1998) theorizes about an exaptive–adaptive cycle in the context of the wireless market; Lane (2011) elaborates an adaptive–exaptive model of innovation based on technology adoption that includes technological, organizational, and societal considerations, which he calls *exaptive bootstrapping*.

Strategy and Entrepreneurship

A behavioural theory of entrepreneurial firms, effectuation theory (Dew et al. 2008) moves from the observation that entrepreneurship involves the creations of new market niches by firms and markets in the absence of well-defined goals. In a state of Knightian (1921) uncertainty (Dew et al. 2004), entrepreneurs make choices using a logic of design, rather than a logic of decision, such that they "make decisions now in terms of goals that will only be knowable later" (March 1976, p.75). Accordingly, effective firms act not only within market environments, but also upon them, and in some cases end up creating new markets not predictable *ex ante* even by the very stakeholders involved in the negotiation process. Not taking the environment as given and/or predictable also implies that adaptive or other types of reactive strategies are inadequate and even inappropriate in the effectual process. Instead, entrepreneurial firms that use an effectual logic tend to develop exaptive strategies[14] (Dew et al. 2008).

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[14] Several examples of effectual entrepreneurship can be found in (Read et al. 2010).

R&D Management

Exaptation implies a change of perspective on R&D and inventions. If a significant fraction of innovations are triggered by the hidden potential of existing technologies (to generate new functions), then innovation-by-exaptation complements a market-pull or technology-push logic and provides a strong rationale for the management of serendipity (Merton 2004). Grandori (2007) suggests looking for the *performance potential* implicit in existing technologies rather than the *performance gaps* that may drive the development of new technologies. With this perspective, the exaptive search focuses on potential applications of endogenous knowledge and technology. The *unshelving* technique rooted in the transformative capacity idea (Garud and Nayyar 1993) offers a starting point. Similarly, Dew et al. (2008) suggests that slack is a crucial factor for exaptive discoveries. By reducing slack, efficiency-driven management approaches effectively put sources of organizational creativity at risk.

This brief review of relevant literature hints at the breadth of issues and range of frameworks that exaptation has inspired. However, significant ambiguities, inconsistencies, and problems persist with regard to meaning of exaptation and its application in social sciences. These difficulties stem from a double source: first, as Kauffman argues in several publications, exaptation is a dynamic process that makes sense only in an open *non-ergodic* universe, that is, a universe in which the possibilities of evolution are ontologically, and not only experimentally, unknown and unknowable. The lack of foreseeability of the evolution of complex systems extends from the macro to the micro picture: technologies also show an ontological lack of foreseeability regarding their range of applications. Exaptation is an attempt to frame such indeterminacy within an evolutionary framework. However, the multifarious role of technologies generates difficulties as to how to exactly define the parameters of the evolutionary frameworks. This difficulty is reflected in the way the literature describes the change of applications that are at the core of exaptation. Terms such as ‘function’, ‘functionality’, ‘applications’, and ‘purpose’ get used interchangeably in extant literature – often in the same text – to broadly indicate the emergent functional shift (often including the emergence of a new economic entity) typical of exaptation. In reality, these terms imply significantly different aspects, such as what a module does, what a module is for, what it has been selected for, or what it has been designed for. Scholars rarely specify which meaning their terminology prioritizes.

Second, the use of concepts imported from evolutionary biology requires a careful discussion about the validity and limit of the evolutionary biology–technological evolution analogy. The fundamental evolutionary concepts of function and selection are critical to understand and define exaptive processes, but without a critical discussion about the technological context, they risk becoming metaphors without analytical power. Although the evolution of species and technologies share some fundamental dynamics, their differences must be identified to ensure the validity of analogical thinking. In particular, the concepts of modularity and function, common to both technological and biological systems and crucial to understand exaptation, are characterized by specific features that are context-dependent and as such need to be carefully evaluated in the specific context of operation.

Function, Functional Modules, and Modular Exaptation

A key concept in Joseph Schumpeter's theory of economic development is the necessity of a dynamic process of innovation (that he famously defined 'creative destruction') as a fundamental complement to the static 'equilibrium flow' (Schumpeter 1934). By means of relentless 'creative destruction' the capitalist economy incessantly changes itself from within. Schumpeter sometimes used evolutionary terms, and the general features of an evolutionary theory show up in his works, but was very critical about the usage of theoretical concepts or techniques borrowed from biology in the economic domain (Fagerberg 2003): in fact, his interest was to create a radical, dynamic general theory of economic development rather than to propose an analogy between economic and biological micro-processes. However, Schumpeter's work is all-important in justifying evolutionary economics because by exposing the limits of the equilibrium vision of economic development he postulated the necessity of models able to analyse complex dynamic systems.

After Schumpeter, the usefulness of an evolutionary theory of technological change (and more broadly of evolutionary theories in economics studies in general, for example, Penrose (1952) has been critically debated. Unfortunately, a number of evident disanalogies (for example, Ziman 2000, p.5) create problems in the direct application of evolutionary models to the technological domain, suggesting to some scholars the necessity of invoking Lamarkian features, which are very controversial in biology (Nelson and Winter 1982). Recent discoveries in evolutionary biology, related in particular to bacterial evolution, have reignited the interest in the analogy between technology and biology (for example, Hartwell et al. 1999) and confirmed the role of exaptation (for example, Ganfornina and Sanchez 1999), outlining also a new, broader perspective of evolution, in which a multiplicity of patterns can be legitimately adopted (Doolittle and Bapteste 2007).

Building on these results we explore the viability of a rigorous biological-technological analogy, choosing *the artefact* as the evolving unit in our evolutionary theorizing: although the choice of the artefact as the primary unit for the study of technological change may seem naïve, a number of scholars endorse it. According to technology historian George Basalla:

> The artefact – not scientific knowledge, nor the technical community, not social and economic factors – is central to technology and technological change. (Basalla 1988, p.30)

Modularity

Our departure from Basalla's and other extant theories of technological change is marked by the explicit inclusion of the modularity of the artefact. Indeed, in our conceptualization the artefact is modular, that is, an artefact can be modelled as composed of separate elements called modules, each of which is recursively[15] composed of lower-level modules. An artefact can be represented by a multi-level tree in which at each level the modular set represents a partition of the whole artefact: this is a simple conceptualization often used in the technological domain (Figure 1(a)). A similar representation is accepted in biology for describing – for example, modularity at sub-cellular level (Figure 1(b)).

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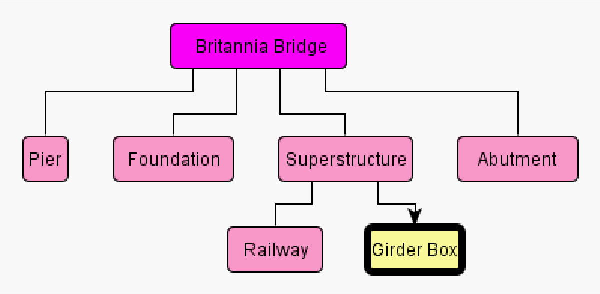
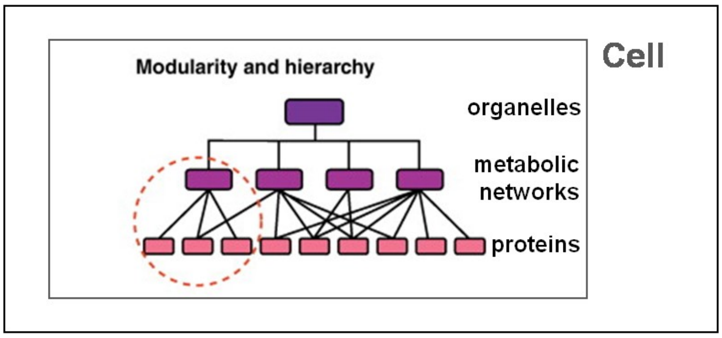
[15] A module is composed of other modules, at each level of the modular tree. The hierarchical decomposition of a module is therefore recursive.

Figure 1



Note: Britannia Bridge: the 'Girder Box' functional module is evidenced.

Figure 1(a) Modular tree of a technological artefact



Source: Reproduced and modified from Zhu et al. (2012). *Trends in Microbiology*, 20(2): 94–101.

Figure 1(b) Modular tree of a microbial cell

The concept of modularity, however, is much more complex than the stylized one described before, and central in understanding complex systems. Herbert Simon (Simon 1962) proposed modularity as a systemic concept, describing how a complex system can be decoupled into subsystems (modules) that perform nearly independently of each other. Simon describes near-decomposability as characterized by the following properties:

"the short-run behaviour of each of the component subsystems is approximately independent of the short-run behaviour of the other component" "in the long run, the behaviour of any one of the components depends in only an aggregate way on the behaviour of the other components" (Simon 1962, p.474).

Near-decomposability applies to various levels of a complex system, because it *"is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure"* (Simon 1962, p.468). Simon argues that near-decomposability is common in complex systems, as exemplified in the domains of physical, chemical, biological, technological, and social systems.

Function

The analogy between biological and technological modules is problematic, because of the presence of evident disanalogies (for example, the intentionality of technological design). It is even more surprising, therefore, that recent biological research has re-proposed modularity as a key concept shared by technological and biological systems, constituting a powerful link between the biological and technological domain. Hartwell et al. (1999) for example, write that "the notion of function and functional properties separates biology from other natural sciences and links it to synthetic disciplines such as computer science and engineering". In good accordance with the technological concept, they define a functional module as "a discrete entity whose function is separable from those of other modules". Moreover, they argue that functional modules constitute "a critical level of biological organization" (Hartwell et al. 1999, pp.C47–C48). It is important to notice that Hartwell and colleagues do not refer just to 'modules', but to 'functional modules'. Function constitutes a new definitional concept that enters the picture. Unfortunately, the concept of function is difficult and problematic in technology, thus potentially capable of disrupting the biological-technological analogy.
Indeed, while the term 'function' and the related concept of contextually driven 'functional shift' emerge from all the definitions of exaptation, a variety of different terms holding ambiguous and sometimes overlapping meaning are used. This aspect is crucial: in fact, depending on how broadly or narrowly we define a function of a trait/module, we end up with different results regarding the occurrence or not of exaptation.
The ambiguity is generated by the fact that exaptation implies functional discontinuity but technological continuity. As a function depends on what the object does and/or what the object

has been designed for, and is linked to the form and phenomena that the underlying technology exploits, then assessment of functional shift depends on the definition of function itself. For instance, solid gripping of a tennis racquet or a pen constitutes only a subset of the possible uses of the human hand. What is the function for which the human hand was selected? There are two options; the former encompasses a broad definition of function for the human hand, that is, the hand’s function is tool-using. In this case holding a pen, tennis racquet or Palaeolithic sharpened stone would not qualify as exaptations. They are a subset of the generic functions of the human hand. The latter option is based on the observation that in evolution selection pressures are specific. Organisms are selected on the basis of fitness-increase deriving from specific capabilities. For the human hand, that was the modification of available naturifacts to produce weapons. From this standpoint tennis playing and writing become exaptations of the human hand (Linde-Medina 2011).

This problem becomes even more acute in the technology domain. The classical exaptation example of the microwave oven is instructive. In 1945 working on a magnetron (a subsystem of a radar system that emits microwave radiation) engineer Percy Spencer noticed the effect of magnetron radiation on food. Spencer studied the novel phenomenon and applied for a patent (Osepchuk 1984). Two years later Raytheon commercialized the first microwave oven.

Indeed, the question whether the microwave oven is an exaptation of the magnetron hinges on the definition of function. If we base it on the underlying scientific/technological phenomenon, that is, conversion of electrical energy into electromagnetic radiation, then *strictu sensu* there is no exaptation. Both magnetron and microwave oven convert electricity into microwave radiation. If instead, as we suggest, we adopt a contextual and historical definition (what the object was selected for), according to which the magnetron function is to supply power to radar systems and the microwave oven function is to cook food, then there no doubt about the magnetron exapting into a microwave oven. Clearly we need an operational definition of function to support a theory of exaptation in the technological domain.

When we adopt an evolutionary analogy in studying technological change and innovation we deliberately embrace an etiologic concept of function: “The explanation to why something exists intimately rests on how it became what it is” (Dosi 1997, p.1531). Neander (1991) defends the etiological concept defining the proper function of an item as a ‘selected effect’. Millikan (1999) identifies the direct proper function of items with the reproduced physical dispositions that *causally* contribute to the existence of the items. In other words, an etiological definition of function responds to functional *backward-looking questions* of the kind: 'Why is X there?' (De Winter 2010).

The term function, widely used in papers on Darwinian evolution, starting with Darwin himself (especially when discussing *organs*), is therefore to be intended in this etiological sense, albeit used in a more liberal way in biological practice (De Winter 2010). The standard etiological theories of biological function (for example, Neander 1991) are based on the causal history of biological items.

The etiological concept on which biological function is founded seems to pose a critical threat to the biological-technological artefact-centred analogy we are discussing. Indeed, technological artefacts (artefacts intended for a practical purpose) are intentionality created by a designer and a manufacturer: intentionality seems therefore to play a constitutive role (Krohs and Kroes 2009). Technological artefacts ostensibly exist (that is, were (re)produced) deliberately for performing the function(s) intended by the designer and manufacturer. The connection seems so obvious that the intended function often gives artefacts their proper name: (a nutcracker, a dumper, Wright's 'Flyer' and so on). In De Winter's formulation the intended function responds to '*forward-looking questions* of the type: *Why will x be (re)produced? Why will x be maintained? Why will x be integrated in system s?*' (De Winter 2010, p.5)

This leads to an apparent contradiction between the etiological concept necessary to biology ('the effect for which x was selected') and the intentional one necessary to technology ('the effect for which x will be reproduced'). Indeed, some scholars (for example, Vermaas and Houkes 2006) argue that an etiological concept of artefacts' function is untenable and therefore any evolutionary analogy of technological innovation is doomed from its very beginning. Countering this objection is therefore necessary to our conceptualization: we believe it can be countered in two ways:

First, in a narrow way, our focus is on inventions, prototypes and in general technologies in the fluid state of evolutionary development where the role of historical accidents is more pronounced than in incremental innovations that follow the so-called 'linear innovation model'.

Second, a more general objection is that emergence of technologies is a collective co-evolutionary process where agency and intentionality play a role alongside multiple other causal and contextual factors, making technological change much more akin to a generalized evolutionary process (Arthur 2009; Jacobs 2000; Bickhard and Campbell 2003) than the simple consideration of intentionality would lead us to believe. It follows that the use of an etiological definition of function is justified in the technological arena, especially in the cases in which serendipitous discovery (Dew 2009; Merton 2004) plays a role.

The use of an etiological definition of function clarifies another ambiguous aspect of exaptation. The literature on exaptation presents two broad classes of examples. The former, the most extreme case, concerns functional shift based on the exploitation of a different scientific/technological phenomenon. For instance, a table lamp converts electricity into light, and at the same time converts electricity into heat. According to this kind of example, using a table light to keep food warm qualifies unquestionably as exaptation.

The latter concerns functional shift absent phenomenon change. These cases are less clear-cut. The use of MP3 technology (Dew et al. 2004) for music storage and reproduction is one of such cases. MP3 was designed as a digital compression technology originally for legal documents. The extension to music doesn’t change the underlying phenomenon but represents an unexpected market change. From an etiological point, selection is driven by features that enhance fitness (or market appealing, in the technology case) and hence both types qualify as exaptation.

On the basis of these considerations we adopt an etiological concept of function that is in our opinion tenable in both the biological and the technological domain and can therefore be used to found a well-formed complex analogy between biological and technological exaptation. We argue that our concept of function applies to all artefacts, but for most ‘mature’ artefacts it is less significant: in fact, for most artefacts the intentional concept of function and the etiologic concept of ‘proper’ function coincide, because the function(s) for which the artefact (and indirectly its modules) were selected by the user are exactly those for which the designer designed them and the manufacturer manufactured them.

On the contrary, the intentional and etiological concept of function are different for novel artefacts, especially radical innovations: they are often modular and are assembled from existing modules/subsystems some of which were originally designed and manufactured for different functions.

While certainly belonging to the world of technical artefacts, radical inventions are possibly less studied from the point of view of the philosophy of technology, and maybe less understood.

Actually Preston (2009, p.48) states that “Novel artefacts, in short, have no proper function.” While this could be true for the whole novel artefact, that has no history, it is not true for its modular components, often horizontally transferred [16] from other industries or technological lineages (Utterback 1996; Hargadon 2003; Arthur 2009).

In this regard it is interesting to reconsider a famous historical case of innovation, the Britannia Bridge, a Victorian engineering marvel built in 1845–1850 across the Menai Strait. This railway bridge has been regarded as a discontinuity in structural engineering, which at first sight confirms the untenability of the etiological concept of function in technology (Vermaas and Houkes 2003). The bridge featured a unique engineering solution: “On this bridge, regarded as highly innovative in its days, trains travelled through a horizontal, hollow iron tube, upheld by piers” (Vermaas and Houkes 2003, p.278). Vermaas and Houkes cite this case to demonstrate why the etiological definition of technological functions may be untenable in the technology domain, in that “surely the function of the railway bridge was to make possible railway traffic across a body of water, not to withstand water pressure while keeping the ship afloat” (p.280). But a closer historical scrutiny that takes into account the modularity of the artefact (Figure 1(a)) reveals the true origin of the ‘new’ technological function (Vincenti 2000). The function of the whole bridge was indeed “making possible railway traffic”, as Vermaas and Houkes (2003) write (p.279), but its tubular beam – the hollow iron tube – (a modular component, referred to as a box girder in both bridge and ship construction) was designed to resist flexural and torsional structural challenges (not only to withstand water pressure) and was borrowed from naval engineering. In fact, Sir William Fairbairn, an experienced naval engineer, was involved in the Britannia Bridge design. This case thus reveals that what at a higher modular level seems a new function (a bridge enabling railway traffic) reveals itself at component level as an existing

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[16] Horizontal Genetic Trasfer (HGT) is the transfer of genetic materials codifying functional modules across different lineages. It is recognized in biological evolution as an important evolutionary mechanism, especially in bacterial evolution (Hartwell et al. 1999). By analogy, in this chapter we define horizontal transfer the transfer of technological functional modules across different technological lineages.

function transferred from a different technological lineage (tubular beams designed to withstand structural stresses). The transfer of box girder technology form shipbuilding to civil engineering – is therefore a confirmation rather than a critique to the etiological concept of function we propose.

The Britannia Bridge case is not unique in the history of technology: most radical, seemingly discontinuous inventions from the bow and arrow (Carignani 2016; Lombard and Phillipson 2010), to the turbojet (Giffard 2016), reveal historical continuity at modular lower levels. We can therefore adopt the etiological concept of function in technology.

So far, we posit the centrality of the concept of functional module recognized by recent biological research as 'a critical level of biological organization', as a key concept in founding a robust biological-technological analogy. We also show that the etiological concept of function is tenable in technology when applied to modules rather than to whole artefacts. Under this assumption, the concept of technological functional module closely resembles the analogous biological concept.

Since exaptation is by definition associated to functions, and functions are associated to modules (functional modules), the concept of *modular exaptation* follows a straightforward consequence of this reasoning.

Modular Exaptation

We define *modular exaptation* the process in which a module previously designed and manufactured for a certain function is later selected (i.e. replicated) for a different function. A few examples are instructive in understanding why the concept is important.

We observed previously that the behaviour of any artefact or module is a larger set than that imagined by its designer and manufacturer, which we defined its purpose. In most cases, purpose and function coincide, and users select artefacts for their designed function. But this coincidence does not have to exist. Users (and manufacturers or inventors) co-opt artefacts for uses for which they were not designed. Co-opted usages may be trivial: "John may want to stand on a folding chair to clean the shelves of his kitchen" (Vermaas, 2006 #1091, p.264),[17] or very significant, such as if the user's selection triggers a purpose–function bifurcation that prompts the emergence of new artefacts and markets. For example:

The CD-ROM was originally designed and patented as a digital-to-optical recording and playback system. Later it was selected by the users for a different, unexpected function, namely, as a data storage medium for computers (Dew et al. 2004).

The engine of agricultural tractors was strong and stiff enough to provide a structural function for the whole tractor, substituting the chassis and enabling the emergence of the modern internal combustion engine tractor (Dew et al. 2004).

The magnetron (a component of a radar system) was used as the core of a new technology (microwave oven) to convey thermal energy into food (Andriani and Carignani 2014).

As these examples show, the term 'exaptation' describes different processes, sharing a common selective mechanism. In each of these cases, the user or the inventor discovered that a subset of the artefact's behaviour (or of one of its modules), already in existence but not coincident with the one for which the artefact or module was designed and built, could be exploited to support a new function. After the exaptation process, the artefact was reproduced to support the new function, which became the purpose of the new artefact.

A cursory look at the examples shows that for the CD-ROM, the entire artefact was exapted, and a new product – memory storage – appeared in perfect technological continuity in the market space; in the tractor case, an internal component of an existing product was exapted and generated differentiation in the (existing) tractor market, without however altering the artefact's purpose. The magnetron case differs from the previous two, insofar an internal component of the radar system was exapted and, through a process of technology–technology combination, created a new product (microwave oven) and a new market. Moreover, in the first case,

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[17] This case is inconsequential in our selectionist approach because it is unrelated to the selection of the chair.

selection operated on the same level, whereas in the second and third examples, it applied to both the final product level and the exapted component level. The process of selection can take place at the same or at *a higher modular level* from that of the exapted module. Indeed, the exaptation of a biological module (e.g. an organ) improves the fitness and therefore triggers the selection of the organism, at a higher level, while in technology the exaptation of a module can have affect at a higher level (the microwave oven case) or at the same level (the Viagra case). These examples show that a non-ambiguous definition of exaptation should include first, the artefact's modularity, to integrate the possible multilevel effects, second, the distinction between function and purpose and third, a selection-based use of function.

Modular Exaptation and Complex Analogy

The choice of the artefact as the evolving unit, based on Basalla's and other scholars' arguments (for example, Arthur, 2009), is reinforced by a number of recent discoveries in biological evolution, proposing in particular the centrality of functional modules. However, borrowing such a concept from biology requires solving the apparent contradiction between 'intentional' function (purpose) and biological 'proper' function, an etiological concept. Our discussion above leads to the conclusion that the etiological concept of function is tenable also in the technological domain, suggesting that the resemblance between the biological and technological domain can be formalized into a complex analogy. The main advantage of founding a 'complex analogy' is that we can reliably base scientific reasoning on it. This section is aimed at discussing how to clarify such an analogy.

Analogy: A Very Short Background

Analogic reasoning is a fundamental cognitive competence used by humans for understanding new domains on the basis of known ones. It is a powerful tool for several diverse human activities, including management (Gavetti et al. 2005). Even more, analogy is, according to Hofstadter "the very blue that fills the whole sky of cognition" (Hofstadter 2001, p.499). Indeed, the power of analogy in science has been emphasized over the centuries, from Aristotle ("Hidden nature, is known only through analogy" (Physics , Book One) to Konrad Lorenz in his Nobel Prize acceptance lecture (Lorenz 1974).

The core idea of analogical scientific reasoning is that two *domains* can be described, at a certain level of abstraction, by the same cognitive structure. The knowledge we already possess about one of the domains (the *base* domain) can therefore be useful in understanding the second one (the *target* domain). Albeit straightforward in principle, setting a 'deep' analogy in scientific research needs a rigorous methodological approach. In fact, a number of authoritative scholars have warned about the traps associated with the superficial usage of analogy in interdisciplinary research, often leading not to useful analogies but rather to *sloppy metaphors* (Lass 1990, p.79). Gavetti et al. (2005), more specifically, warn against faulty analogical reasoning in strategic management, but at the same time posit that sound analogies are critical to strategy, especially in presence of radical change. The novel construct 'modular analogy' (Andriani and Carignani 2014) that we have already introduced and that we are going to better formalize in this section has therefore the potential of contributing to strategic thinking.

Gentner's Complex Analogy

According to Gentner's *structure-mapping theory* (Gentner 1983) a *complex analogy* is a comparison in which (most) relations, but few or no objects' attributes can be mapped from base domain to target domain. In a complex analogy:

Attributes tend not to be transferred;
Relations are transferred;
Coherent sets of relations are preferred (*systematicity principle*).

Other principles coherently complete the original definition (Gentner and Jeziorski 1993, p.450):

No extraneous associations: only commonalities strengthen the analogy;
No mixed analogies: the relational network to be mapped should be entirely contained within one base domain.

Under these conditions, the two domains share a similar *inherent relational structure*: "An analogy is an assertion that the structure that usually applies to a domain can be applied to another domain" (Gentner 1983, p.156).

A beautiful example drawn from the history of science (Gentner and Markman 1997) is Johannes Kepler's analogous thinking in *Astronomia Nova*. In order to demonstrate the possibility of an action at a distance – an abhorrent notion to natural philosophers of the time – Kepler posited the analogy between motive power (causing the motion of planets around the Sun) and light, transmitted similarly through ethereal empty space, but not visible in the ethereal empty space.

The history of science and technology is replete with similar successful cases of analogical thinking. Indeed, in ideal continuity with Kepler's scientific thinking, Rutherford's famous analogy between the solar system and the atom exemplifies the key concept that relations, rather than attributes, are the foundational link between different domains in scientific *complex analogies*. The atomic nucleus hardly shares any *attribute* with the Sun (it is not hot, nor massive, nor yellow), nor planets share any *attribute* with electrons, but the *relatio*ns between Sun and Planet ('attracts'; 'revolves around') led eventually to the common abstraction of the 'central force' (Gentner 1983, p.160).

In synthesis, in order to found a *complex analogy* "common relations (between the base and target domain) are essential, common objects are not" (Gentner and Markman 1997, p.46). This is promising, because, when considering a biological-technological analogy, it is apparent even at a cursory glance that artefact and organism are hardly similar in terms of shared attributes. But the relations the two domains share support the building of the complex analogy: "a clever, sophisticated process that can be used in creative discovery" (Gentner and Markman, 1997, p.45).

Definitions

This section is aimed at framing the concept on Modular Exaptation into an artefact-centred technological-biological complex analogy conforming to Gentner's requirements. In order to do so, we formalize the discussion we proposed in the preceding sections by defining key definitions and constructs.

Artefact

The standard definition of artefact is associated to purpose: for example, "An artefact may be defined as an object that has been intentionally made or produced for a certain purpose" (Hilpinen, Artifact and Zalta 2011). In this chapter we adopt an extended concept of artefact, defined as follows: An artefact is an object that has been intentionally made or produced or selected (and replicated) for a certain purpose.

Functional Module

A functional module is a component of a modular artefact that is:

(a) internally cohesive;
(b) clearly separated from the other modules by a boundary while connected to them through an interface;
(c) associated to a single *function* or a discrete set of *functions*.[18]

Modular artefact

We define modular artefact an artefact composed of functional modules, each of them an artefact.

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[18] In principle, one or more function can be associated to each module. The (functional) modularity of a system is not a discrete attribute (modular/non-modular). In a technological system (artefact) there may be different degrees of modularity between a perfectly modular system in which functions are mapped to modules one-to-one (each module performs one function) and a perfectly integral system in which all modules perform all functions (Ulrich 1995). In a biological system (microorganism) the situation could be more complex, because a functional module "may belong to different systems at different times" (Hartwell et al. 1999, p.C48). The key point, however, is that in microbiology: *"the notion of a module is useful only if it involves a small fraction of the cell components in accomplishing a relatively autonomous function"*(Hartwell et al. 1999, p.C48). Hartwell's note reinforces the analogy between the biological and the technological concept of function, in that that technological functions are usually autonomous.

Function and behaviour

According to the definition, each functional module is associated to a function (or a set of functions). It is useful to encase the concept of function into a broader frame: we therefore define the following concepts:

Behaviour[19] (B-set): the complete set of effects, included all the possible actions, processes and operations that a module can perform.

Function (F-set): the subset of Behaviour for which a module (or the artefact of which the module is a component) was selected for replication.

We notice that Function may or may not coincide with the intentional function (purpose) intended by the functional module's designer.

Making Explicit the Complex Analogy

Biology is the base domain in our complex analogy. In particular, the elements (objects) composing the base domain at our chosen level of organization are living entities, usually defined *organisms,* while those of the target domain are *artefacts*, as defined before. According to Gentner (1983, p.156) "Objects may be clear entities (e.g. 'rabbits'), components parts of a larger object (e.g. rabbit's ear) or even combinations of smaller units e.g. 'herd of rabbits'); the important point is that they function as whole at certain level of organization."

Our chosen level of organization at the biological level is that of the organism, which is generally considered the preferred object of selection in biological evolution (Mayr 2001).

Attributes and relations

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[19] We borrow the concept of behaviour from John Gero's FBS (Function Behavior Structure) conceptual framework developed for engineering design (Gero 1990).

The distinction between attributes and relations is important: "*Attributes* are predicates taking one argument and *relations* are predicates taking two or more arguments. For example COLLIDE (x,y) is a relation, while LARGE (X) is an attribute" (Gentner 1983, p.157).

In setting up a complex analogy between the biological and technological domain, therefore, the fact that the attributes of an artefact (say, a turbojet engine) are ostensibly different from an organism (say, a bacterium) is not a fatal critique to the viability of the analogy. What is important is that a number of relations can be coherently mapped across the domains. Indeed, recalling the concepts presented in the previous sections of this chapter we can easily recognize the resulting predicates as relations rather than attributes: artefacts *are made of* modules; organisms *are made of* modules; each module (organic, biological) is *separated from* other modules by a boundary; each module *is associated to* a Behaviour (a subset of which is called *Function*).

Evolution and systematicity

Evolution is made possible by two[20] fundamental processes: *variation* and *selection* (Bell 2008). Variation provides the super-production of diverse evolving phenotypic objects[21] to the evolutionary processes. Selection is the key mechanism through which only a limited number of the evolving objects are given the resources for further replication.

Variation and *selection* (and the third process '*retention*', through which organisms – and artefacts – are replicated and transmitted to the next generation) are the epistemological foundation of a generalized evolutionary system (Bickhard and Campbell 2003). What we propose in this paper is founded on the idea that technological change is analogous to biological evolution, in that both domains are generalized evolutionary processes (Arthur 2009; Jacobs

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[20] Biologists (and complexity scientists) such as Kauffman (1995, 2000) and Wagner (2011) add a further process, self-organization, to the triad variation-selection-retention.

[21] Organisms in the biological domain, artifacts in the biological domain. The term 'phenotypic' refers to the fact that both organisms and artifacts are 'tangible' objects that can interact with the environment.

2000; Bickhard and Campbell 2003). Gentner’s theory of complex analogy supports the legitimacy of this analogy across two different complex systems.

In order to complete the verification of the theory we discuss the *sistematicity principle*. The *sistematicity principle* states that not all the relations that can be selected in the base and target domain are equally significant. According to Gentner, a complex analogy should be based on “a system of connected knowledge, not a mere assortment of independent facts. Such a system can be represented by an interconnected predicate structure in which higher-order predicates enforce connections among lower-order predicates” (Gentner 1983, p.162).

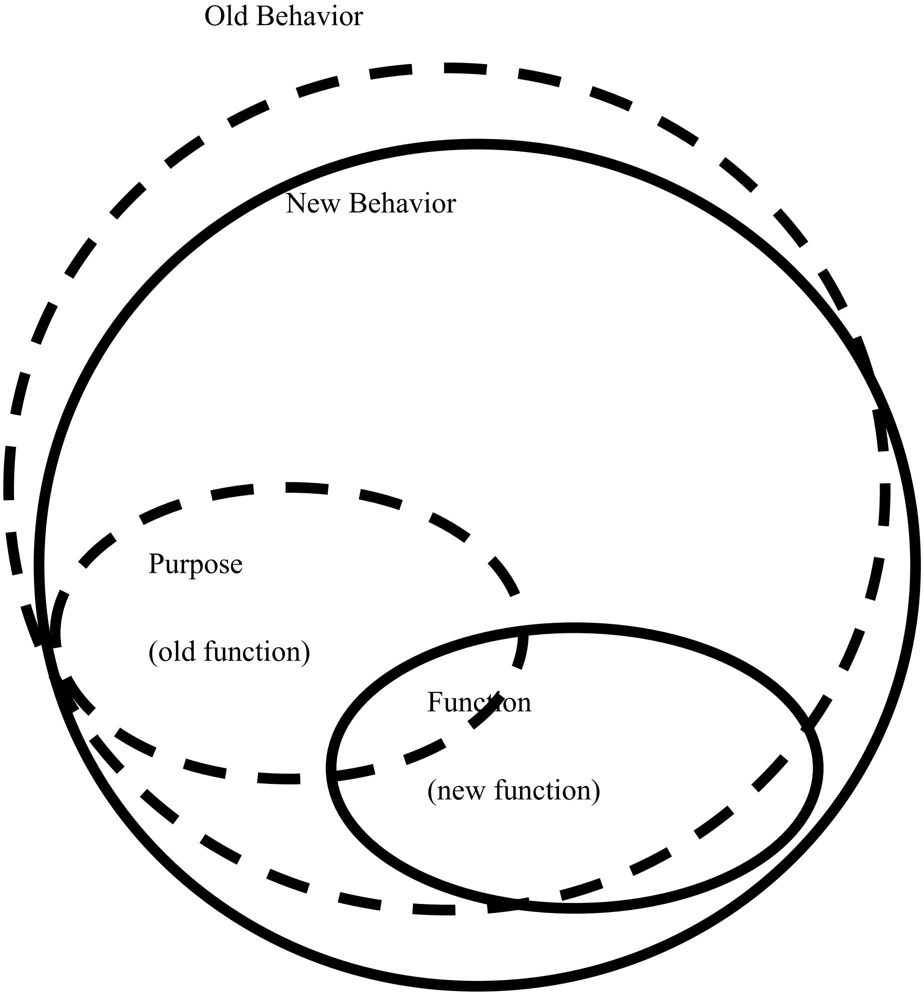
The *high-order predicates* required are therefore high-level relations that hold and maintain their meaning in both systems. It seems natural to associate them to the foundations of generalized evolutionary systems. We think that the Campbellian epistemological approach we build upon provides a strong platform as a requisite ‘system of connected knowledge’. This approach allows to overcoming a critical issue in applying the sistematicity principle, which concerns the difficulty of defining ex ante what ‘connected knowledge’ may mean.

Indeed, as a consequence of our previous discussions, it becomes straightforward to describe the fundamental processes of *variation* and *selection* in generalized terms maintaining their meaning in both the biological (base) and the technological (or target) system.

Variation. By definition, each functional module is associated to a *Behaviour*, which can be seen as a discrete set of effects: all the possible actions, processes and operations that the module can perform given the current state of its development. Function is a subset of Behaviour. Due to adaptation and to other evolutionary processes (for example, drift, self-organization), behaviour changes over time, gradually generating variations that spread across the population, so that there are objects (functional modules) characterized by different behaviours (Figure 2).

Selection. When certain boundary conditions are fulfilled exaptation takes place. The event is simple: a subset of Behaviour, different from the previous Function (Purpose), is selected as the new function (Figure 2). The novel function is selected either because it gives a competitive advantage to the artefact in its present niche, or because it gives it the opportunity of colonizing or creating a new niche. In the most radical cases, exaptation gives origin to a new technological lineage, thus marked by a bifurcation in the technological trajectory, that gradually drifts away from the original lineage.

Figure 2



Note: Exaptation as modular functional shift, from an existing function P (that could coincide with the purpose) to a new function F. In general, the new function may overlap the old function (as shown in figure). A Variation of Behavior (in figure, from Old Behavior to New Behavior) may enable exaptation.

Figure 2 Exapatation as modular functional shift

As we can see, exaptation in an emergent phenomenon that is analogous in both the biological and the technological system, because they share the coherent set of relations that are the foundation of a generalized evolutionary system. Identifying the sistematicity principle as the fundamental cognitive structure of a generalized evolutionary system completes the application of Gentner’s ‘complex analogy’ theory thereby confirming the legitimacy of analogy across two different complex systems. It also contributes to ascertaining under what conditions transferability across complex domains is legitimate.

Empirical support

While not required by the original theory of *structure mapping*, the necessity of empirical validation of the *complex analogy* has emerged in successive research. Modular exaptation describes at a detailed, artefact-specific level how the process of innovation driven by the emergence of functional shift takes place. Since the process includes morphological changes, it is possible to identify in the historical records the events marking the exaptive phenomena, finding actual instantiations of the stylized process that can described as follows:

Competition and other social and technical phenomena incessantly expand the set of available functions, by changing the way in which the intentional *function* (*purpose*) of each module is obtained and by generating new intentional functions. New materials are developed, production systems improved, and ultimately the *behaviour* of each functional module changes over time. While *intentionally* improving the purpose, this restless activity *blindly* changes the behaviour of each functional module (*variation*), generating a growing set (in evolutionary terms a *population*) of diverse functional modules.
In other words, competition changes the functional modules' 'adjacent possible' (Kauffman 2000), that is, the set of new functions that become theoretically achievable given the state of development of the modules. Since this happens in each module and at each modular level, the possibilities of functional shift and successful recombination are consequently multiplied. Exaptation is therefore a process in which emergence of new functions is reinforced by a combinatorial dynamics, whose space is expanded by modularity. Consequently, we posit that the emergence concept of *modular exaptation* is central for a complete understanding of technological change.

By grounding modular exaptation into the empirical historical record we also show how the process can be classified into different evolutionary phenomena (internal exaptation, external exaptation, radical exaptation). The two-way exchange of knowledge supported by the complex analogy is confirmed when we notice that in the technological domain each functional module can be transferred to a different industry (across different technological lineages), and the analogous process (Horizontal Gene Transfer) is documented in biological evolution.[22]

Conclusions: the Power of Complex Analogy

In this final section we summarize the contribution and discuss its methodological value. The application of the complex analogy framework to the problem of exaptation is the general methodological contribution to the study of complex systems we propose in this chapter. The opportunity of rethinking the biological-technological analogy stems from recent discoveries in evolutionary biology, and in particular in bacterial evolution. The recognition of the functional module as "a critical level of biological organization" (Hartwell et al., 1999, C47–C48), suggests the possibility of reframing the artefact-organism analogy already proposed by several scholars (for example, Basalla 1988, explicitly including the modular nature of the artefacts. However, we explicitly observe that the viability of the concept of 'functional module' in the technological domain is disputed, hence potentially disrupting the foundation of our analogy. This is due to the fact that technological function is tightly, though not exclusively, coupled with human intentionality, which instead plays a limited role in biological evolutionary systems. The first contribution of this paper is, therefore, to indicate the tenability of etiological concept of biological function ('proper function') in the technological domain. A consequence of this

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[22] Most organisms living today in fact are *bacteria*, which are composed by a single cell. In fact, most of the discussion about functional modules in biology (for example, Hartwell et al. 1999) is referred to the bacterial world. In the bacterial domain functional modules can be transferred across lineages, the distinctive process called Horizontal gene Transfer, or HGT. This importance of this process is much more limited among multicellular organisms (eukaryotes) where vertical inheritance is dominant.

deceptively subtle idea is that technological function becomes intrinsically (by definition) associated to selection (an evolutionary concept) rather than to intentionality. Framed this way (this implies an extended definition of artefact), the biological concept of functional module is therefore a valid analogue of the technological one.

This is the gateway towards a formal *complex analogy* between the biological and the technological domain, our second contribution. Following this thread, we formalized the analogy between the two domains evidencing their common *structure mapping*. We do this by showing that *relations*, rather than *attributes*, are shared by the biological and technological domain, and that the epistemological foundations of generalized evolutionary systems (based on variation, selection, retention[23]) can fulfil the requirement of systematicity.

Finally, we outlined a stylized process describing in evolutionary terms how technological innovation can have an exaptive origin. Many historically documented innovations seem to confirm this framework.

The *complex analogy* we outline can in fact be considered as a tool for studying complex systems, taking advantage of the foundational property of the complex analogy: the core idea of analogical reasoning is that two *domains* can be described, at a certain level of abstraction, by the same *relational structure*. The knowledge we already possess about one of the domains (the *base* domain) can therefore be useful in understanding the second one (the *target* domain). The flow of concepts between the biological and the technological domain can therefore be reliably (even if carefully) explored, considering the knowledge accumulated in the base domain for usage in the target domain – and vice-versa.

We elucidate the usefulness of the complex analogy by showing how the concept of functional module based on the etiological vision of function naturally led to the novel concept of *modular exaptation*. Modular exaptation provides a potentially useful concept based on analogy. Even more, the concept suggests a different way of thinking about innovation, in which concepts drawn from evolution coexist with these developed in innovation science.

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[23] As noted earlier, this account doesn't include self-organization.

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On the origin of technologies: the invention and evolution of the bow-and-arrow

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Abstract

The bow-and-arrow was a major radical innovation and ‘a nearly ubiquitous example of the evolution of a cultural trait’ whose diffusion led to extraordinary socio- economic developments. Unfortunately, the emergence of this new technology is not easy to research: most modules composing the weapon – made of perishable materials – rarely survive, so the remaining physical evidence is found mainly in small stone components: the arrowheads. Moreover, the evolutionary theories of technological change face difficulties in explaining the inception of this kind of discontinuous, radical innovation. This paper addresses the bow-and-arrow case through a novel evolutionary approach to technological change based on the evolution of bacteria rather than that of eukaryotes and therefore acknowledging Horizontal Transfer (the recombination of functional modules across diverse lineages) as an evolutionary force as powerful as Vertical Inheritance. The interplay between technological and cultural processes clearly emerges through the evolutionary trajectory of the bow-and-arrow, in that it is impossible to understand it without considering it both a technological radical innovation and a cultural trait. Finally, the author argues that the same evolutionary pattern could apply to many a radical innovation, opening new interesting research avenues both for innovation management and for evolutionary archeology, and possibly contributing in shedding some light on the nature and origin of technology.

Introduction

In 1939, at the very beginning of the golden age of science-fiction, Lester Del Rey wrote the short story ‘The Day is Done’ in which he described the fatal encounter between two humans, Hwoog, a Neanderthal, the last of his tribe and possibly of his species, and Lagoda, one of our sapiens ancestors. Lagoda is the fictional inventor of a new ‘magic’ weapon, the bow-and-arrow. A compassionate character, he tries to teach the Neanderthal how to use it, but Hwoog, “whose fingers are large and maladroit, is unable to wield this new weapon. There are two aspects of the Neanderthal disability: the first is that he is anatomically maladapted, the second more insidious factor is that Hwoog has given up mentally” (De Paolo 2003). But upon reading Del Rey’s vintage narrative, we learn the real nature of Hwoog’s failure: he is utterly unable to understand the new weapon: “The spear was too tiny to kill more than rodents”, he thinks “and the big stick had not even a point” (Del Rey 1939). Dispirited, Lagoda gives up his teaching. “This weapon is not for you” is his sad final remark: the Neanderthal cannot understand how the bow-and-arrow functions, thus his species is doomed.1 Surprisingly, but not for the first time, science fiction has given us here an early insight into later research, anticipating the contemporary debate on the inception of mechanically-projected weaponry: were the Neanderthal actually unable to master the cognitive processes needed for conceiving and implementing composite technology as some research suggests (Lombard and Haidle 2012) or were they limited in their technological inventiveness by contextual, non-cognitive issues, as others believe (Shea and Sisk 2010)[24]?

In either case, the bow-and-arrow invention is now recognized by many scholars as an enabling technology which supported the successful dispersal of Homo sapiens out of Africa, provoking, eventually, the extinction of all other competing Homo species (Shea and Sisk 2010). “If they were armed with the bow and arrow,” paleoanthropologist Sally McBrearthy proudly writes about our ancestors, “they would have been more than a match for anything or anyone they met” (McBrearthy 2012: 532). Building on recent archeological discoveries related to the bow-and-arrow (Brown et al. 2012), McBreathy argues that the humans who manufactured it could have developed not only novel cognitive capabilities but also the ability of passing technological knowledge down the generations. In synthesis, composite weaponry technology is increasingly being recognized as a distinctive trait of modern humans: the extraordinary

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[24] Shea and Sisk argue that the Neanderthal, burdened by their higher (in comparison with the Sapiens) daily caloric requirements, could not allot the time and resources necessary to develop mechanically-projected weaponry. The Neanderthal mastered composite (modular) technology (and in particular hafted tools and weapons) well before the invention of the bow-and-arrow (Wragg Sykes 2015) but no evidence of Neanderthal-made bow-and-arrows has been discovered yet.

importance of the invention and diffusion of the weapon, therefore, can hardly gain more recognition. This notwithstanding, the mechanisms which led to the invention are not well understood: there is a clear gap both in innovation science and in evolutionary archaeology about the inception of bow-and-arrow technology. One obvious reason explaining the gap could be the fact that precious little physical evidence of early bow-and-arrows remains: most modules of the weapon – made of perishable materials – rarely survive, so the majority of the research is based on the study of stone artifacts (the arrowheads) and contextual assumptions. On the other hand, a second more subtle reason could be found in the lack of a theory explaining the causal chain leading to radical invention: the bow-and-arrow breakthrough marks a technological discontinuity which is difficult to frame in the current evolutionary theories of technological change. The aim of this article is to try and shed some new light on the case, considering the new archaeological discoveries, through the interpretive framework of an extended model of technological change, based on the evolution of bacteria rather than that of eukaryotes, and therefore acknowledging Horizontal Transfer (the recombination of functional modules across diverse lineages) as an evolutionary force as powerful as Vertical Inheritance.3
The paper is organized as follows:
first of all, I briefly present the physical and engineering principles of the bow-and-arrow, introducing in particular the concepts of modularity and functional module, which is central to the following evolutionary approach to the case study;
second, I introduce the novel archaeological evidence that provides the factual base on which the evolutionary account proposed in this paper is founded;
third, building on a theoretical framework developed for innovation management, I explain why the bow-and-arrow should be considered a radical innovation and what this implies;
fourth, I introduce the background of the evolutionary approaches to technological change and briefly describe the novel ‘Woesian’ model of technological change which I apply to the case of the bow-and-arrow;
fifth, in the core chapter of the paper, I apply this model to recent archeological discovery inferring the evolutionary trajectory of the bow-and-arrow, evidencing in it the key role of horizontal transfer and modular exaptation;
finally, I discuss the implications of this evolutionary interpretation of the case. I argue that the same evolutionary patterns can explain many a radical innovation and that some of the concepts

can apply outside the technological arena and have some explanatory value for evolutionary archaeology and innovation management, and could contribute to a better understanding of the origin and nature of technology.

Background

The Bow and Arrow as a Modular Artifact

Concept

A bow-and-arrow set is composed of two main elements: (1) the *bow*, a stave made of wood or other elastic material, bent and held in tension by a string; (2) the *arrow*, a thin wooden shaft with a *tip* (or *arrowhead*, 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. The exosomatic storage and subsequent fast release of elastic energy is the distinctive engineering principle of mechanically-projected weaponry[25] (according to the terminology proposed by Lombard and Haidle (2012) which I adopt in this paper).

Function and Functional Module

The bow and arrow is a modular artifact: it is composed of discrete components (modules) each of which is in turn composed of other lower-level modules. The modular hierarchy (referred to also as the architecture) of the artifact can therefore be represented by a modular tree (Fig.1). Moreover, each module is associated with a discrete function. The association module-function in artifacts and its biological counterpart is a foundational concept in the evolutionary model outlined in this paper.

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[25] 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.

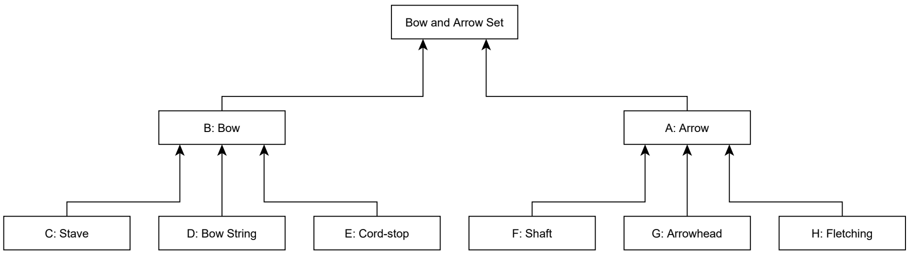

Fig. 1 *The bow-and-arrow modular tree. The modular tree is a simple representation of a modular artifact. The components (functional modules) of the artifact are represented at each level by the nodes of the tree. The arcs connecting the nodes across levels describe the composition of each module*

The concept of functional module is currently acknowledged as central in biological research. For example, Hartwell Hopfield, Leibler and Murray in their influential paper (1999: C47) strongly argue for functional modules "*as a critical level of biological organization*". Moreover, they claim that it is a distinctive link between the biological and technological domain: "*the notion of function and functional properties separates biology from other natural sciences and links it to synthetic disciplines such as computer science and engineering.*" Unfortunately, the concept of function and functional module is not as straightforward as it seems in technology.[26] In this paper, however, I will adopt the consensus concept of biological function (aka 'proper function'). In accordance with this definition, the 'proper function' of an artifact is not what the artifact (or module) is designed for, but what it is selected for: "*the proper function of an item is to do whatever it was selected for*" (Neander 1991: 171).

Exaptation

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[26] for example, Baldwin and Clarke (2000), while introducing an elaborate and important theory of modularity in complex technological systems explicitly refuse the concept of function as a foundational property of modularity. Their definition of modularity "*is based on relationship among structures, not functions" because functions "are inherently manifold and nonstationary*" (ibid: 63, footnote 2).

Adopting the biological concept of '*proper function*' for artifacts has the advantage of taking into account the changeability of technological functions. Indeed, it disconnects the concept of function from the intentionality of the manufacturer linking it instead to the selection by the user. The selection of an artifact (or a module) for a new function (different from the one for which it was designed or manufactured) is generically defined as '*functional shift*' or more specifically preadaptation or exaptation. The concept is not new in biological evolution or in technological innovation. The importance of functional shifts in biological evolution was recognized by Darwin himself, who referred to it as "*the wonderful metamorphoses in function*" in the summary of Chap. 6 of 'Origin' (1859). The concept was later defined 'preadaptation' by the French naturalist Lucien Cuènot (1914). Cuènot's '*preadaptation*' refers to traits whose functional shift increases the fitness of an organism. The concept was reframed by Gould and Vrba in their famous 1982 paper (Gould and Vrba 1982), in which they coined the fortunate term *'exaptation*' to describe the process (rather than the effect) of functional shift. The analogous process of functional shift, called exaptation or preadaptation, has also been researched in technological change (Dew et al. 2004; Cattani 2005, 2006; Andriani and Cohen 2013). The importance and explanatory value of the concept is still debated: indeed, some scholars believe it is finally being abandoned in biological evolution because it is intrinsically weak, while maintaining a value in cultural evolution (Larson et al. 2013). Here, I argue for a different perspective because, ironically, but in accordance with the bacterial analogy on which this paper is founded, the importance of functional shift is again gaining consensus, not in eukaryotic, but in bacterial evolution, where it is considered "*a central mechanism for evolutionary change*" (Ganfornina and Sanchez 1999). Accordingly, I will adopt the concept of 'modular exaptation', in which functional shift is referred not to a whole artifact but to its modules (Andriani and Carignani 2014). I propose modular exaptation as a critical process in the invention of the bow-and-arrow.7

The Invention of the Bow-and-Arrow: Archeological Evidence

Recent archeological discoveries, regarding in particular the Howieson's Poort culture, have provided new evidence supporting the existence of mechanically- projected weaponry in Sub-Saharian Africa between 71,000 and 64,000 years ago (Brown et al. 2012; Lombard and Phillipson 2010). At this moment these are the oldest archeological records which can be related to bow-and-arrow technology.

This evidence has triggered new interest in the bow-and-arrow origin, because some researchers claim that mastering the manufacture and use of complex composite (modular) artifacts has important cognitive implications and could possibly be considered a proxy for modern human cognition (Lombard and Haidle 2012). The consequent impact on the successful worldwide dispersal of the Sapiens species is also emphasized in research literature (Lombard and Haidle 2012): the availability of a lightweight, accurate and powerful alternative to contemporary hand-delivered weaponry gave the humans who were able to use it an upper hand over other human species. The competitive advantage of the bow-and-arrow as a hunting weapon was not just the limited increase in range, but moreso the possibility of carrying a weapon capable of shooting many arrows in sequence with good accuracy and enough penetrating power to kill or wound small and medium-sized animals10: a perfect weapon for following game over long distances on difficult terrain (Lombard and Phillipson 2010). Accordingly, Sisk and Shea (2009) define projectile weapons as ‘a niche-broadening technology’, since they decrease the risks associated with preying on large, dangerous animals and increases the returns on hunting smaller, fast-moving terrestrial mammalians, birds, and fish. The bow-and-arrow is ubiquitous: it was re-invented in many places and at different times over the millennia. However, I will refer to Lombard and Phillipson (2010), as the primary source for this paper: discussing the new discoveries from Sibudu Cave (KwaZulu Natal, South Africa) Lombard and Phillipson also expose contextual evidence which not only robustly supports their claim about the use of the bow-and-arrow, but also provides a perfect factual base for validating the extended ‘Woesian’ evolutionary theory of technological change. This evolutionary account of the inception of the new radical technology, including the distinctive processes of horizontal transfer, modular exaptation and amelioration, is the core contribution of this paper.

The Bow-and-Arrow as a Radical Innovation

A specific reason for particular interest in the bow-and-arrow invention – and at the same time for the difficulty in positioning it in evolutionary innovation – is its discontinuity with its contextual technological state-of-the-art-ness: it is at first sight what is commonly called a radical innovation. The multidisciplinary approach we pursue in this book suggests trying and clarifying the concept, applying to this pre-scientific and pre-economic case of technological innovation a framework developed in the field of innovation management and usually applied to contemporary technological change (Henderson and Clark 1990).

Figure 2

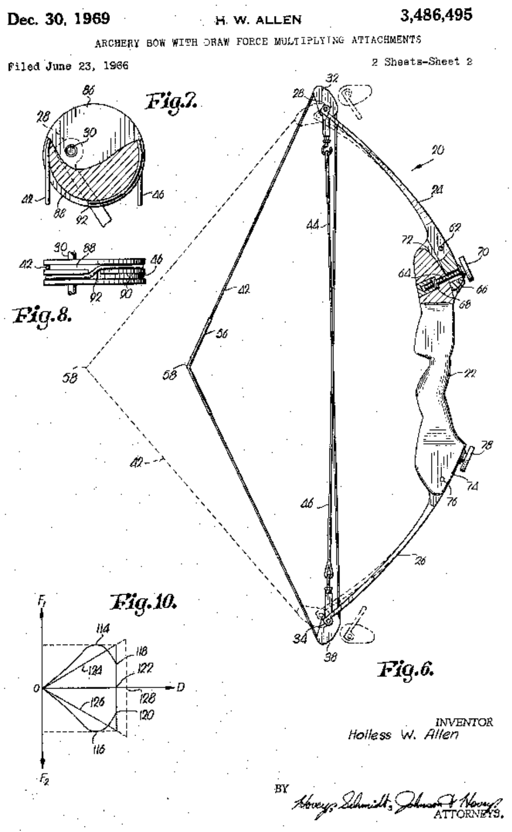

Fig. 2 The compound bow, invented by H.W. Allen in 1969, was a major improvement in archery, but it was not (according to our framework) a radical innovation, since the core concept and first-level modules remain unchanged, as shown in this original patent drawings

First of all, we notice that while bow-and-arrow technology has changed extensively during the latest 64,000 years (and especially in the last millennium) we can still recognize the architecture of the original invention of 64 kyr ago (kiloyears ago). In particular, the first modular level in modern bows still shows the same functional modules, the bow, and the arrow, in turn composed, at the second level, of the same submodules.

It is true that a number of new components are present in modern arrows, and new materials are extensively used, but these components were added to the original modular tree rather than substituted those already in existence. In other cases, ancient components were split into smaller lower-level components, but the new assembly maintains the functional role of the old one. For example, the modern compound bow (Fig. 2) is composed of several new submodules, including cams, axles and pulleys, and has a number of advantages in comparison with the longbows, in that it is less cumbersome and its wielding requires less effort.

The function of the compound bow, however, remains the exosomatic storage of elastic energy, which was the original breakthrough and the core concept that has remained unchanged throughout the millennia. The innovation, thus, perfectly fits into the framework proposed by Henderson and Clark in their seminal paper (Henderson and Clark 1990) (Table 1).

Table 1

		Core Concepts	
		Reinforced	Overturned
Linkages between Core Concepts and Components	Unchanged	Incremental Innovation	Modular Innovation
	Changed	Architectural Innovation	Radical Innovation

***Table 1** – A framework for defining innovation (adapted from Henderson and Clarke, 1990)*

Clearly, the original invention of the bow-and-arrow qualifies as a radical innovation (lower-right quadrant in Table 1), in which both the core concepts and the linkages between core concepts and components (in comparison with previously existing hand-thrown weapons) were overturned. The architecture of the new artifact revolutionized weapons technology, while all the successive modifications, despite some of them having great historical impact, cannot be labeled as radical innovations. Indeed, even if the performances have been of course greatly improved, the modern Olympic bow and arrow and more recent compound arrows (Figure 2) qualify as just incremental or modular innovations.

We can, therefore, define the bow-and-arrow as a radical innovation. Classifying the invention of the bow-and-arrow in terms of modern innovation is not a mere exercise in science. Radical innovation is important in innovation management, because it could lead to the emergence of new dominant designs and open new markets (Abernathy and Utterback 1978; Geroski 2003), but its inception is not well understood. The bow-and-arrow case has the characteristics to be a useful comparison for much more recent radical inventions, showing many similarities and a few differences as well.

Moreover, the comparison could work in both directions, giving the opportunity of applying the concepts and results of modern innovation management to ancient technological change.

Evolutionary Technology

Background

The evolutionary approach to technological change is hardly new: while its inception dates back to pre-Darwinian times, structured theories were developed by a number of pioneers during the nineteenth and early twentieth centuries, and reached maturity in the second part of the twentieth century. In opposition to the naïve vision that attributes radical innovation to 'heroic' inventors creating technological discontinuities, thanks to their extraordinary insights, the evolutionary approaches, due to their Darwinian inspiration, embrace the concept of continuous technological change. Of particular interest for this paper are the theoretical and empirical contributions of Usher (1929) and Gilfillan (1935) whose pioneering books, including the details of engineering development, clearly expound the recombinant nature of technological innovation and develop the concept of cumulative change (Basalla 1988: 20–24). The recent contributions of Brian Arthur (2007, 2009) add the explicit recognition of modularity as a foundational concept of technological change leading to the definition of technology as autopoietic. According to Arthur, technologies are put together from components transferred from other technologies, evolving from simple to complex structures. His model is based on the principles of combination and recursiveness: technologies are formed by combination organized around a working modular architecture which corresponds to the way the parts and their connections work together. Evolutionary archeology (O'Brien and Lyman 2002), which aims to answer archeological questions through evolutionary concepts and methodologies, is founded on the same conceptual framework – the Darwinian concept of descent with modifications, epitomized by the principles of variation, selection, and inheritance – and is therefore of particular interest here.

Horizontal Transfer

Alas, radical innovations hardly fit into the evolutionary framework of the theories overviewed in the previous paragraph: one of the critical issues, as we shall see shortly, is that all previous theories of technological (and cultural) change are based on the canonical Darwinian model whose primary evolutionary process is vertical inheritance and whose consequent iconic representation is the *tree of life*. Indeed, an evolutionary process based solely on Vertical Inheritance poses a critical disanalogy to the model since, as pointed out by anthropologist Alfred Kroeber in his authoritative textbook (Kroeber 1948) cultural evolution is better represented by a network than by a tree. It is apparent that cultural evolution (like technological innovation) shows a reticulate pattern, not a hierarchical one. The evolutionary theory I adopt here – while of course in accordance with the Darwinian principles of variation, selection, and retention – is not based on the canonical model whose dominant evolutionary process is Vertical Inheritance, but includes as an equally important evolutionary process Horizontal Transfer.

An Extended Model of Technological Change: The Woesian Perspective

Horizontal Transfer is widely recognized as a viable mechanism in cultural transmission, but it is sometimes seen as an anomaly and a difficulty on theory (Greenhill et al. 2009). On the contrary, in the model I adopt here (shortly outlined in this paragraph, and described in detail in Cattani et al. 2013b) Horizontal Transfer is not only acknowledged as an evolutionary force as powerful as Vertical Inheritance, but proposed as a structural part of an extended theory of technological evolution.

The extended model of technological (and possibly cultural) evolution seeks its biological counterpart domain not in the evolution of eukaryotes, in which Vertical Inheritance is still acknowledged as the dominant evolutionary process, but in the evolution of bacteria, where Horizontal Genetic Transfer is today recognized as a major evolutionary mechanism (Ochman et al. 2000; Koonin et al. 2001; Woese 2002; de la Cruz and Davies 2000).

What actually could happen in bacterial evolution is that part of a gene or a whole gene or a cluster of genes is transferred from one organism to another via HGT, regardless of the lineage they belong to. After this transfer, the genes must be maintained in the recipient cell (the retention process). Next, they have to undergo a strong selection phase and eventually spread within the bacterial population – the strain – which is generated through replication of the recipient organism (the fixation process).

Finally, the transferred genes must increase the fitness of the function they carry in their new lineage – they can actually be considered genetic functional modules –, which means that they need to adapt to the lineage phenotype, a process referred to as amelioration (Lawrence and Ochman 1997; Eisen 2000).

The adoption of this new perspective clarifies the concept of Horizontal Transfer in technological (and cultural) evolution: what is actually horizontally transferred are not generic 'traits' or other fuzzily defined entities, but *functional modules*. This more formal concept can support a structural extension of the theory which, while seamlessly extending the Darwinian model, embraces a new vision based on pattern pluralism (Doolittle and Bapteste 2007) rather than the single 'tree of life' pattern, and opens new perspectives and avenues of research not only in biology (Woese 2004), but also in technological and cultural evolution.

In particular, this new perspective is necessary in order to explain radical innovations, because the gradualist models of evolution are at a loss in doing so while other theoretical concepts, like punctuated equilibria or the inheritance of acquired characters, cannot support robust analogies because they are scientifically discredited in biological evolution.

On the contrary, when Horizontal Genetic Transfer is acknowledged as a structural evolutionary event it is natural to represent biological evolution by a *phylogentic network* (also called a *phylogenetic graph*) rather than by the familiar phylogenetic tree. The notable aspect is that this is the same topological pattern evidenced by Kroeber in his tree of cultural evolution: the disanalogy between cultural and biological evolution seems to disappear under the Woesian model. When the impact of Horizontal Transfer is massive [27] the organisms involved are described as chimeras because they result from the assemblage of functional modules originating from diverse lineages. Analogously, many radical innovations can be described as ‘evolutionary chimeras’ (Woese 1987: 230). The bow-and-arrow is such a case.

The Invention and Diffusion of the Bow-and-Arrow: A Woesian Perspective

Introduction

Technological artifacts – and in particular inventions and innovations – are to be regarded as cultural traits (O’Brien et al. 2010). The nature of technological artifacts, and in particular of radical inventions, however, set them apart from quintessential cultural traits like language: indeed, the intentional harnessing of natural phenomena in response to an existing need appears to be the driver of novel artifacts. Invention, according to Arthur (2009: 274), is a process of linking some purpose or need with an effect that can be exploited to satisfy it. It may begin with a purpose or need for which existing methods are not satisfactory; this forces the seeking of a new principle (the idea of an effect in action).

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[27] Carl Woese conjectured the existence of a critical discontinuity in biological evolution, the Darwinian Threshold. Before the Darwinian Threshold Horizontal Transfer was rampant, species did not exist, and evolution was essentially reticulate. The existence of the Darwinian Threshold is not a necessary hypothesis for the extended model of technological evolution I adopt here that the importance and ubiquity of Horizontal Genetic Transfer in bacterial evolution is independently recognized in literature. However, I adopt the term ‘Woesian’ model because the fascinating representation of evolution preceding the Threshold given by Woese seems to capture perfectly the dynamics of the industrial revolutions, in which radical innovations arise and new industries are born: ‘only global invention arising in a diverse collection of primitive entities is capable of providing the requisite novelty.’ (Woese 2002: 8746)

Or it may begin with a phenomenon or effect itself – usually a freshly discovered one – for which some associated principle of use suggests itself. While in general accordance with Arthur's concepts, I would like to emphasize the importance of the interplay of technology with the socio-cultural environment: in short, recognizing radical technological innovations also as cultural traits. Indeed, engineering breakthroughs do not blossom in the desert: they find their nurture in technological 'traditions' (artifacts, tools and knowledge), and in turn they are selected and supported by the socio-technical environment with which they co-evolve.

Contextual Conditions: Setting the Stage for Radical Innovation

Lombard and Phillipson 2010 (640, 641) describe a number of cognitive, technological and natural conditions which are contextual to the invention of the bow-and- arrow in KwaZulu Natal, circa 64,000 years ago.
In order to elucidate the Woesian evolutionary account I am building, I propose a reclassification of Lombard and Phillipson's checklist into classes instrumental in understanding the evolutionary process:

1.The environment: socio/economic, climatic and ecological context:

- changes in faunal assemblages;
- changes in climate and vegetation.
- fishing and fowling;
- broad based, varied game procurement.

2. Available functional modules (general purpose technologies)

- formal knots;
- formal hafting technology;
- long, strong cords;
- stone tipped spears.

3. Technological artifacts in use (including exaptable functional modules)

- snares;
- bow drills.

Lombard and Phillipson also include in the list the use of latent energy in flexed wood. Borrowing from evolutionary archeology (O'Brien and Lyman 2002). I prefer to describe this empirical knowledge[28] as part of the replicator of the functional module (the bow) which stores latent (elastic) energy. Each artifact has therefore a twofold description: the physical entity (also called the *interactor*) and the knowledge (and tools) necessary for its replication (also called the *replicator*)[29].

Invention (Horizontal Transfer and Exaptation)

The invention of the bow-and-arrow is clearly a case of recombinant innovation in accordance with Arthur's model: the inventor[30] recombined the existing technologies into the novel artifact. In particular, we can easily recognize by the modular tree that the recombination has two distinct main branches, defined in Fig. 1 and in Fig. 3 as the *arrow side* and the *bow side*

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[28] It is hardly necessary to notice that scientific knowledge of the underlying phenomena is useful but not necessary to technology development

[29] Here I refer to the deceptively simple definitions given by O'Brien and Lyman (2002: 26): 'a replicator is an entity that passes its structure directly through replication'. The concept will be discussed in more depth later in this paper.

[30] Actually, the *inventors*, since the process happened several times in different places and times. Arthur dislikes the term *inventor* because it '*has connotations of lone eccentric at work*' (Arthur 2009: 111), suggesting the adoption of the term originator instead. On the same wavelength Basalla (1982) warns against the naïve concept of *heroic* inventor. I cannot disagree with these distinguished scholars from an evolutionary point of view. But there is also a human side to inventions. Indeed, the persons who originate radical innovations are remembered in the historical record as men and women of vision and commitment who struggled to transform their ideas into reality, engaging in what can often be defined a *heroic* battle against conventional wisdom and established expertise. The unknown people who invented the bow-and-arrow were probably no exception: I will therefore skip Arthur's '*originator*' suggestion maintaining, instead, the more romantic term *inventor*.

Figure 3

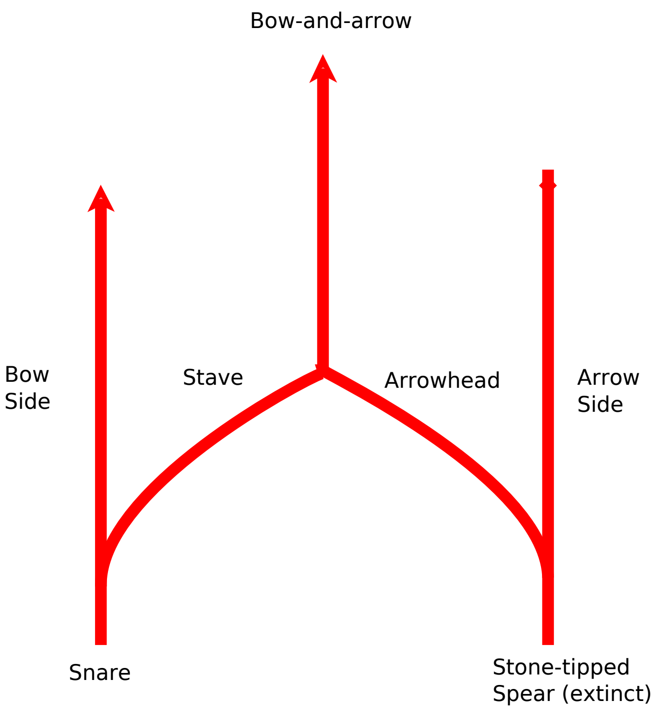

Fig. 3 The bow-and- arrow stylized phylogenetic graph. Horizontal Transfer takes place at the intersection between the stave (bow) and the arrow directed arcs, from which a new lineage (the Chimeric Artifact 'bow-and-arrow') is created

The breakthrough, i.e., the idea of *exosomatic storage of elastic energy*, took place in the bow side. It is therefore necessary to investigate the origins of this revolutionary idea in more detail. Lombard and Phillipson (2010) emphasize the presence of two kinds of different artifact 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 *bow-drill*, used for starting a fire or for piercing resistant materials and the *snare*, a spring-trap used for capturing small animals. The usage of the bow-drill is documented through archaeological physical records (drilled holes in hard materials like stone or bone) in periods preceding or concomitant with the invention, both in the South African site and in other places. Spring-traps are not archaeologically documented but they are traditional artifacts still in use in Southern Africa, for example in the Kalahari Desert.

Both are candidate to have provided the key module (the bow) of the invention. Clearly, both were components of artifacts intended for completely different function (namely, drilling hard materials, starting a fire, or capturing small animals).

The inception of the bow-and-arrow suggested by Lombard and Philippson seems straightforward: a natural phenomenon (the fact that the energy stored in the flexed-wood component of the snare or of the bow-drill was able to launch a small spear) was perceived by the inventor. Then he or she selected this functionality, already part of the *behavior* of the artifact, as the new *function* around which he or she assembled the first crude bow-and-arrow. This is the evolutionary signature event of the invention: a module already in existence became the central component of a novel artifact thanks to a *modular exaptation*[31]. As I already pointed out, the mechanism is hardly new in technological change, in that it is documented in a number of case studies (e.g. Dew et al, 2004).

In the seemingly easy assemblage of the first prototype of the novel artifact using a stave cut from a spring-trap - or possibly an existing bowdrill – a number of cognitive processes can be presumed to be at work, in that the inventor, after grasping and harnessing a physical phenomenon re-modularized the artifact associating each module to a discrete function.

While embracing the caveat of Usher who in his seminal book declared that “The requirements of historical analysis of the development of mechanical appliances do not impose upon us the

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[31] We notice that while the *phenomenon* underlying the invention is the same in snares and in bow-drills (the flexural behavior of certain materials physically described by the Hooke law), two different *functionalities* are exploited for the two artifacts: *providing a tensional force* is the functionality for which the bow is used in the drill, while *storing and discharging elastic energy* is what it provides in the snare. So, while the drill-bow is more similar to the form of the bow in the weapon the functioning of the weapon is better understood by seeing a snare in action.

task of minute examination of the internal aspects of the mental processes. (Usher, 1929:16)" it is however interesting noticing that technological modularization could possibly be associated to abstract thinking, since the same conceptual structures (i.e. the hierarchical modular architecture) are also central in other manifestation of symbolic human cognition, e.g. the language.[32]

The origin of the second key module, the arrow, follows the same line, but is less difficult to understand, since tipped stone points were commonly in use, so functional shift was not necessary: they were probably crudely adapted in the prototypes (as inventors and engineers do even today) and underwent later engineering refinement (*amelioration*).

The breakthrough was then technically made possible by borrowing from the collection of *general purpose technologies* that where present, including the mastering of the tools (higher-order cultural traits) and procedures necessary for their manufacturing. The prototyping of the first bow thus included cords and formal knots, already developed for other technological artifacts (e.g. fishing lines, hafted tools).

In synthesis, *horizontal transfer* of existing modules and *modular exaptation* are the processes through which the novel artifact was generated. The bow and arrow is an *evolutionary chimera* - possibly the first one - since it had not an history in its own right but recombined components across diverse technological lineages.

Diffusion of the Bow-and-Arrow: The Evolution of a New Cultural Trait

In accordance with the etiological definition of function a *selection* by the users is the distinctive event marking a functional shift: indeed, the *invention* can successfully become a full-fledged *innovation* only when the users – in this case hunters and possibly warriors - select

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[32] According to Herbert Simon (1962) modularity is a systemic property of complex systems in general and artifacts in particular, and one of the mainstays on which a *science of the artificial* (Simon 1996) can be founded.

the new weapon as a better fit to their needs. As we already noticed, the bow-and-arrow decreases the risk of hunting big game and increases the returns on hunting smaller, fast-moving prey (Sisk & Shea 2009) – possibly including humans. The advantage for single high-skilled hunters over groups of hunters chasing animals with spears in periods of disappearance of big mammals seems a straightforward consequence, confirmed in principle by the replication and diffusion of the bow-and-arrow, carried by the groups of Sapienses during their successful dispersal out of Africa (McBrearthy, 2012).

In this case we clearly see how *needs* can follow the invention rather than precede it. The intentional explanation of invention as a straightforward response to need does not grasp the complexity of the process. The bow and arrow case shows how the innovation originated by a microtechnical event of horizontal transfer and exaptation, interacting with the context, triggered a coevolutionary socio-technical process with far-reaching consequences.

In the long evolutionary phase following the Horizontal Transfer the novel architecture was refined without being overturned and innovation became incremental rather than radical. The well-known pattern of Vertical Inheritance became the dominant evolutionary process, and a tree-like pattern characterized by technological *clades* emerged. Each chimeric bow-and-arrow became the root of the evolutionary tree, and one of them is the common ancestor of all modern Western bow-and-arrows, including the longbow and the compound bow.

A significant process showing how Horizontal Transfer seamlessly extends rather than contrasting the traditional models of evolutionary archeology lies in the adaptive transition of the horizontally transferred modules to the definitive form. Indeed, an adaptive process follows nearly any event of horizontal transfer, because the transferred modules are not perfectly fit for working in the new artifact, and therefore need to be adapted. This signature process finds a perfect analogue in the adaptive process which follows HGT events in bacterial evolution, where it is called *amelioration* (Lawrence and Ochman 1997, Eisen 2000).
An important characteristic of technological *amelioration* is that it implies morphological changes in the modules composing the new artifact, and these morphological changes can be detected and measured, helping in locating the HGT event.

Hard evidence of this adaptive process in the case of the bow-and-arrow can be found in the evolution of the arrowheads, important because they are the only remaining physical records of early bow-and-arrows and their evolution have been extensively studied. The adaptive path of the arrowheads diverge from that of the other spears from which they originated through horizontal transfer, and this clearly locates in time the bifurcation which is the signature event marking the radical invention. For example in Figure 4 the bifurcation is clearly visible in stratum 5, clearly marking the emergence of a new design sub-space characterized by morphological attributes disconnected from those of the originating artifacts (for the concept of design space in cultural traits see O'Brien et. al, 2013).

Figure 4

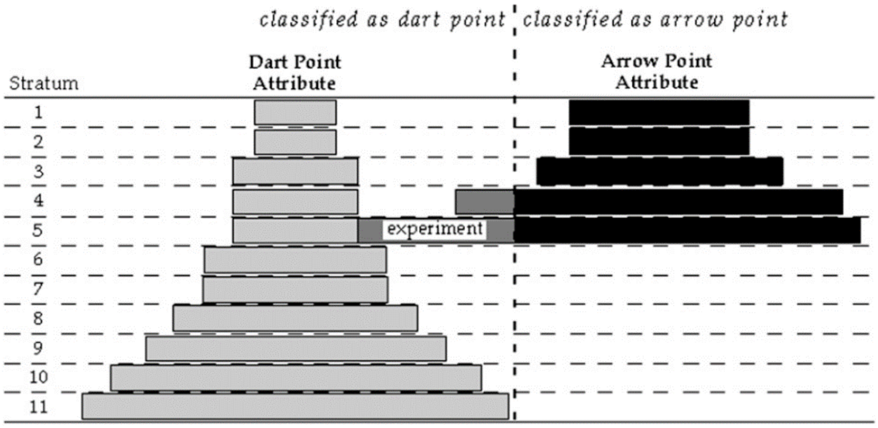

Figure 4: The Horizontal Transfer bifurcation is marked by morphological evidence, here clearly visible in stratum 5 where the divergence between dart points attributes and arrow points attributes originates a separate design space (Adapted from Lyman et al, 2008b)

Another adaptive engineering process is the evolution of modularity, through addition of other modular components, which can improve the performance of the artifacts without overturning its core concepts. The 71,000-year-old microliths proposed by Brown et. al (2012) as related to bow-and-arrow technology are early examples of modular evolution. Another example is fletching (stabilizing the flight of the arrow through a stabilizer connected to the end tip of the arrow, usually with feathers); fletching is not strictly necessary for a working bow-and-arrow and could have been adapted from other technical modules or from naturifacts[33]. The evolution of modularity[34] of the bow-and-arrow is well documented in archeological records and subsequently in history, leading in due time to modern development of the weapon, including the compound bow.

In turn, the successive engineering adaptative processes (amelioration),pushed the development of tools and processes for manufacturing the weapon, higher-order cultural traits contributing to increasing the set of *general purpose technologies* available. Indeed, general-purpose technologies usually evolve from technologies developed for specific usages. (Arthur, 2009). Moreover, the bow-and-arrow diffusion can also be seen also as source of exaptable new modules ready for generating new *'chimeric'* radical invention. For example, although speculative and supported only by contextual evidence the bow-and-arrow could have provided a key module exapted in the invention of the mouthbow (a musical instrument used for example in the Kalahari) and later of other string instruments.

Discussion: emergence, transmission and replication of technological cultural traits

The mechanisms of emergence, transmission and replication of cultural traits are central issues in cultural evolution. The specific case of modular artifacts –like the bow-and-arrow, moreover, shows specific micropatterns that seems typical of technology, but could also suggest a novel approach to significant research questions in the broader context of cultural evolution:

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[33] The term 'naturifact'is used by Basalla (1988, page 50) to indicate natural objects that 'could serve as models to initiate the process of technological evolution'

[34] Modularity is a gateway to Open Collaborative Innovation (Baldwin and von Hippel 2011); the evolution of the modular architecture of physical artifacts can empirically be recognized in Internet –driven open collaborative innovation (e.g. Carignani, Andriani and De Toni, 2008).

1. the bow-and-arrow (like many other innovations) appeared at different times in different places, '*a nearly ubiquitous example of the evolution of cultural traits.* (Lyman, Todd, Van Pool and O'Brien, 2008). What are the reasons for this ubiquity?
2. as all cultural traits, the bow and arrow can be seen as a unit of transmission and as a unit of replication as well (O'Brien et. al, 2010). But what are the microprocesses responsible for technological (and possibly cultural) transmission and replication?

The key concept in answering both questions lies in recognizing the *modular artifact* as the primary unit of analysis in evolutionary technology. Basalla in his seminal book strongly argued for this deceptively naïve approach, because:

"The artifact – not scientific knowledge, nor the technical community, not social and economic factors – is central to technology and technological change." (Basalla, 1988:30) [35]

In order to address the first question, I would like to point out that multiple independent inventions like the bow and arrow are hardly unique in the history of technological change: many radical innovation have been reinvented several times in several places. For example, turbine jet propulsion was independently conceived and prototyped by Hans von Ohain in Germany and Frank Whittle (later Sir Frank Whittle) in the UK in the decade preceding WW2 (Basalla, 1988; Arthur, 2009). This is not an isolated case: the history of technology is replete

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[35] *This is particularly true in this study since scientific knowledge and the technical community were not very developed in Paleolithic times.*

with such examples. A common trait of these cases is that we usually can discover lesser differences between the independent inventions, but they resemble each other because they share the same *modular architecture*, which seems the invariant entity in multiple invention.

The analogy with biology is enlightening: we find the analogous phenomenon in biological evolution, where independently evolved organs are called *'analogues'* (in opposition to *'homologues'* which have a common ancestor), as pointed out by Konrad Lorenz in his Nobel Acceptance Lecture (Lorenz, 1973). The Nobel laureate strongly argued for the power of analogy *'as a source of knowledge'*, discussing in particular the analogy between the biologic and technologic domain. He emphasizes the difference between homologues and analogues in biological evolution discussing the case of the parallel evolution of eyes in cephalopoda and in vertebrata. These organs are not *homologues* but *analogues*. They evolved independently, but have a strong resemblance: to be more precise, *they share the same modular architecture*, since in both we can recognize the same functional modules. 'Engineering' reasons seem responsible for this convergence. The multiple invention of the bow-and-arrow fits the pattern: there is a limited repertoire of feasible architectures for harnessing the breakthrough concept of exosomatically storing and releasing elastic energy, therefore when all the contextual conditions are in place *the inventor of the bow-and-arrow is bound to appear.*

The difficult but possible coexistence between evolution and intentionality – a vexed issue in evolutionary technology – finds here a possible clarification: the invention is intentional, but its inception, its success and its diffusion are determined by the socio-cultural environment and follows an evolutionary path.

The centrality of the (modular) artifact as the unit of analysis also hint at the answer to the second question about transmission and replication: technology has the power of transmitting itself down the generations through its products, the artifacts.

Nonetheless, the knowledge associated to each artifact, and to each functional module, is only in part included into the artifact itself. Amazingly, the naive idea that all the knowledge necessary for understanding and replicating an artifact is included in the artifact itself is proposed by many authoritative scholars outside the field of engineering: for example Gould (Gould 1987:70) states that *'five minutes with (...) a bow and arrow may allow an artisan of a culture to capture* *a major achievement of another'*. On the contrary, the necessity of a replicator different form the interactor is demonstrated by several cases in the history of technology: a beautiful example is the study by Cattani, Dunbar and Shapira (2013), showing how the failed transmission of tacit knowledge makes impossible to replicate the Cremonese string instruments today, albeit a number of them being still in existence and having been comprehensively analyzed.

What emerges from the bow-and-arrow case study is that the concept of *technological replicator* needs possibly an extension: not only it is something much more complex that just knowledge, including organizational procedures and social (as well as technical) learning, but has a tangible component in the form of manufacturing tools (higher-level cultural traits).

The Bow-and-Arrow Woesian evolution: a Common Pattern of Radical Innovation?

In this paper, I applied to the case of the bow and arrow an extended 'Woesian' model of technological change, in which *Horizontal Transfer* of *functional modules* across technologies is acknowledged as a primary evolutionary mechanisms as powerful as *Vertical Inheritance* and the distinctive processes of *modular exaptation* and *ameloration* play a key role.

The Woesian model extends rather than contrasts the evolutionary models of technological change : indeed, radical innovations[36] and possibly other cultural discontinuities can be explained through Horizontal Transfers *across* lineages while the concepts and methods for studying cultural Vertical Inheritance remain valid in studying incremental innovation, in which the processes of horizontal transfer are not so critical.

According to this extended model technological evolution is driven jointly by Vertical Inheritance and by Horizontal Transfer, interacting in a stylized feedback cycle that can be described as follows (Andriani and Carignani, 2013): the process begins when recombinable and exaptable functional modules are available to humans. Then two processes can take place:

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[36] Henderson and Clark (1990) sensu

1. Radical Innovation through Horizontal Transfer and Exaptation: functional modules composing other artifacts are recombinated by inventors. In this phase functional shift usually takes place, because the existing functions for which the modules were designed do not perfectly fit the new function. The invention harnesses natural phenomena (the storage of elastic energy in the case of the bow-and-arrow) through engineering creativity, but the engineering is fostered by the socio-technical environment (availability of *general purpose technologies* and tools, i.e. second order cultural traits) and exaptable modules. Horizontal Transfer is the signature evolutionary process;
2. Incremental Innovation, diffusion and diversification: if the socio-technical environment selects the novel artifacts (including their functional modules) they are reproduced for the new functions, sometimes creating a new industry in which their performances are improved through a process of engineering adaptation to the new function, beginning with technological *amelioration* of the transferred functional modules. This usually long phase is characterized by selection by users, coevolution with the changing social and cultural environment and engineering adaptation. Vertical Inheritance becomes the dominant evolutionary force as the novel architecture becomes the common ancestor of a tree-shaped cluster of technological *clades.*

The process generates not only new artifacts, but also new tools (higher-order cultural traits) and new functional modules which in due time can become *new general purpose technologies*, which in turn act as complex *replicators*. Since the new modules may exhibit new *behaviours* they can again be exapted: the inventors can discover new functions for them and recombine them in novel creative ways.

What emerges is the concept of radical innovations as *evolutionary chimeras*, which have no direct ancestors because their composing modules originate from different technological lineages, sometimes including functional shifts. A number of notable examples in the history of technology seems to fit this feedback cycle.

The digital camera, for one, can be considered an *evolutionary chimera*. It is a modular artifact in which one of the original key modules, the chemical film, was displaced by the CCD (Charge Coupled Semiconductor Device) imager, invented at Bell Laboratories in 1970 (Boyle and Smith, 1970). First used in astronomy and in other scientific applications, digital photography eventually invaded both the professional and the mass market of general photography, leading to the eventual extinction of chemical photography.

Technological evolutionary chimeras are often lead examples of ‘disruptive innovation’ (Christensen, 1997): this in particular applies to the case of the digital camera which all but destroyed the leading industry in traditional photography – Kodak - notwithstanding the fact that Kodak itself pioneered this innovation (Lucas and Goh, 2009).

Figure 5

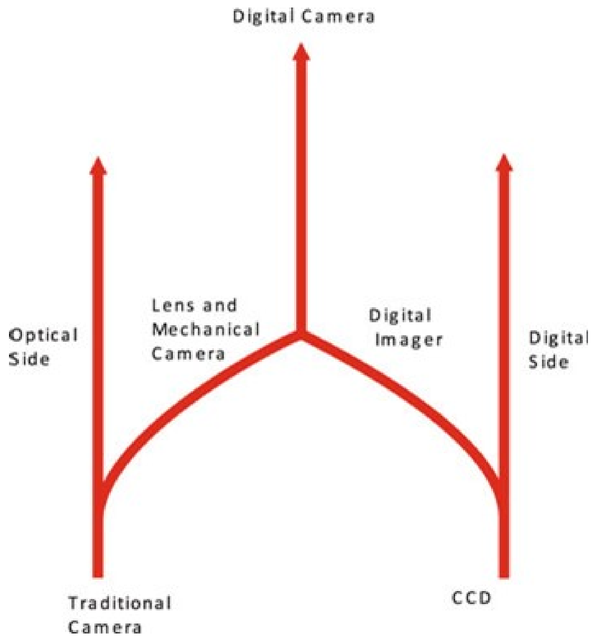

Figure 5. Digital Camera stylized phylogenetic graph. The evolutionary mechanisms and graph topology strikingly resembles those discussed about the bow-and-arrow origin.

Digital photography and the bow-and-arrow can be seen both as typical technological *evolutionary chimeras*, located at the extremes of human technological development, 64,000 years apart. The case of the digital camera can be described by a ‘philogentic graph’ (Figure 5) whose resemblance to that of the bow and arrow (Figure 3) is striking – and both exibit the very topological patterns shown by biological phylogentic networks. This seemingly common pattern of radical innovation is shared with other cases of radical innovation which can be found throughout the history of technology: the microwave oven (Andriani and Carignani, 2014), the bicycle (Bijker, 1995) or the already mentioned turbo-jet power plant (Constant, 1980), just to mention a few.

Two possible contributions emerge from the discussion:

First, the usefulness of *Horizontal Transfer* in understanding discontinuous innovation. As in many radical innovations seemingly marking a discontinuity, the underlying gradual process of evolution emerges when we consider as the unit of analysis not the whole artifact, which is an *evolutionary chimera* and thus has no history of its own, but its *functional module*s, transferred across different technological lineages.

Second, the proposal of an extended concept of *technological replicator*. A number of tools, manufacturing processes and procedures, and technological knowledge already available were necessary in supporting the development and diffusion of bow-and-arrows, cars, jet-propulsion power plants, microwave ovens, digital cameras. Mechanical precision tools, advanced alloys, radar technology, electronics and ICT played in different times the key role of the replicators that formal knots, strings and hafting had for the bow-and-arrow.

The conclusion, and main avenue of research suggested by this paper, lies in the potential impact that the extended theory could possibly have in evolutionary archeology and cultural evolution of the one hand, and on innovation science and innovation management on the other. In evolutionary archeology, and cultural evolution at large, the integration of Horizontal Transfer as an evolutionary force as powerful as Vertical Inheritance in a general theory of technological evolution should be seen not as a difficult on theory able to jeopardize current methods (Greenhill et al., 2009), but as a great opportunity. Indeed, embracing pattern pluralism (Doolittle and Bapteste, 2007) as a useful epistemic view of evolutionary archeology opens the way towards the borrowing from geneticists of novel powerful methodologies -some of them already available - to study technological (and cultural) reticulate evolution.

Conclusion: on the origin of technology

This paper investigated the origins of the bow and arrow under two perspectives: the bow and arrow as a cultural trait and the bow and arrow as a technological radical innovation. The two perspectives, of course, are not in contrast: technology is part of the cultural environment with which it coevolves. Nonetheless, it is often perceived as something different, because it has distinctive traits: technology obeys its own rules, derived by natural laws through creative engineering.

This paper is broadly oriented at reconciling and connecting the two perspectives: the bow and arrow was an invention originated by an engineering breakthrough made possible by the existence of previous modular artifacts, but its transformation into a full-fledged innovation and further diffusion would have been impossible without social learning and cultural co-evolution.

This also suggests some possible research opportunities also in innovation management: radical technological innovations are the clearest examples of Schumpeterian *creative destruction*. They often begin as inferior technologies, underestimated by the incumbent industries, which may later become *dominant designs*, displacing the existing technologies, with the potential of creating new markets and disrupting whole industries – in some cases, like in that of the bow-and-arrow, whole civilizations. Indeed, considering the sad story of many previously successful incumbents – from Hwoog to Kodak – hardly anyone will deny the importance of understanding the evolutionary forces able to generate new *evolutionary chimeras*.

But the story of the bow and arrow encourages also a multidisciplinary approach to innovation management, in that some answers to *management* dilemmas could lie in the knowledge of anthropologist and cognitive scientists rather than in that of economists and management scholars.

Indeed, the story of the bow-and-arrow suggests not only that technology should not be considered a brainchild of *Homo Scientificus* – we saw how bow-and-arrow technology predates science by some 60,000 years - , but also that it not generated by the selfish behavior of *Homo Economicus*, but deeply rooted in the very cognition and culture of *Homo Sapiens*.

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Evolutionary Chimeras: a Woesian Perspective of Technological Change[37]

Abstract

This paper proposes a novel perspective of technological change based on the 'Woesian' model of cell evolution to study technological change and in particular the origins of radical innovation. The biological model identifies horizontal gene transfer (HGT) as a critical process that drives evolution and complements the Darwinian theory of vertical inheritance. Our perspective highlights the key role of the horizontal transfer of functional modules in generating radical innovation, and unveils the striking similarities between biological and technological evolution. We use the turbojet revolution to illustrate the key features of the model and elucidate the conditions under which horizontal transfer is a crucial evolutionary process leading to radical innovation. We then elaborate on the implications of the model for how organizations should search for radical innovation and emphasize the role of a firm's *replicative capability*, i.e., the ability to 'replicate with modifications' existing functional modules integrating them into a novel architecture.

Key words: Horizontal Gene Transfer; Artifact; Functional Module; Modularization; Technological Evolution; Radical Innovation; Exploration/Exploitation; Mirroring Hypothesis; Replicative Capability; Turbojet Revolution.

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Introduction

The turbojet was the most important innovation in aviation history since the Wright Brothers, with consequences so profound “to be acclaimed by pundits as an ‘age’ – the ultimate accolade of successful technological revolution” (Constant, 1980, p. 1). The innovation marked the transition from propeller-driven to jet-driven aircraft, revolutionizing first the aero-engine industry, and later the whole aviation industry (military, civil and general aviation) with a cascade effect in the travel and tourism industry, extending to the social realm – igniting the so-called jet age. The turbojet revolution is an iconic and well-documented case of radical innovation: its inception in aero-engines is the quintessential example of paradigm change because all the distinctive events and processes marking the emergence of novel technological trajectories can be recognized in historical records. Accordingly, historians of technology and management scholars have investigated the case extensively. Surprisingly though, the inception of the turbojet revolution remains controversial among aviation historians.

Two conflicting perspectives – continuity vs. discontinuity – are still debated. In his seminal book, for instance, Constant (1980) argued in favor of the discontinuous nature of the turbojet revolution, while acknowledging the “contradictory” fact that “the turbojet is heir of two centuries of turbine development” (p. 3). Recently, however, in a carefully documented study that incorporates new evidence from primary archival sources, technology historian Hermione Giffard advocates for the continuous nature of the turbojet revolution: “contra Constant, who emphasized the revolutionary nature of the new power plant, I emphasize the deep structural and institutional continuities between piston engine and jet engine development” (2016, p. 9). The most influential historians who studied the turbojet revolution in the past are equally split between these two positions. For instance, in a book written shortly after the introduction of the turbojet, Schlaifer and Heron (1950) embraced the *institutional continuity* perspective – recently championed by Giffard – and included first-hand interviews in their account of the revolution. Most scholars subsequently abandoned this position in favor of the discontinuous nature of the turbojet revolution. Several influential management scholars have also examined the turbojet revolution and exposed its implications for technological evolution (e.g., Tushman and Anderson, 1986). Yet, the origins of the revolution, which ignited a new technological trajectory and ushered in the emergence of a new technological paradigm (Dosi, 1982), are not explicitly discussed in management studies that usually take for granted Constant's historical account.

In contrast with Constant, Basalla (1988) proposed an artifact-centered perspective and argued for continuity in the evolution of artifacts, including the turbojet. He also criticized the one of the crucial assumptions that underlie Constant's explanation: that technology is "primarily knowledge" (Basalla, 1988, p. 29). In Basalla's opinion, the artifact (including the knowledge and the tools necessary for producing it) is the fundamental unit of analysis.[38] Despite recognizing the artifact as being central to technology and technological evolution, however, Basalla (and most of the literature after him) falls short of explaining how 'continuity' is substantiated in radical innovation through historically documented micro-processes. He invokes instead the existence of intractable disanalogies between biological and technological evolution. As we shall see, the turbojet revolution could be described as a case of *recombinant innovation* – since the recombination of existing components was clearly the main mechanism behind it. However, the recombination process is merely a description of what in fact took place and so it does not elucidate the reasons of the success of a particular architecture over many others that were designed and prototyped during the long inception of the revolution. Indeed, in his seminal book Constant felt the necessity of proposing a general, *tentative* (1980, p. 6), model that has been tacitly accepted by most scholars since then. Unfortunately, this model is not supported by recently discovered historical evidence (Giffard 2016).

In light of this new evidence, which unveils the crucial role of other evolutionary mechanisms whose importance was unknown to both Basalla and Constant, this paper proposes an evolutionary model of technological change, and particularly radical innovation, based on the

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[38] Dosi and Nelson (2013) recognize the complex nature of technological knowledge (including artifacts) emphasizing how it can be described as "a set of pieces of knowledge, both directly 'practical' … and 'theoretical' … know-how, methods, procedures, experiences of success and failures and also, of course, physical devices and equipment" (pp. 151-152).

‘Woesian’ model of cell evolution (Woese, 2002, 2004). This model complements the Darwinian evolutionary theory by suggesting horizontal gene transfer (HGT) as the fundamental process driving cellular evolution. According to Darwin (1859), biological evolution follows a bifurcating evolutionary process whose branches are the result of descent with modification—through vertical gene transmission or inheritance—from a common root or ancestor, as represented by the so-called ‘Tree of Life.’ It is today recognized that descent with modification is but one of the possible transmission processes, and a tree-like evolutionary pattern is an incomplete representation of biological evolution, which itself exhibits a reticular structure (Bapteste *et al*., 2004). Recent findings in comparative genomics (Gogarten and Townsend, 2005) have further validated the ‘Woesian’ model of cell evolution by showing how HGT and vertical inheritance are both at work in biological evolution. By explicitly considering the horizontal transfer of functional modules, a Woesian model sheds new light on historical facts, including the recent historical sources discussed by Giffard (2016). As we shall see, the model helps reconcile discontinuous and continuous perspectives of technological change, but also provides the opportunity to revise the incipient phase of other radical technological innovations. In this sense, the model complements, but also extends, extant models of technological evolution.[39]

Our primary concern in this paper is with radical innovations that originate from the horizontal transfer of functional modules across distinct technological lineages or trajectories. Following

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[39] Arthur (2009) acknowledges HGT as a mechanism capable of *“creating novel things by combinations of themselves”* (p. 187), but does not regard HGT as a possible foundation of a novel analogy because “*combination (at least for higher organisms) cannot select pieces from different systems and combine these in one go*” (p. 187). We concur with Arthur that simple recombination of functional modules cannot produce ‘*higher*’ organisms (those complex organisms that biologists acknowledge as eukaryotes), yet it can give rise to less complex organisms like bacteria, which sometimes can be viewed as *chimeras* because they result from the assemblage of functional modules with different origins. HGT has been shown to occur massively in bacterial life, representing both a highly significant process and a major evolutionary force in cell evolution (Lawrence, 1999; Koonin *et al*., 2001; Kreimer *et al*., 2008).

Henderson and Clark (1990), by ‘radical’ innovation we mean an innovation that “establishes a new dominant design and, hence, a new set of core design concepts embodied in components that are linked together in a new architecture” (p. 11). This type of innovation often leads to the creation of a new market or even an entirely new industry (e.g., Garcia and Calantone, 2002). We use a well-known and richly documented case of radical innovation – i.e., the introduction of the turbojet – to illustrate the significance of the horizontal transfer of functional modules as a crucial evolutionary process leading to radical innovation. By mapping functions to (horizontally transferred) modular components, the model also clarifies why modularization is “an evolutionary process that is pursued and gradually advanced, but never fully completed, rather than an architectural property that is set as a design goal, achieved, and stabilized” (MacDuffie, 2013, p. 11).

The paper is organized as follows. In the next section, we briefly review extant evolutionary models of technological change that have discussed radical innovation. We then introduce the Woesian model of cell evolution and elucidate its basic evolutionary processes: vertical inheritance and horizontal gene transfer. Next, we present our model and use the turbojet revolution to illustrate the key features of the model and expose the new insight from applying this model to explaining such an iconic case of radical innovation. We then elaborate on the implications of the model for how organizations should search for radical innovation and emphasize the role of a firm’s *replicative capability*, i.e., the ability to ‘replicate with modifications’ existing functional modules integrating them into a novel architecture. We conclude by summarizing the main contributions of the study and delineating possible viable directions for future research.

Theoretical Background

Extant Models of Technological Change

Given our focus on (modular) radical innovation, in this section we review two models of technological change that have received considerable attention in the innovation and technology literature: the punctuated equilibrium model of technological change and the model of technological speciation. Both models look at technological change but through different theoretical lenses. The punctuated equilibrium model describes the technology life cycle as characterized by periods of incremental innovation that are punctuated by sudden bursts of radical innovations (e.g., Abernathy and Utterback, 1978; Mokyr, 1990; Tushman and Anderson, 1986). Although radical innovations are rare events, their occurrence marks the beginning of a period of technological ferment during which alternative technologies and product forms compete for dominance.

This sustained phase of experimentation and competition usually ends with the emergence of a new dominant design, that is, a design that reflects product-class standards (Abernathy, 1978; Utterback and Abernathy, 1975; Sahal, 1981). Radical innovations can be either competence-destroying or competence-enhancing depending on whether "they destroy or enhance the competence of existing firms in an industry" (Tushman and Anderson, 1986, p. 442). Innovations are competence-destroying when they require new skills and knowledge base, and competence-enhancing when they build on existing skills and knowledge base within a product class. Yet, while exposing the consequences of radical innovations, the punctuated equilibrium model does not completely clarify their origins nor does it expose the specific mechanisms that propel such innovations.

Understanding the genesis of radical innovations requires a careful examination of the underlying micro-processes and forces leading to them. Focusing on these processes and forces would reveal how the belief that certain innovations stem from revolutionary upheavals in technology can be attributed instead to a loss or concealment of crucial antecedents. As Basalla (1988, p. 30) puts it, "key artifacts – such as the steam engine, the cotton gin, or the transistor […] illustrate the evolutionary hypothesis despite the fact that initially they appear to be excellent candidates for use in supporting the contrary discontinuous explanation." For instance, Tushman and Anderson (1986) offer a very insightful analysis of the impact of a technological discontinuity – e.g., the turbojet revolution – on industry incumbents and new entrants, but do not discuss the more micro level processes and forces responsible for that discontinuity. As we shall see, the origins of several radical innovations such as the turbojet can be traced to the horizontal transfer of functional modules across different technological lineages. Explicitly accounting for the functional shift of existing modules makes "the abrupt appearance for radically novel technologies suddenly seem much less abrupt" because these technologies "somehow must come into being as fresh combinations of what already exists" (Arthur, 2009, p.

19). This explains why, for instance, the turbojet was not a competence-destroying discontinuity at least for some aero-engine manufacturers.

Extant studies on technological speciation (Levinthal, 1998; Adner and Levinthal, 2002; Cattani, 2006), on the other hand, emphasize how a new technology often emerges from the re-deployment of a firm's skills and knowledge base into a new application domain. From this perspective, even radical innovations originate from existing skills and knowledge base. These studies, however, insist on the role of the selection criteria (user needs and performance requirements) of this new domain as a necessary condition for a speciation event to occur. Probing the interaction with the environment is important for understanding how new technologies develop and come to commercial fruition after they are invented. Current research on technological speciation, in fact, mainly focuses on the phase when an existing technology adapts to the selection criteria of a new application domain, but does not explain how the functional shift of this technology (or any other artifact) comes about and the mechanisms triggering that shift. Identifying the determinants of a radical innovation, therefore, requires a finer grained investigation of the micro-processes and evolutionary forces responsible for its emergence (Cattani, 2006).

To this end, we propose a model of technological change that is based on the 'Woesian' model of cell evolution to study the origins of radical innovation (Woese, 2002, 2004). The notion of *artifact* is central to our model (Arthur, 2009; Basalla, 1988). We chose the artifact not only as the primary unit of the study, but also as the principal evolving entity, the object of selection, and the technological counterpart of the organism in the biological domain. From Darwin to the present day, most evolutionists have considered the individual organism to be the principal object of selection (for a comprehensive review, see Mayr, 1997).[40] The choice of the artifact as the analogue of the organism may seem not only natural but even naïve. Yet strong reasons support the artifact as the primary unit for studying technological change. In particular, the

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[40] As Mayr (1997) pointed out, however, this does not mean consensus among evolutionists: "Even though most evolutionists agree that the individual organism is the principal object of selection, there is great dissension about also accepting as the object of selection the lower or higher levels in the hierarchies of the living world" (p. 2091).

“artifact—not scientific knowledge, nor the technical community, not social and economic factors—is central to technology and technological change” (Basalla, 1988, p. 30). Although the artifact is the primary unity for studying technological innovation, typically it consists of several interdependent components that, consistently with technology scholars (e.g., Ulrich, 1995) and evolutionary biologists (e.g., Wolf and Arkin, 2003), we call *functional modules*. Focusing on the horizontal transfer of functional modules uncovers the evolutionary origins of what might appear as a technological discontinuity. Indeed, in many cases of radical innovation – e.g., fiber optics (Cattani, 2005, 2006), the bow and arrow (Carignani, 2016; Lombard and Philippson, 2010), the microwave oven (Andriani and Carignani, 2014), digital photography (Lucas and Goh, 2009) – the functional modules that were initially recombined were horizontally transferred across different technological lineages. This point has important implications for the type of search behavior that might be conducive to the generation of radical innovation.

By choosing the artifact as the object of selection, the physical artifact is the natural *interactor*, i.e., the entity that “directly interacts as a cohesive whole with its environment in such a way that replication is differential” (Hull, 1980, p. 318), while the knowledge embodied in the transferred functional module is the *replicator*, i.e., the entity that “passes on its structure directly in replication” (Hull, 1980, p. 318). Keeping these two levels distinct helps explain why efforts to reproduce and/or improve on existing artifacts may or may not be effective. For instance, the exact reproduction of stringed instruments made by Cremonese masters (e.g., Antonio Stradivari and Guarneri *del Gesù*) would require complete knowledge of their production methods and techniques (Cattani, Dunbar, and Shapira, 2013). As detailed written records of how to make stringed instruments were not kept, the masters passed their knowledge on to their apprentices through close and daily interactions that typically spanned several years. This (largely tacit) knowledge cannot be resurrected simply through reverse engineering. While the interactor (the actual instrument) is available, the replicator (the knowledge embodied in it) is no longer fully available. In the following section, we offer a brief technical description of the Woesian model of cell evolution, discuss the impact of HGT in bacterial evolution, and define the basic concepts upon which the model is built.

Models of Bacterial Evolution

Evolution is the result of two essential forces: *variation* and *selection* (Baquero and Cantón, 2009; Bell, 1997). Variation represents the substrate of evolution and refers to the force providing material in the evolutionary processes. Selection represents the mechanism of evolution and identifies the force by which evolution is able to adapt genetic innovation to environmental needs in the organic world. According to the traditional Darwinian theory of evolution (Darwin, 1859), variation provides innovation in the evolutionary processes by random mutation in the genotype (replicator) (Table 1). The organism carrying the mutation displays it as phenotype (interactor) (Table 1). If it better fits the present environment, it is then selected, and so it can transmit the variation to its descents through vertical transmission or inheritance (VT). This is true, though not the entire truth, in the bacterial world because most determinants of this variation are not based on simple mutations, but on a sort of information reshuffling through horizontal transfer of parts of the replicator, henceforth referred to as *modules* (Ganfornina and Sanchez, 1999). As these modules impart new and consequential functions, they are called *functional modules* (Wolf and Arkin, 2003) and the process behind their transfer is called *horizontal gene transfer* (HGT; Syvanen and Kado, 2002).

Until two decades ago, evolutionary biologists were hesitant to invoke HGT as an explanation for the variation prompting evolution in bacteria. Then, different cases were identified in which vertical transmission, and the resulting phylogenetic bifurcating tree (Table 1), was not sufficient to explain evolution (Gogarten and Townsend, 2005). Acquisition and dissemination of antibiotic resistance (Table 1) among human and animal bacterial pathogens (a biological agent that causes disease or illness to its host) are probably the most paradigmatic, well-known, and exciting examples of HGT as the driving evolutionary force in the bacterial world (Baquero and Canton, 2009; Mazel and Davies, 1999). The massive option for therapies based on antibiotics during the last fifty years has faced a severe efficacy loss due to the progressive appearance of new resistant bacterial populations. That was the result of the response of different bacterial ecosystems to the diffusion of large amounts of toxic agents, i.e., antibiotics in the biosphere. This is the best known example of very rapid adaptation of bacterial populations to strong selection pressures. How did bacteria develop the new function (i.e., resistance to antibiotics)? This new function was transferred across lineages via HGT instead of being generated through mutations within each lineage (Baquero and Canton, 2009).

This example points to a multi-stage process of evolution (Eisen, 2000) where two main evolutionary forces interact: HGT and VT (Figure 1). Usually, bacterial cells generate and accumulate variation through random mutations within a population, identified as a lineage. At some point, a functional module is randomly transferred from one bacterium to another via HGT (the *acquisition* stage), regardless of their lineage. After the transfer, the functional module must be maintained in the recipient cell (the *retention* stage, where a recombination event takes place to allow the retention). Only if retention is successful, can the recipient cell display the new retained module, which undergoes a strong *selection* phase that is niche-dependent. If selected, the new module spreads across the bacterial population, creating a lineage that is generated through replication of the recipient cell (the *fixation* stage). While spreading, the new module also adapts (or exapts) by accumulating mutations through VT in order to properly function within its interactor (the *amelioration* stage). In this process, the basic building block of evolution is the functional module and HGT is the evolutionary force that prompts variation. Before going deeper into these key aspects of the new evolutionary model, we briefly describe the Woese's model of cell evolution.

Table 1 – Definition of Key Biological Constructs

Genotype – It is the organism’s full information which can be inherited, i.e., replicated and passed on to the next generations.

Phenotype – It is the organism’s actual observed properties and functions, such as morphology or development.

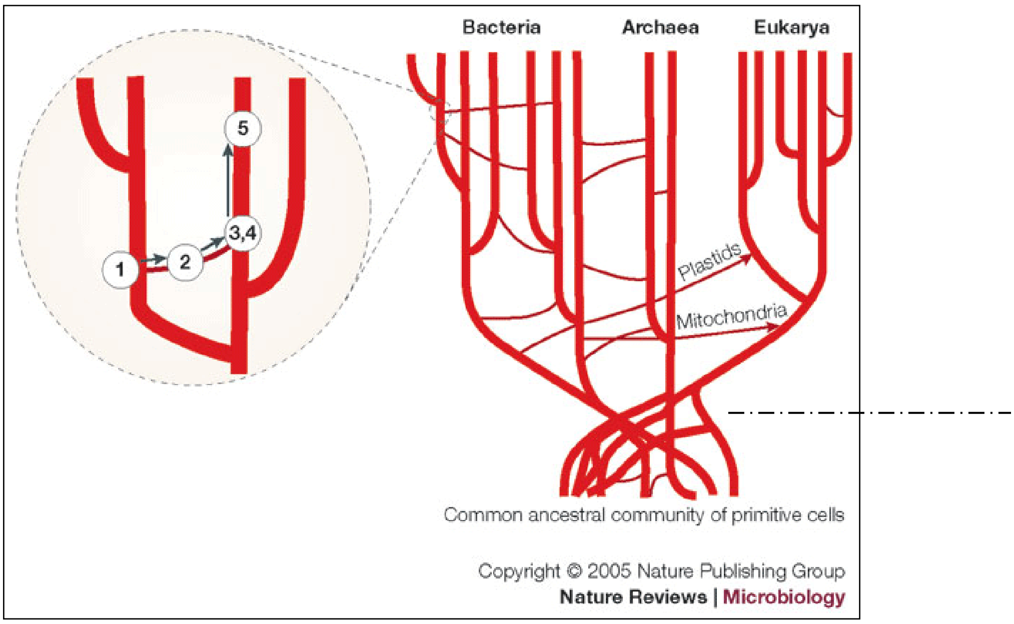
Phylogeny – It refers to the origin and evolution of a group of organisms, usually a species. It is commonly used to describe a pattern (a phylogenetic tree) of genealogical relationships between species, understood as a succession of bifurcations. It is typically represented through the metaphor of a ‘tree’ that shows the history of all living and extinct organisms.

Antibiotic resistance – Function of a bacterial cell that preserves it from the disruption caused by the antibiotics, a pharmaceutical drug.

Common ancestor – A single organism (genome) from which all contemporary organisms (genomes) in a particular group descend.

Eukaryote – Organism made of eukaryotic cells, i.e., cells with replicator contained within a compartment called nucleus. Different from bacterial cells in which the replicator is free within the cell, without structures enclosing it.

Figure 1 – Current Representation of Evolution: Vertical Transmission (VT) and Horizontal Gene Transfer (HGT)



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Left: Stages of bacterial evolution from horizontal transfer and retention (1 and 2), through selection and fixation (3 and 4) to amelioration by vertical transmission (5).

Right: Representation of the Woesian model of evolution; the dashed line shows the critical point when the common ancestors established themselves between the fluid phase with rampant HGT (below the line) and the following speciation phase with massive VT (above the line) – reproduced from Smets and Barkay (2005).

The Woesian Model

In the modern synthesis of the Darwinian view, evolution has been synthesized as descent with modification through inheritance and represented by a bifurcating tree, the so-called "Tree of Life" (Darwin, 1859). In the early 2000s, microbiologist Carl R. Woese (2002) speculated that a natural hierarchy might not extend into the bacterial world, which embraces perhaps two-thirds of the biota and the first two-thirds of life's history. In his two influential articles, Woese (2002,

2004) advanced a model of evolution – still rooted within the Modern Synthesis (Mayr, 1993) of the Darwinian theory of evolution – in which he expressed his concern about bacterial evolution and the traditional Tree of Life. According to his model (Figure 1), bacterial cells – the only living organisms at the very beginning of life – freely exchanged parts of their replicators, i.e., functional modules, in a common pool via HGT. The result was the assemblage of functional modules with different origins in the same organism, that Woese called an *evolutionary chimera* (Woese, 2002).

During this *fluid phase*, the high level of novelty that cell designs needed to evolve was a product of *communal* invention via horizontal transfer and recombination of functional modules rather than intra-lineage variation. That led to a high number of successful radical changes in the bacterial communities, which then evolved rapidly. In that scenario, massive HGT caused the expansion of the (genetic) information beyond species boundaries, making it impossible for individual species to emerge. So, at that time speciation was impossible. As organisms became increasingly complex and their *common ancestor* appeared (Table 1), evolution reached a critical point defined by a switch from a rampant horizontal transfer to a massive vertical inheritance. After the establishment of the *common ancestor*, organisms mainly ameliorated by vertical inheritance of modifications that led to incremental rather than radical changes within lineages. During this phase speciation became an important event. Horizontal transfer of functional modules across lineages continued to occur producing radical changes, as shown in the recent example of antibiotic resistance (Baquero and Canton, 2009; de la Cruz and Davies, 2000). Here, the small event of a module transfer had a great effect on the bacterial lineage created by the successful recipient cell, allowing it to survive despite the antibiotic attack and to spread, giving rise to a new niche.

In the last few years, several studies of bacterial replicators have supported Woese's conjectures on cell evolution (Bapteste *et al.*, 2004; Doolittle and Bapteste, 2007; Gogarten and Townsend, 2005). These studies confirmed that HGT remains a critical evolutionary force in producing novelty in a rapid way, even after the *common ancestor* appearance, and this turned out to be true not only among bacterial cells (Gogarten and Townsend, 2005; Koonin *et al.*, 2001), but also between bacterial cells and eukaryotes (Smillie *et al.*, 2011; Brown, 2003), and within eukaryotes (Bock, 2010; Keeling and Palmer, 2008) (Table 1). Nowadays evolutionary biologists (Bapteste *et al.*, 2004; Doolittle and Bapteste, 2007; Gogarten and Townsend, 2005) argue that a descent with modification through vertical inheritance is only one of the possible processes prompting evolution, and a single tree-like pattern is not the expected result when different evolutionary processes co-exist (Figure 1). The implication is that biological evolution exhibits a *reticulate* structure better represented by a *phylogenetic network* (Theobald, 2010), similar to that observed in cultural evolution in general and technological evolution in particular (Solé *et al*., 2013). This is consistent with the recognition among technology historians (e.g., Basalla, 1988, p. 138) and cultural anthropologists (e.g., Kroeber, 1948, p. 260, Figure 18) that technological evolution and, in general, cultural evolution is reticulate. By emphasizing the reticulate nature of evolution, whose natural representation is a phylogenetic network rather than a phylogenetic tree, therefore, the 'Woesian' model resolves what was once considered a critical disanalogy (Ziman, 2000, p. 5).

Key Concepts: Horizontal Gene Transfer, Modularity and Function

In general, HGT describes the process whereby a recipient organism acquires information from a donor organism (for a review see Syvanen and Kado, 2002). This is clearly distinct from the inheritance by descent in which information travels vertically across generations. The use of 'transfer' instead of 'exchange' indicates that an organism can be either the recipient or the donor as HGT does not involve reciprocal simultaneous exchanges of information. Also and more important, even if HGT is referred to simply as 'gene transfer' (Eisen, 2000), what is transferred is a part of a replicator containing a cluster of genes, single genes, or a part of it—which Wolf and Arkin (2003) refer to as *genetic functional modules* as they are associated with a specific function. The evolution of antibiotic resistance in bacterial cells suggests that the acquisition of the functional module into the recipient cell does not ensure successful HGT, unless the transferred material is stably incorporated and maintained in the recipient cell (retention). This is the key condition for the functional module to be replicated and eventually selected if useful for the organisms, allowing the fixation phase.

By recognizing the role of HGT in evolution, the concept of (genetic) functional module (Wolf and Arkin, 2003) becomes a crucial building block of the Woesian model. Like the concept of species in the case of vertical inheritance, the concept of functional module is now regarded as one of the main organizing principles from unicellular bacteria to pluricellular eukaryotic organisms. Woese himself noticed that when HGT is a major evolutionary force, the structure of organisms "is necessarily modular" (Woese, 2002, p. 8746). The biological modules are any kind of repeated, preserved cohesive genetic entities that are loosely coupled (Pereira-Leal, Levy, and Teichmann, 2006) and have discrete functions that arise from interactions among their components, namely proteins and small molecules. Specifically, embedding "particular 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, p. C48). The presence of modules associated to a function that can be transferred and reshuffled by HGT represents a powerful evolutionary force that produces variation within the time of 'one single generation' and acts as a source that can rapidly introduce innovation to the organism without waiting for the descent generations. When the transfer concerns one or few unrelated functional modules, the innovation imparts a new function to the organism, and if successful, have a great impact on the rapid spread of the organism itself and its colonization of a new niche (Goldenfeld and Woese, 2007; Ochman, Lawrence, and Groisman, 2000; Woese and Goldenfeld, 2009), as in the example of the antibiotic resistance. In some cases, the acquisition and retention affect a number of modules with different functions, and the resulting innovation is not simply the sum of the different functions, but a *superfunction* like in the case of the acquisition of pathogenicity by not-virulent bacteria (Hacker and Kaper, 2000). The superfunction is associated to a module of higher level, composed of the recombined modules, the so-called pathogenicity islands in our example. Having outlined the main features of a Woesian model and the key concepts on which it is built, the next section expounds on the implications of this model in the technological domain.

A Woesian Model of Technological Change

This section presents a model of technological change that builds on the artifact-centered perspective of technological evolution pioneered by Basalla (1988). The departure point from this perspective is that in our conceptualization the modular nature of the artifact is explicitly recognized: we propose the functional module as the evolutionary entity that can be transferred across technological lineages, not as a broad, metaphorical concept, but as a deep, complex analogy with biological evolution. The horizontal transfer of functional modules can thus be seen as the 'missing' process necessary to integrate Darwinian 'descent with modifications' and so elaborate a perspective of technological change, where both incremental and radical innovation can be explained on evolutionary grounds. After discussing the concept of *functional module* as a formal construct, we describe the five-stage Woesian evolutionary model first in abstract terms and then through an analytic narrative of a paradigmatic and controversial case of radical innovation: the turbojet revolution.

Functional module. The concept of (genetic) *functional module* (Wolf and Arkin, 2003) and its technological analogue is a crucial building block in our evolutionary model. In line with the definition of functional module in biology (see previous section), we define a *technological* functional module as a component of a modular artifact that is: a) internally cohesive; b) clearly separated from the other modules by a boundary; c) associated to a single function or a set of functions. While the concept of modularity is general and in principle applies to any complex system (Simon, 1962), our interest here, and so the *scope* of this definition, is limited to technological functional modules as analogous to biological functional modules, i.e., the components of organisms.

The concept of function in technology. The concept of function is natural in the technological domain because it is related to the design of artifacts, which is defined as "the process of inventing things which display new physical order, organization, form, in response to function" (Alexander, 1964, p. 1). Accordingly, Ulrich (1995) views a modular product architecture as a scheme in which each component (module) is associated with a very specific single function. In contrast, Baldwin and Clarke (2000) explicitly refuse to ground their definition of modularity on functions because, in their conceptualization, functions "are inherently manifold and nonstationary" while their definition of modularity is based "on relationship among structures, not functions" (see footnote 2 on p. 63 of their book). We posit that our definition of modules based on *functions* is not in contrast with a definition based on *relationships* among structures: behind each cellular function there is a biological network or biological structure that is based on modules consisting of many types of *interacting* molecules (Barabási and Oltvai, 2004). Upon closer inspection, also the '*nonstationary*' character of a function does not pose a critical theoretical challenge because it subsumes well-known processes: the evolutionary concepts of preadaptation (Cuenot, 1914) and exaptation (Gould and Vrba, 1982), both of which have been acknowledged as important forces in biological (e.g., Bock, 1959; Ganfornina and Sanchez, 1999) and technological (e.g., Andriani and Cattani, 2016; Cattani, 2005, 2006; Dew, Sarasvathy, and Venkataraman, 2004) evolution. In our definition of technological functional module, we embrace the evolutionary concept of function in biology that is based on selection rather than purpose: “the proper function of an item is to do whatever it was selected for” (Neander, 1991, p. 173).[41] Framed this way, our construct of functional module is based on semantic *relations* rather than *attributes* – a condition that theoretically supports complex analogies according to structure-mapping theory (Gentner, 1983): the artifact is *made of* functional modules, and each of them, at any level, is *associated to* a function. There is, therefore, a structural mapping between the bacterial and the technological domain that is the basis on which the five-stage process of technological change is coherently based.

It is worth noting that horizontal transfer of functional modules is strictly connected with the concept of ‘modular operator’ discussed in Baldwyn and Clark (2000), particularly ‘augment’ (adding a module that was not part of the system before) and ‘porting’ (create a shell around a module so that it works in systems other than one for which it was initially designed). Although, at first glance, modular operators seem to describe what we define as horizontal transfer, substantive reasons justify why one should keep them distinct. First, the modular operators have a prevalent descriptive and taxonomic objective. Indeed, Baldwin and Clark emphasize that they regard their list of modular operators as “the beginning of a useful taxonomy” (2004, p. 192). On the contrary, we frame the horizontal transfer of functional modules into process in which the explanatory and causal aspect are central. One thing is to argue that technologies move across domains and their nesting in new architectures enhances pre-existing functions into novel products, a different one is to precisely show how and when (under which conditions) this transfer causes the emergence of radical innovations. Second, horizontal transfer has a complex evolutionary meaning that is not captured simply by ‘porting’ nor by any other modular operator. While not the focus of our paper, horizontal transfer could qualify as a novel complex ‘modular operator’ in which recombination generates a novel higher-level superfunction (as

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[41] For a detailed discussion of an appropriate definition of function in technology see also Andriani and Carignani (2014).

discussed in the previous section on key concepts in evolutionary biology) through the required acquisition and retention phases.

A Five-Stage Evolutionary Model of Technological Change

We have argued that the artifact – which consists of a set of functional modules – is the object of selection, the counterpart of the organism. Functional modules can be transferred horizontally between diverse technological lineages.[42] Many technological artifacts can thus be seen as *evolutionary chimeras* because they are composed of functional modules with different origins (e.g., aero-engines from turbines, burners and compressors), not from modules of 'parent' artifacts from which they descend through some form of vertical inheritance. Having defined the conceptual building blocks of our model, we describe now the five stages through which technological change unfolds. For the sake of clarity, we present them sequentially, though they may overlap and persist even when a new stage begins. These stages, which mirror those of the Woesian model of cell evolution, are:

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[42] The construction of the Britannia Bridge is instructive (Vincenti, 2000). Built across the Menai Strait (UK) in 1845–1850, this railway bridge has been regarded as a unique case of radical innovation in bridge engineering. A more careful historical analysis, however, reveals that a functional module (the 'horizontal iron tube') was responsible for this apparent radical innovation. This functional module was transferred from naval engineering to steel bridge construction. Thus, what initially seemed to be a discontinuity—a radical innovation without an evolutionary history—actually is an evolutionary chimera, in which a functional module (a 'replicator' in the form of blueprints and engineering expertise) was horizontally transferred and 'ameliorated' – i.e., subsequently adapted to the new context (bridge building). Another, more recent, example of horizontal transfer across different industries is the use of Li-ion battery cells in the form developed for the cell-phone industry (18650 form factor) to the Tesla Roadster, a radically innovative all-electric sport electric car (Berdichevsky *et al*., 2006).

- **Acquisition:** a new artifact originates from recombining functional modules from a pool of existing modules. The pool results from module variation within and across different technological trajectories.
- **Retention:** the novel chimeric artifact demonstrates its functioning and, therefore, can be successfully replicated generating an identical or ameliorated functioning copy.
- **Selection:** the novel functioning artifact is selected for an existing or a new niche. The selection is due to a new superfunction (i.e., a function associated to a module of higher level, consisting of the recombined modules), which improves the performance required in that niche.
- **Fixation:** the novel artifact diffuses from the initial niche and colonizes other niches.
- **Amelioration**: the recombined functional modules adapt to one other, thus improving the performance (fitness) of the chimeric artifact under the selective pressure of the niches into which the artifact diffuses.

The previous five-stage evolutionary model extends, but does not contradict, the variation-selection-retention model generally adopted in evolutionary theorizing (e.g., Aldrich, 1999; Campbell, 1975; Nelson and Winter, 1982). The model reveals the centrality of horizontally transferred functional modules – whose new function can differ significantly from the original one – for the retention, selection and subsequent improvement (amelioration) of a new artifact.

Research Design

Our case analysis focuses on the invention of the turbojet, which – as an alternative to the reciprocating internal-combustion engines, the established and widespread approach for powering aircraft – had a major impact on military, civil, and general aviation. Indeed, an industry that had grown with propeller-driven planes had "to come to grips with the idea of throwing away the propeller and piston engine and replacing them with a propulsion system that worked on completely different principles" (Pool, 1997, p. 59). Yet, despite its promise, the turbojet was not the inevitable result of prior systems but rather the culmination of a process of technological change, which required the "prior successful co-evolution of piston aero-engines and streamlined airframes" (Constant, 1980, p. 241). We use an historical approach to examine the interplay between contextual events, technological developments, and efforts by both existing organizations and individual inventors in shaping the turbojet revolution. The adoption of a historical case method is appropriate to analyze a rare event which displays complex dynamics and context-specific meanings (Hargadon and Douglas, 2001; Cattani *et al.*, 2013); it also allows for the necessary distance needed to observe how the complex interplay between the forces and actors involved unfolded over time (Kieser, 1994). By analyzing the introduction of a new revolutionary technology, we can understand how it was effected; who did what and why; what political, social and institutional reactions the new technology provoked; and how, why, and to what extent it gained acceptance.

Our historical analysis is based on turbojet histories and archival documents. Several bibliographical sources and publications, from classic authoritative references (e.g., Constant, 1980; Schlaifer and Heron, 1950) to more recent contributions that shed some new light on the origins of the turbojet (e.g., Pool, 1997; Giffard, 2016), as well as original archival sources (Griffith, 1937) describe the invention of the turbojet in great detail and offer important contextual information. The availability of archival sources was critical because it gave us the opportunity to examine the key steps and decisions shaping the invention of the turbojet through the eyes of those involved, as well as to identify precisely when those steps occurred and how those decisions were actually made, so reducing significantly the risk of retrospective sense-making.

We present here a stylized account of the inception of the turbojet revolution in the form of an artifact-centered narrative. The Turbojet Revolution spanned a period of about thirty years (1930-1960) and saw the involvement of most industrial countries (including the UK, the US, Germany, Italy, and the Soviet Union). However, since we are interested in understanding the transition trajectory which led to the new paradigm, we focus on the long 'presumptive anomaly'[43] (over the 1922-1939 period) that came to an end when the first turbojet-powered airplanes began to fly. Moreover, we discuss the origins of two families of turbojet engines – the turbojet and the turboprop – and two firms – Rolls Royce and General Electric – which emerged as the true winners and are still major manufacturers of turbojets.[44] Our goal is to use this historical material to illustrate and sharpen our Woesian model of evolution, not to provide an empirical test of it. In this sense, we employ the turbojet case as an inspiration for new understanding. We have bracketed the key events and decisions shaping the turbojet revolution into a chronological narrative of successive periods, which mirror the five stages of our evolutionary model.

In the following section, we focus on the early evolutionary phase of the turbojet revolution and show how during this initial fluid phase the 'pure' turbojet architecture was but one among a large number of potentially viable re-combinations that could have marked the transition from propeller-driven to jet-driven aircraft. We then describe the five evolutionary stages through which technological change unfolded and how the re-combination of horizontally transferred preadapted modules were retained, selected and ameliorated or improved over time.

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[43] The concept of *presumptive anomaly* was first introduced by technology historian Edward Constant (1980). According to Constant, a technological presumptive anomaly occurs "not when the conventional system fails in any absolute or objective sense, but when assumptions derived from science indicate either than under some future conditions the conventional system will fail (or function badly) or that a radically different system will do a better job" (Constant, 1980, p. 15). Constant's theory ostensibly draws from Kuhn (1970) as he adopts the Kuhnian concept of anomaly as the origin of scientific revolutions. The resemblance between the 'presumptive anomaly' preceding the Turbojet Revolution (circa 1921-1937) and the state of the semiconductor industry at the end of the Moore's law has been noticed by several scholars (e.g., Khan *et al*., 2016).

[44] The development of the German turbojet can also be described in evolutionary terms through our model following the five-stage process, but was driven by different selection criteria (Giffard, 2013)

Reframing the Turbojet Revolution

The Origins of the Turbojet Revolution: The ‘Pure’ Turbojet Concept

The so-called ‘pure’ turbojet – which initiated the Turbojet Revolution and dominated its early period – is a modular artifact whose core is based on three functional modules, namely a compressor, a combustor and a turbine (Figure 2). Its functioning, in principle, is remarkably simple: the compressor-turbine rotor is maintained in motion through the energy provided by the hot gases energized by the burner (or combustor), flowing through the turbine. As more fuel is added to the combustor, the speed increases and excess ‘gas horsepower’ is generated – so providing the propulsion force (thrust) when exiting through the jet pipe and nozzle. This recombination is called the ‘pure’ turbojet – in contrast to more complex solutions, such as the turbo-prop (Figure 3) and turbo-fan, in which other components (e.g., propellers or fans) provide the propulsion force. The concept was initially considered so simple and straightforward that Sir Frank Whittle, the celebrated British inventor of the turbojet, stated that his revolutionary engine had just one moving part, the compressor-turbine rotor, directly connecting the two main functional modules (Whittle, 1979, p. 6, Figure 2).

The first puzzling element emerging from the history of the turbojet revolution is that this astoundingly simple and revolutionary engine concept was dismissed by scientists, experts and incumbent firms for a very long period, namely from the very beginning of the Turbojet Revolution in the early 1920s (the first documented ‘pure turbojet’ concept appears in an obscure French patent, filed in 1921)[45] till when it demonstrated its value by powering real

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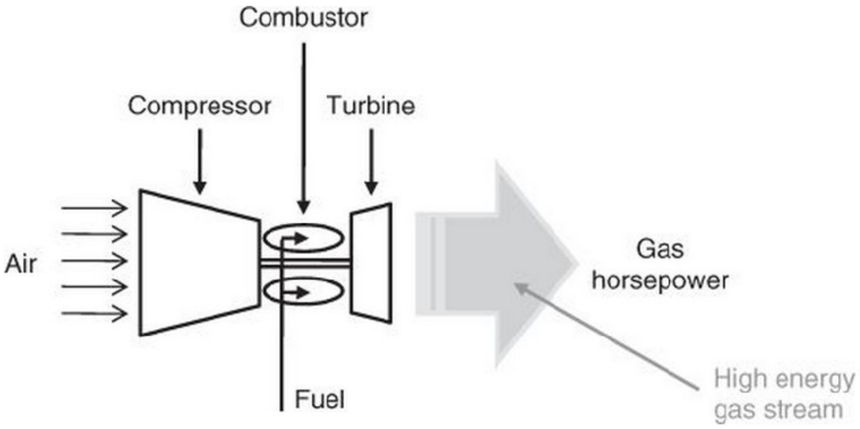
[45] French Patent (Brevet d’invention) No. 534.801, filed in 1921 and issued in 1922 to M. Maxime Guillaume (an agricultural engineer) shows also the modular structure of the pure turbojet, in which we can recognize the three key modules: Compressor (A), Combustor (g), and Turbine (B). Guillaume’s patent is amazing because it presents a crude and very naïve sketch that, incredibly, depicts the actual modular and functional structure of what would

aircraft in 1938. Reconstructing when and why this happened unveils critical decision points in the turbojet revolution that also correspond to critical phases in the five-stage evolutionary process discussed before.

Figure 2 – Functional Modules in the Turbojet Revolution: The Pure Turbojet



Schematic of the 'pure' turbojet showing the three key horizontally transferred functional modules: compressor, combustor, turbine and their connections. Turbine and compressor are preadapted, so they can be interfaced (connected, as a condition to the retention of the module) through a simple shaft. Adapted from MacIsaac and Langton (2011).

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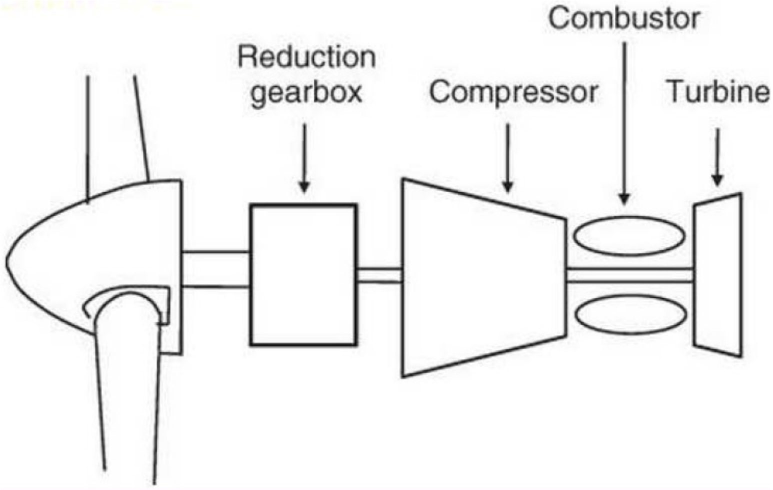
eventually emerge as the turbojet final Dominant Design embodiment, the axial turbojet, more than twenty years later. However, the naivety of the technical content is demonstrated, among other details, by the noticeable presence of a hand-crank. Mr Guillaume's early Patent suggests that the idea of recombining certain functional modules vastly precedes the actual feasibility (retention) of the recombined artifact.

Figure 3 – Functional Modules in the Turbojet Revolution: The Turboprop



Schematic of the turboprop: The turboprop lineage was originated from the horizontal transfer and subsequent retention of a new functional module (the propeller, on the left) to the existing artifact, the pure turbojet, whose original modular architecture (compressor, combustor, turbine) is clearly recognizable (on the right). The newly transferred module is retained when interfaced through a reduction gearbox (a general purpose technology). Adapted from MacIsaac and Langton (2011).

Variation: Availability of 'Preadapted' Functional Modules

As the propelled-driven engines' intractable physical limits became increasingly clear (what Constant calls 'presumptive anomaly'), the potential usefulness of turbo-compressors and turbines in aero-engines was well-known throughout the aviation industry. For instance, Alan A. Griffith's research on internal combustion turbines began in 1926 and was supported by the Aeronautical research council in UK (Constant, 1980, p. 111), while Herbert Wagner's axial turbojet research program began in 1936 in Germany (Constant, 1980, p. 204). In the United States original research on the usage of gas turbines and jet propulsion had been conducted since the mid-1920s (including the work by Jacobs Eastman already cited) with the support of the National Advisory Committee for Aeronautics (NACA). On the basis of these early efforts, a substantial number of recombinant engines had been proposed, and sometimes patented and prototyped, by both free-lance inventors and incumbents firms (for a complete report and discussion, see Constant, 1980; Giffard, 2016). Among the myriad of R&D projects by incumbent firms the 'pure turbojet' was not common.[46] The projects that proved critical for the emergence of the new dominant design were initiated outside or at the periphery of the aero-engines scientific and technical community.

One of the reasons of this skeptical attitude was that the adoption of a jet-stream to propel an aircraft was perceived as being not scientifically sound.[47] It was anyway pursued independently of the gas turbine as thrust generator, for instance, in the so-called 'free piston engines,' or in motor-jet prototypes (e.g., a research project – nicknamed Jake's Jeep - started in 1939 by Eastman Jacobs, an esteemed aerodynamicist who worked for the National Advisory Committee for Aeronautics, in the US; or the Campini-Caproni experimental jet plane, designed by Italian engineer Secondo Campini, which flew in 1940, showing disappointing performances). On the

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[46] For example, in the US incumbents started several projects in the late 1930s and "by the end of 1941, there were at last seven indigenous gas turbine engines being developed by American companies: turboprops were being developed at Northrop (Turbodyne); Pratt & Whitney (PT-1 free gas turbine); General Electric's steam turbine division (TG-100); turbojets were being developed at Lockheed (L-1000), Westinghouse (19A), and Turbo Engineering Corporation (booster-sized turbojet); a turbine-driven ducted fan was being developed by Allis Chalmers" (Giffard, 2016, p. 135).

[47] According to historian Giffard, "The historiography of the American jet engine almost universally blames the 1922 report by Edgar Buckingham of the Bureau of Standards, titled Jet Propulsion for Airplanes, for discouraging research into jet engines in the United States" (Giffard, 2016, p. 135). In fact, the report, scientifically sound, was possibly misunderstood by the American industry, and probably unknown by the Europeans inventors. The union of the gas turbine and jet propulsion, the great insight of the European engine turbojet program (Giffard, 2016), was, therefore, propitiated the inventors' *focused naïveté* – i.e., "a useful ignorance of prevailing assumptions and theories that allows them to attack problems generally regarded as impossible or uninteresting by specialists" (Gieryn and Hirsh, 1983, p. 91).

contrary, industry experts considered the use of a gas turbine (instead of a reciprocating engine) for powering a propeller (turbo-prop) or a ducted fan (turbo-fan) to be more promising. Among them, a prominent example is the Rolls Royce turbojet development program, started in 1939 under the guidance of Griffith, then the leading British expert in gas turbines (Constant, 1980, p. 110).

These attempts, however, required a major R&D effort because the necessary components were not available, and had to be designed and prototyped 'ad hoc;' on the contrary, the components for the simpler 'pure' turbojet were much easier to adapt. For example, Rolls Royce Griffith's CR.1 turboprop was based on a contra-rotating axial compressor which "called for its fourteen-stages to move independently form one another" (Giffard, 2016, p. 76) – a feat that proved too complex even for Rolls Royce' mechanical sophistication.

One of the most famous documents in the history of the Turbojet Revolution is Whittle's first patent (UK Patent n. filed in 1930 and issued in 1931) in which it is clearly recognizable the 'pure turbojet' architecture. We can understand through the historical record why the revolutionary architecture, whose concept was supported by sound scientific reasoning (Whittle, 1979, p. 4), was dismissed. Indeed, before filing the patent, Frank Whittle – then a newly appointed Pilot Officer and only 22 years old – presented the concept to Griffith, at the time considered to be an eminent scientist and an expert in gas turbines. The outcome turned out to be very discouraging for Whittle. Griffith was extremely skeptical about the feasibility of the project, foreseeing major technological challenges: "[…] the net outcome was a letter from the ministry to the effect that it was considered that any form of gas turbine was impracticable in the light of and lack of materials capable of withstanding the high combination of temperature and stress in turbine blading" (Whittle, 1979, p. 4).

As of 1930, Griffith's opinion was supported by the lack of available functional modules that could effectively work for two reasons: materials capable of withstanding the high combination of temperature and stress in turbine blading were not available, and the performance of state-of-the-art compressors, burners and turbines in 1930 was still inadequate – having resulted in a long history of failure. At that time, the 'pure' turbojet architecture was an early, not yet very promising, attempt among the many tentative re-combinations of compressors, turbo-compressors, turbines, burners, propellers and ducted fans that were yet to emerge. Whittle's confidence in his own idea became so low that he even failed to pay the renewal fees of his patent (Whittle, 1979, p. 5).

Acquisition

The functional modules required for the 'pure' turbojet became gradually preadapted thanks to their performance improvement in other industries, including the aero-engine industry, that needed high 'compression ratio' compressors and materials maintaining high strength at high temperatures.[48] In particular:

- high-compression centrifugal compressors were developed for improving the power of supercharged reciprocating engines, especially for high-altitude bombers.[49]

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[48] The pre-adaptation process can be quite long, and only when all the necessary functional modules become preadapted the successful recombination (acquisition and retention) can take place. For example, the 'pure turbojet' architecture, requires 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, p. 84) first appeared.

[49] Most jet engines today are based on 'axial' compressor and turbines. Axial turbojets have several advantages, in that its front section is small and the air stream is almost straight (axial). This notwithstanding the compressors used in the early British and American turbojet were of the centrifugal type. In this case, they compress the air by spinning and accelerating it from the compressor central axis to its periphery. The reason why this inherently inferior compressor design was chosen is again preadaptation: "centrifugal compressors used in centrifugal jet engines were close to existing designs of turbo air compressors and could therefore be developed more quickly than unfamiliar axial compressors, although they were limited in performance by their radius" (Giffard, 2016, p. 17). Again, horizontal transfer of existing functional modules as soon as they were preadapted was demonstrated 'ex post' as the right strategy towards successful radical innovation.

- the material that Whittle adopted for his gas turbine, Firth Vickers' steel Stayblade used in steam turbines (non-preadapted for the higher temperatures required in gas turbines), was later replaced with G18B, a special steel developed mainly for aero-engines exhaust valves.

Interestingly, the development of a special steel for turbojets was not intentional because, unlike the internal combustion engine, the turbojet (still in its infancy and with an uncertain future) did not justify huge investments in metallurgy. This suggests that the evolutionary phenomena of *preadaptation* (Cattani, 2006) taking place in the initial phase of recombinant innovation are largely independent of research efforts aimed at radical innovation, but are instead technological spillovers from more established and funded research.[50] A concomitant phenomenon of *modular exaptation* (Andriani and Carignani, 2014) then takes place in which the preadapted components are forced into a novel function, and inventors stretch their performance until the point whereby the minimum level of performance required of a new artifact to function is reached. In fact, in

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[50] The nature of 'preadaptation' is evident in the following technical report, explaining how and why the battery was the critical functional module for the electric car that originate 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 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, p. 1).

the initial phases of design and prototyping of the novel artifact, the functional modules were re-designed (replication with modifications) in order to reach the requisite performances. For example, in the prototyping of the first turbojet the burner reached a “combustion intensity of the order of 24 times anything previously achieved” (Whittle, 1979, p. 7).

Retention

Formally, the distinctive event marking retention is a functioning prototype that can be successfully replicated. In the turbojet history, this turning point was reached in 1937, when the successful first run of a ‘pure’ turbojet under its own power took place almost contemporaneously in UK and Germany (Figure 4). In UK, this historical event occurred on April 12th, 1937, when Power Jets, a startup firm founded by Whittle himself with the help of a few colleagues and funders, prototyped Whittle’s ‘W.1’ engine. In Germany, the first turbojet, the Heinkel He-S1, designed by a physicist, Hans von Ohain, underwent its first run about a month earlier (von Ohain, 1979, p. 33). The value of a novel artifact is recognized during the ‘retention’ phase when the possibility of replicating a functioning artifact becomes apparent as its performance can be measured and evaluated. This critical moment can be located in history: according to Whittle’s memoirs, Rolls Royce became interested in Whittle’s ‘pure turbojet’ after having ascertained that the thrust produced by the crude, simple prototype manufacture by Power Jets (1,000 pounds) was equal to that produced by the Merlin (at the time the most sophisticated reciprocating engine manufactured by Rolls Royce) in a Spitfire at 350 mph (Whittle, 1979).

Selection

Reaching the ‘retention’ stage, however, does not guarantee the survival of a novel artifact: it still has to go through a ‘selection’ phase, which is niche-dependent. This was one of the critical moments in the history of the turbojet.[51] Whittle's 'pure turbojet' had reached retention in that the engine functioned under its own power, but – though surprisingly in hindsight – contemporary experts did not consider its intrinsic characteristics to be useful. It was a functioning, replicable engine that appeared almost useless. The newly invented 'pure' turbojet was not immediately selected because there was no clear market (niche) for it. Indeed, Griffith's opinion – expressed this time in an official report – was that "in its present form the proposed jet propulsion system cannot compete with the conventional power plant in any case where economical flight is demanded (e.g., the transport of the maximum percentage of useful load over a given distance). It is of value only for special purposes such as the attainment of high speed at high altitude for a short time in cases where take off requirements are not stringent" (Griffith, 1937, p. 1).

Griffith correctly evaluated the shortcomings of the new engines: high fuel consumption and slow thrust at low speed in comparison to state-of-the-art reciprocating engines. In turn, this shortcoming called for long runways, not commonly available at that time, making any military jet plane in the critical long take-off phase more vulnerable. Even more important and apparent in Griffith's writing, the aerial warfare doctrine of 1937 did not consider the attainment of high speed at high altitudes as a particularly valuable performance. The concept of the 'invulnerable' bomber was taken for granted in the mid-1930s, by both military and civilian decision-makers, deeply influenced by the seminal book by the Italian early theorist of air power Giulio Douhet (1927). The iconic phrase "the bomber will always get through" – pronounced by former British Prime Minister Stanley Baldwin during a speech to the House of Commons on November 10th 1932 – eloquently captures the spirit of the times. The very idea of intercepting bombers flying at high altitude seemed outright futile, since in the 1930s high-speed bombers were faster than most fighters, and it was not possible to localize them. Only with the Battle of Britain, in 1940,

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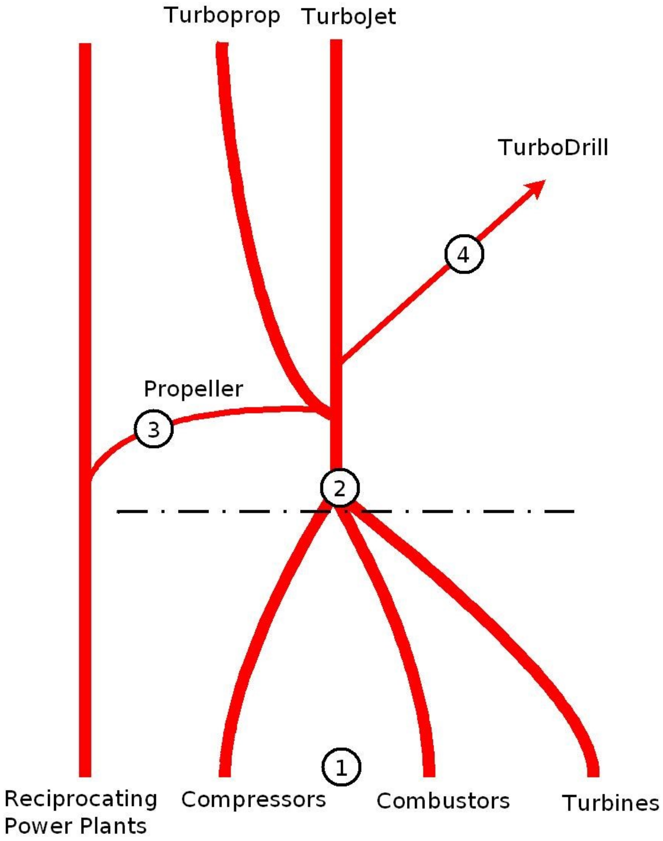
[51] Not surprisingly, it corresponds to a troubled time for his start-up Power Jets, which will eventually be appropriated by Rolls Royce. We argue (see discussion) that the selection phase marks the opportunity for incumbents of appropriating externally developed radical inventions.

did the possibility of defense against bombers emerge. As the efficacy of strategic bombing was confirmed, the vulnerability of strategic bombers to fighter-interceptors proved to be higher than expected under high-altitude combat conditions. The novel engine, therefore, was first selected for this task in July 1941, when British Prime Minister Winston Churchill decided to push its production against high-altitude German bombers that were posing a serious threat to Great Britain (Giffard, 2016).

Fixation

The emergence of the fighter-interceptor niche initiated a new lineage in which Whittle's W.1 engine literally became the 'common ancestor' of all subsequent British and North-American turbojets. This marked the beginning of a new phase in the evolutionary story: after the successful recombination (retention) and the opening of the first niche (selection for high-altitude fighter-interceptors), horizontal transfer – though still possible – ceases to be the dominant (actually the only) evolutionary process and vertical 'descent with modifications' takes charge. In fact, both processes were important in shaping the subsequent evolution of the turbojet. The key point here is that, despite being a crude experimental engine, the W.1 (the 'common ancestor') was de facto the first functioning artifact based on the 'pure turbojet' architecture, and the new emerging dominant design (Figure 4).

Figure 4 – The Evolution of the Turbojet: Vertical Transmission and Horizontal Transfer in a Stylized Phylogenetic Graph



Representation of the origins and early evolution of the turbojet according to the Woesian model of evolution (time flows form bottom to top): compressors, combustors and turbines, developed in diverse technological lineages (not shown), are the common pool of preadapted functional modules (1). The dashed line (2) shows the critical point when the Dominant Design ('Common Ancestor' or the W.1) was established between the fluid phase with rampant HGT (below the line) and the following speciation phase with massive VT (above the line). The speciation leading to the Turboprop lineage was prompted by Horizontal Transfer of the propeller from the traditional propeller power plans (3). Horizontal transfer to another technological lineage (not shown) is the Turbodrill, which became a component of oil rigs (4).

After the emergence of the first functioning prototype – in our conceptualization the 'common ancestor' – we enter the phase in which vertical inheritance and speciation drive technological evolution (Levinthal, 1998; Adner and Levinthal, 2002; Cattani, 2006). This distinctive decision point can be located graphically in the phylogenetic graph (Figure 4), but its existence is also clearly located in time recalling the early development of jet engines at Rolls Royce as described in available historical records (Constant, 1980, p. 193; Giffard, 2016, see the chapter "Rolls Royce and the Turbojet").

The development of the turbojet by vertical inheritance can be recognized in the successors of the original WR.1 engine (Giffard, 2016, Appendix C). Indeed, the W.2B engine (a powered-up direct descendant of the W.1) was the first turbojet production engine made by Rolls Royce (February 1943); the direct descendant of the W.2B, called the Welland (beginning the Rolls Royce tradition of christening jet engines by names rather than numbers) underwent limited production in November 1943. By November 1944, one hundred Welland engines had been manufactured. Still in November 1944, the first turbojet entirely designed by Rolls Royce, called the Derwent, was built. While the architecture was the same as that of its predecessors, its performance was improved (ameliorated). By December 1945 five hundred Welland engines had been manufactured (Giffard, 2016).

A distinctive event, also part of the model and shown in the phylogenetic graph (Figure 4), occurred during the development of the pure turbojet at Rolls Royce: the emergence of the first functioning Rolls Royce turboprop prototype, called the Trent**,** in 1944. The turboprop is an internal-combustion turbine driving a propeller (Figure 3): compared to the pure turbojet it delivers better performances at low altitude and intermediate speed, and requires shortest runways. The concept was pursued unsuccessfully by several firms, including Rolls Royce. What proved so difficult to do through direct R&D efforts was instead realized with the acquisition of a novel module (the propeller) through horizontal transfer. The propeller – evolved as a component of the reciprocating propulsion plants that had been used since the dawn of aviation – was transferred to the novel engine, the pure turbojet, which maintained its architecture. The Trent was “created in 1944 by adding a propeller to a Derwent engine. In fact, the Trent has been a successful product of collaboration between the Derby and Barnodswick turbojet teams that exploited continuities with both piston engine practice and the firm’s growing turbojet expertise. For the Trent, the diameter of the Derwent’s compressor was reduced, and the energy extracted by the turbine that was no longer needed to turn the (now smaller) compressor was used instead to power a propeller via a gearbox, which was designed at Derby" (Giffard, 2016, p. 91).

The origins of the first turboprop by evolutionary acquisition shows that horizontal transfer is possible also after a novel technological trajectory (the turbojet) has emerged, generating a new 'turboprop' lineage. Even more, the development of diverse turbojet types ('new lineages' in evolutionary terms) by Rolls Royce is an indication that the firm – one of the few surviving and thriving incumbents after the Turbojet Revolution – was also 'preadapted' (in an organizational sense) with respect to the architectural change in the technical domain due to the new architecture. Indeed, Rolls Royce possessed some of the key competences required to support successful acquisition: for example, it had designed the gearbox – a functional module which connects the turbine to the propeller in the Trent turboprop – at its Derby plant. This suggests that, after a technological revolution, some firms already control the organizational modules that can be re-modularized to 'mirror' the novel technological architecture (Colfer and Baldwin, 2016).

Amelioration

The adoption of jet engines in fighters, in turn, initiated a steady process of incremental improvement of the engine and the airframes, punctuated by other horizontal transfers (e.g., the already cited turbo-prop) that helped the new engine invade existing niches in military aviation. Indeed, at the end of WWII and throughout the Cold War, the turbojet engine was adopted for almost every military application, from bombing to transportation, before expanding into civil aviation. By 1970, the transformation of the aviation system was complete (Geels, 2006). The important point is that its distinctive performances, albeit inadequate for a general use, were nevertheless fine for smaller niches (e.g., the new role of fighter-interceptor in 1940) in which the turbojet engine was able to survive and evolve. Interestingly, after working on Griffith's contra-rotating axial turbojet for a long time, Rolls Royce developed its first commercial axial turbojet (the Avon) in 1950, not as a result of deliberate R&D efforts, but thanks to the previous evolutionary development of centrifugal turbojets. Axial turbo-compressor and turbines have a number of advantages over the centrifugal type used in the early turbojets, but scientific and technological problems inhibited their development in early British and American turbojets.[52] As the previous evidence suggests, on the market (demand) side, adaptation of the new architecture to new niches (e.g., the turbo-prop) drives the amelioration phase; on the supply side, on the contrary, the amelioration phase is driven by the opportunity to improve performance (e.g., from centrifugal to axial turbojet in the case of the 'pure turbojet').

Discussion

Drawing from recent advances in research on bacterial evolution, we reinterpreted a well-known case of radical innovation, i.e., the turbojet revolution, recognizing the analogy between the distinctive five-stages of bacterial and technological evolution, and so extending the classic variation-selection-retention evolutionary framework. This reinterpretation is not merely a semantic choice, but exposes a more precise causal explanation of historical records. A Woesian model of technological evolution, in which the two key processes of bacterial evolution—vertical inheritance and horizontal (gene) transfer—coexist, affords a more accurate description of how new technologies, and particularly radical technologies, are generated. Specifically, the case analysis unveiled the significance of the horizontal transfer of functional modules and their holistic recombination into a higher-level functional module as a crucial evolutionary process leading to a radical innovation. While extant research emphasizes how innovations typically originate from the recombination of available knowledge, the specific processes by which recombination occurs and when (i.e., in which evolutionary phase) they are supposed to be at work are not examined explicitly. By exposing the nature of these processes, it is possible to distinguish between the case in which new functions emerge and then new artifacts are designed to perform those functions from the case in which (like in the turbojet revolution) existing

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[52] Axial turbojets, on the contrary, were developed earlier by the German aero-engines industry, but they were dangerous engines whose early adoption was chosen by war necessity (Giffard, 2013).

functional modules can be integrated into a radically new architecture generating a higher level function that endows the novel artifact extraordinary performances.

The model also clarifies why what initially looked like a discontinuity—a radical innovation without an evolutionary history—is in fact an evolutionary *chimera* – i.e., the result of the assemblage of functional modules with different origins (Koonin, Makarova, and Aravind, 2001; Kreimer *et al*., 2008; Lawrence, 1999). Indeed, the apparent contradiction between continuity and discontinuity is seamlessly solved in a Woesian model of evolution.

Incorporating new historical evidence discussed in Giffard (2016), the case analysis reveals how, in the turbojet case, a novel superfunction[53] – providing thrust – originated from horizontally recombining existing components (i.e., a compressor, a turbine and a burner). In particular, we shed some light on the "complex, diffuse and often contradictory" character of the turbojet revolution: the turbojet, in fact, was "heir of two centuries of turbine development" but at the same time "a holistic system with unprecedented performance capabilities" (Constant, 1980, p. 3).

By analogy with bacterial innovation, in the evolution of a modular artifact (e.g., the turbojet) there is an industry-specific fluid phase potentially dominated by horizontal transfer of functional modules, very often from other industries; and, from this fluid phase a novel artifact could emerge that initiates a different evolutionary process dominated by vertical inheritance.

During the fluid phase preceding the emergence of a novel dominant design, incumbents should scout for existing functional modules that can be transferred horizontally both within and across organizational boundaries – e.g., through open and user innovation (e.g., Von Hippel, 2016). Although the case analysis further shows how the horizontal transfer of functional modules can occur even after the end of the fluid phase, their frequency tends to decline. Following the emergence of a new dominant design, incumbents should leverage their architectural

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[53] This is consistent with analogous phenomena in bacterial evolution, i.e., the pathogenicity islands (Hacker and Kaper, 2000).

knowledge, understanding of the market, as well as ability to design, prototype improve and adapt functional modules, integrating them into a novel architecture – i.e., what we call *replicative capability* (see below). We further elaborate on these implications in the next two sections.

Searching for Radical Innovations

Although some innovations have no clear antecedents because they originated from new scientific discoveries (Arthur, 2009; Strumsky and Lobo, 2015),[54] the vast majority of new technologies are not created from scratch, but are instead “constructed—put together—from components that previously exist; and in turn, these new technologies offer themselves as possible components—building blocks—for the construction of further new technologies” (Arthur and Polak, 2006, p. 23). Yet the implications of this ‘construction’ process for the search of radical innovations is less obvious. A Woesian model of evolution bears the promise of shedding new light on this aspect. To see how, a useful starting point is the *near-sighted watchmaker metaphor*, first discussed in Dawkins (1978) and then used by Winter (2008) to examine the development of evolutionary theory in strategic management and emphasize a departure from a Darwinian perspective:

“The evolutionary progress in biology is blind, unconscious and automatic, taking place without any element of intentionality. Therefore, if there is a designer or a creator, namely, the watchmaker, he must be blind. However, managers and engineers can intentionally manipulate things in organizations to produce novelty, and seek profit in doing so. To a limited extent, they can test their proposals to see if they work locally. However, they cannot reliably predict the

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[54] However, even when a new scientific discovery supports the implementation of a radically new technology – e.g. nuclear energy – the path towards a functional new artifact requires the recombination of existing functional modules – e.g., the electric and mechanical components necessary to build an atomic bomb or a nuclear power plant

consequences of efforts in large-scale implementation; hence, they are nearsighted watchmakers. Therefore, variety is a crucial factor in evolutionary processes, shaped by intentional activities, experimentation and learning" (Viipuri Prize Lecture, May 14, 2008; reported in Jantunen and Sainio, 2008, p. 218).

Clearly, the watchmakers cannot reliably predict the consequences of their efforts in large-scale implementation, as exemplified by the turbojet case. We already discussed how Griffith turned down Whittle's pure turbojet not once but twice: one in 1930, on the basis of unfeasibility, and the other in 1937, postulating the lack of purpose. However, it is hard to say he was at fault: this can only be argued in hindsight. The position of the experts was understandably mirrored by incumbent aero-engine producers: many of them made significant investments in R&D, developing turbojet architectures that only in hindsight proved to be failures. For example, Rolls Royce pursued the advanced but unworkable CR.1 axial turbojet designed by Griffith himself. However, in doing so they improved their design and prototyping capability that was later useful in replicating and improving Whittle's design (Giffard, 2016). Also, and even more astounding, the inventors themselves had no clue about the revolution they were about to initiate. Frank Whittle only anticipated the possible usage of his first engine as follows: "We had in mind a small 500 mph plane … carrying 500 lb of mail across the Atlantic in six hours" (Golley, Whittle, and Gunston, 2010, p. 81); while Hans von Ohain admitted that "I cannot claim I had a clear picture of the imminent need for jet propulsion" (von Ohain, 1979, p. 29). Yet, and more subtly, the watchmaker metaphor suggests how the *local* scope of intentionality can coexist with the *global* reach of evolution, including the emergence of radical technological innovation.

In technological evolution, radical changes often result from transferring technological modules horizontally: existing modules can be viewed as available building blocks for the development of new technologies, even though they were not originally developed for their new function, a process known as *exaptation* or *preadaptation* (e.g., Cattani, 2006, 2008; Dew *et al.*, 2004). The same module, whether or not currently in use, might end up performing a very different function for which it turns out to be functionally 'preadapted.' In the turbojet case, historical records show how initially the key functional modules did not come from the aero-engines industry, but 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 (Whittle, 1979, pp. 6-7).

Although even “visionary inventors often fail to anticipate the ultimate use of their discoveries” (Wagner and Rosen, 2014, p. 2), which explains why incumbent organizations often fail to effectively exploit their storehouse of technology (Garud and Nayyar, 1994), the simultaneous efforts of several near-sighted watchmakers involved in different lineages may still lead to radical innovation if functional modules are transferred horizontally across such lineages. In general, firms develop functional modules but without fully anticipating their subsequent uses in other application domains. These modules, however, later on may prove functionally useful (preadapted) for alternative, as yet unknown, applications as new environmental conditions and information about possible novel uses gradually come along. But if the number of possible uses of a functional module is greater than its current use(s) seems to suggest, organizations can enhance their ability to innovate – and even generate radical innovation – by searching for new applications of that module. While near-sighted watchmakers are needed to continue improving on functional modules that are currently in use, new uses can emerge from transferring modules horizontally across technological lineages. As the previous discussion of the turbojet revolution has shown, exploiting existing modules in new applications is a critical source of radical innovation. In this sense, the concept of horizontal transfer of functional modules clarifies and extends Winter’s insight.

The realization that even visionary inventors cannot predict the ultimate use of their discoveries further suggests that innovations, and especially so radical innovations, increasingly must “rely not on individuals, but on populations—from collaborating groups to competing teams” (Wagner and Rosen, 2014, p. 2). Interestingly, this is true not only within the context of technology but also in biological evolution.[55] To facilitate the identification of these novel

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[55] “In biology, this was first fully realized early in the twentieth century during the birth of population genetics, the discipline that aims to describe how new variants of genes and genomes spread through populations. Although highly mathematical, some of its principles are quite intuitive: because evolution proceeds by trial and error, large populations

applications, organizations can make the knowledge about them available internally, e.g., by sharing them among separate organizational units involved with different technological lineages; or externally, e.g., by allowing other organizations or communities to access knowledge of their modules, which is typically the case within the context of open source innovation (e.g., Baldwin and von Hippel, 2011; Chesbrough, 2003; von Hippel, 2005, 2016). In so doing, an organization can realize the broader range of novel applications for which a given module is functionally preadapted (Andriani and Cattani, 2016). This is consistent with Colfer and Baldwin's (2016) notion of "partial mirroring," whereby (especially) in technologically dynamic industries "knowledge boundaries are drawn more broadly than operational boundaries …" (p. 710) to enhance a firm's ability to explore a larger and more diverse set of opportunities.[56]

Firms could search for modules from other technological lineages that can be usefully recombined in their own industry. Unlike exploration that involves searching for new modules (e.g., glass fibers replacing copper fibers in cables used for telecommunications applications), the type of exploration discussed here involves searching *locally* in the neighborhood of an existing module but *globally* with respect to the new re-combinations in which this module can be (re)used. The way 3M leveraged microreplication – one of its core technologies – over time across different technological lineages unveils the basic logic underlying this type of exploration, which complements exploratory search directed to developing entirely new

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experience more trials, and thus have a greater chance to draw the winning lottery ticket" (Wagner and Rosen, 2014, p. 2).

[56] Firms can strategically 'break the mirror' – i.e., the idea that the formal organization structure should mirror the design of the underlying technical system – "first, by implementing modular partitions within their own boundaries; and, second, by building relational contracts that support high levels of technical interdependency across their boundaries" (Colfer and Baldwin, 2016, p. 710).

modules. Microreplication started in the late 1950s when Roger Appledorn invented a new type of optical lens that was initially used to make lightweight, economical overhead projectors for schools. Appledorn replaced the standard "heavy glass lens with a plastic lens that had microgrooves in its surface in order to focus light and increase brightness while decreasing overall weight. He had discovered that changing the surface characteristics of a material could dramatically alter its performance" (Gundling, 2000, pp. 30-31).

Exploring in the neighborhood of existing functional modules by looking for new ways of recombining them with other functional modules used in other application domains, therefore, is a viable search strategy for generating radical innovation. This type of search is different from, though it complements, exploration that entails a long jump, namely "the adoption of alternatives far removed from the organization's current mode of operation" (e.g., Levinthal, 1997, p. 938; see also Nelson and Winter, 1982) – which is typically the case when an organization, for instance, seeks to develop entirely new functional modules. Organizations can indeed enhance their ability to generate radical innovation by searching *locally* in the neighborhood of existing functional modules, but *globally* with respect to new possible applications for them. But this implies that organizations are able to reproduce exactly those functional modules, irrespective of the new function in which they are employed.

***Crossing the Abyss*: The Need for Replicative Capability**

Why did incumbents such as Rolls Royce and General Electric survive the turbojet revolution and prosper afterwards (i.e., crossed the abyss), while many other important producers of aero-engines failed, even if they tried hard? The failure of Power Jets (the start-up company that invented the turbojet) in association with Rover (the firm to whom the 'first mover' advantage was given) in entering the new industry is instructive. In February 1940, the Air Ministry offered Rover, a car maker experienced in aero-engines manufacturing (but not design), the opportunity to manufacture the new version of Whittle W.1 turbojet, which was intended for the first British operational jet fighter (the Meteor). In turn, Rover decided to manufacture directly the compressor-turbine assembly and sub-contract the combustor to Lucas – a manufacturer of automotive components – while Power Jet was supposed to support Rover with engineering and design.

This organizational arrangement proved so catastrophic that by the end of 1942 the Air Ministry handed the project over to Rolls Royce, then a leading manufacturer of traditional aero-engines. Rolls Royce transformed Rover's failure into a spectacular success. The firm was soon able to master the novel technology and in a few months, by June 1943, successfully designed and prototyped its first turbojet, the Derwent. At the same time, on the other side of the Atlantic, General Electric had successfully replicated Whittle's W2B engine and called the replica Type 1. Thanks to its own design and manufacturing capability the firm ameliorated Type 1, prototyping what was in fact its own first design turbojet, which was called Type 1-A (Giffard, 2016). While Rover failed, both Rolls Royce and General Electric[57] succeeded in designing and prototyping their own turbojets, inaugurating the vertical lineage of the pure turbojet – which is still evolving as of today – and gradually phasing out other projects. It is worth noticing that neither Rolls Royce nor General Electric invented the turbojet: initially, they were both working on different architectures that were then recognized as failures. Unlike British Thompson-Houston and Rover, which were first movers, Rolls Royce and General Electric entered the game later but were able to survive the revolution and achieve a competitive advantage that has endured till these days. What emerges from the historical record is the complex nature of the modular 'replicator' and its power in explaining the transition from inventors (often 'naïve' outsiders) to that of established firms as the main locus of innovation, and ultimately which firms are better prepared to cross the abyss (Hill and Rothaermel, 2003, p. 271).

In order to situate the modular replicator into an organizational framework, we emphasize the role of a firm's *replicative capability*, i.e., the ability to 'replicate with modifications' existing functional modules integrating them into a novel architecture. The replicative capability

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[57] many of the US aero-engines incumbents at the time were developing recombinant innovation (see case study), but it was General Electric (which was not an aero- engine manufacturer, but had the competence for building a key component and the opportunity to acquire architectural knowledge from the British) that was able to successfully develop its turbojet from the same 'common ancestor'.

involves not only the mastering of the technological and scientific knowledge associated to the modules, but also the tools, machinery and instruments needed to design and prototype that module. Previous research has shown how the higher levels of "specialization of useful knowledge for design, engineering, and manufacturing of products makes it difficult for firms to rely entirely on in-house learning processes" (Brusoni, Prencipe, and Pavitt, 2001, p. 598). That is why multitechnology firms, which offer products that incorporate multiple technologies, increasingly "coordinate loosely coupled networks of suppliers of equipment, components, and specialized knowledge and maintain a capability for system integrators" (Brusoni *et al*., 2001, p. 597). However, the ability to design and prototype key functional modules is necessary for its effective transfer and replication.[58]

The absence of this design capacity can dwarf the survival of an organization (e.g., Rover) facing radical innovation, if this innovation is triggered by the horizontal transfer of functional modules. In contrast, an organization that integrates all the components of the replicative capability (e.g., Rolls Royce's sophistication in designing and prototyping complex engines, including turbocompressors, i.e., one of the key functional modules) is well positioned to exploit a new architecture even if it did not invent it. Moreover, the fact that General Electric was able to evolve from a subcontractor specialized in turbo-compressors to a leading turbojet manufacturer, and to understand how the different components (modules) of a system or artifact (turbojet) function together, suggests that the replicative capability associated to *the critical modules* is the discriminating resource. So, different predictions are likely to hold depending on whether incumbents or new entrants control the replicator of key functional modules.

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[58] It is important to remember that replication with modifications is critical for biological evolution. By analogy, the replicative capability subsumes a similar evolutionary 'creative' edge: inventors and engineers can modify functional modules when these modules are transferred and have to be adapted to their new use and integrated. This is why an integral component of the replicative capability is the *design* capacity – which, in turn, can be based on scientific, engineering or other type of knowledge required to modify the module and so make it fit its new function.

Based on our model, the capability to replicate the key functional modules endows certain incumbents with an advantage that other firms may not be able to contrast. Although other factors (e.g., organizational inertia, risk of cannibalizing existing products, etc.) also explain why some incumbents resist the introduction of radical innovation and even fail in the face of it, we argue that an equally plausible explanation is whether or not an organization controls the replicator of key modules and is therefore in the right position to learn how to integrated them in a novel architecture – i.e., has the replicative capability. For instance, the research team that at Corning was responsible for the development of the first low-loss optical fiber concentrated on the company's core knowledge in specialty glass technology. While other firms discarded fused silica, because its refractive index was too low for fiber cores and its melting temperature too high, Corning had worked with it for three decades. Corning was also "the only firm in the early 1960s with a furnace that could heat glass to 3600°F to melt fused silica and draw it into fibers" (Cattani, 2006, p. 300). As Donald Keck – one of the research team members – later noted, the process of vapor deposition that Corning scientist Frank Hyde had invented in the 1930s for "use in *other* Corning technologies became part of the fiber-making process" (2000, p. 2, emphasis from the authors). The capability to replicate one of the key modules – fused silica – gave Corning an edge over competition. Thus, for radical innovations that originate from the horizontal transfer of functional modules, organizations that have the capability to replicate the key functional modules have a better chance of introducing and benefiting from those innovations than incumbents and/or new entrants lacking the same capability.

Conclusions

This paper presents a model of technological evolution in which horizontal transfer of functional modules (HGT in the biological domain) figures as a critical mechanism that drives evolution and complements the Darwinian theory of vertical inheritance. The horizontal transfer of functional modules is the dominant evolutionary force during the fluid phase which takes place before the appearance of a dominant design (the analogue of a 'common ancestor' in our model), but remains an important force even after that appearance. By revealing the coexistence of horizontal transfer and vertical inheritance and locating the critical point in which horizontal transfer is substituted by vertical inheritance as the driving evolutionary force, a Woesian model of (cell) evolution unveils striking similarities in structures and processes between biological evolution and technological evolution – which are both inherently reticulate as they exhibit a network structure (Figures 1 and 4). The model allows for a more precise characterization of the key evolutionary processes and forces underlying technological innovation and, particularly, radical technological innovation as the previous analysis of the turbojet revolution illustrates.

This paper makes three main contributions that clarify the suggestive incipit of Constant's book on the turbojet revolution: "Time, not reason, separates real from absurd. What today is, is yesterday's possibility, a selection out of what-might-have-been" (Constant, 1980, p. 1). First, we exposed a novel 'Woesian' perspective of technological change that highlights the key role of the horizontal transfer of functional modules in generating radical innovation. Thus we recognize the functional module as a fundamental building block also in technological evolution. The chasm between HGT-driven evolution and the more familiar period in which vertical descent dominates and speciation is possible marks the separation – made by selection – between the realm of "what-might-have-been" and "what today is" (Constant, 1980, p. 1). But it also marks the transition from the pioneering efforts of entrepreneurial ventures to the role of established firms as the main locus of innovation, whereby some incumbents are able to cross the abyss, while others decline and eventually disappear. What is the reason for this different fate? We contribute to solving this dilemma and also derive some implications for management and organizations. Specifically, at least in our setting, the incumbent firms that crossed the abyss were those with the ability to replicate with modifications the key functional modules integrating them into a new artifact (turbojet). They took the lead in the development of the new technology even if they did not invent it, displacing both individual inventors and first-mover organizations.

Our second contribution is to show the creative and powerful evolutionary role of horizontal gene transfer (HGT) that, through the acquisition and recombination of existing functional modules, prompts variation and creates *evolutionary chimeras* (Woese, 2002). The horizontal transfer of functional modules provides a robust interpretation of an iconic, though still poorly understood, case of radical innovation: the turbojet revolution. The Woesian five-stage model maps into the historical records: noteworthy is the analogy between the common ancestor and the dominant design emerging from the pool of functional modules developed in diverse technological lineages during the 'fluid' phase that precedes the emergence of a radical innovation. Accordingly, Woese's observation that "only global invention arising in a diverse collection of primitive entities is capable of providing the requisite novelty" (Woese, 2002, p. 8746), which refers to the biological domain before the emergence of the common ancestor, can also be extended to technological change.[59] Indeed, what seems to contradict a gradualist evolutionary approach is, on the contrary, consistent with the Woesian perspective: the horizontal transfer of functional modules across different lineages can produce the emergence of radical innovations in one single generation.

Finally, the most striking similarity between evolutionary processes in biological and technological evolution is their reticulate structure, which is comprehensively described by a phylogenetic network rather than the Tree of Life. We argue that this brings to an end what has long been considered an intractable disanalogy between biological and technological evolution (e.g., Basalla, 1988; Kroeber, 1948; Ziman, 2000), and opens up instead unique opportunities for future collaborations among researchers in biology and other fields such as economics and management, so overcoming the conceptual limitations that have haunted extant theories of technological change. While the flow of analogies historically has moved from technology to biology and—after the diffusion of Darwin's theory—from biology to technology (Basalla, 1988), the time has come where the flow might actually move in both directions. The previous implications are a natural extension of the theoretical model and are meant to stimulate future research to delve more deeply into how to search and organize for radical innovation.

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[59] The Woesian perspective suggests how further research can approach a number of puzzling issues regarding the origins of radical innovation: it is no longer necessary to invoke *Lamarckian features* (Ziman, 2000, p. 5) to explain the rapid acquisition of novel functions or even the sudden, unexpected emergence of radical innovation.

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Discussion and Conclusions

Time, not reason, separates real from absurd. (...) What today is, is yesterday's possibility, a selection out of what-might-have-been. (Constant, 1980:1)

This beautiful incipit of Constant's seminal book on the Turbojet Revolution[60] is also the perfect epitome for discussing the contributions of this thesis. Constant describes in poetic but rigorous terms the '*true uncertainty'* that characterizes radical technological innovation, and in particular the inception of an Industrial Revolution, but at the same time suggests a way to study it, since the term *selection* possibly refers to an evolutionary process.

This thesis took Constant's incipit as a broad research question, developing three contributions: First, we proposed a novel approach to technological change, based on the 'Woesian' model of cell evolution. Building on recent research in bacterial evolution (Hartwell et al. 1999) we recognize Functional Modules as fundamental building blocks also in technological change; consistently, we consider Horizontal Transfer across industries (Horizontal Gene Transfer in biological evolution) as a critical process that drives evolution and complements the Darwinian theory of vertical transmission or inheritance. The most striking similarity between evolutionary processes in biological and technological evolution is the reticulate nature of the evolutionary history which is comprehensively described by a phylogenetic network (e.g. Figure 1) rather than by the *tree of life*. This new perspective of evolution sheds new light on the discussion of what has long been considered an intractable dis-analogy between biological and technological change (e.g. Ziman, 2000) opening instead a novel, welcome opportunity of collaboration between researchers in the field of biology[61] and economics (including management) which overcomes the conceptual limitations that have been haunting the evolutionary theories of technological change for decades.

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[60] The Turbojet Revolution is discussed in depth in Paper 3

[61] Giusi Zaina, coauthor of Paper 3, is a biologist and molecular geneticist at the University of Udine

Second, we tried to demonstrate how the creative and powerful evolutionary role of Horizontal Transfer through the acquisition and recombination of functional modules already in existence, prompts variation and creates *evolutionary chimeras* (Woese, 2002) We show how this evolutionary concept can provide a robust interpretation to different iconic yet still poorly understood cases of radical innovation, from the Bow and Arrow (Paper 2) to the Turbojet Revolution (Paper 3). By recognizing the Woesian five-stage process (Paper 3) in the historical (and micro-historical) record we recognize matching key concepts: in particular we emphasize the analogy between the Common Ancestor and the Dominant Design emerging from the pool of functional modules developed in diverse technological lineages during the 'fluid' phase preceding radical innovation. (Figure 1)

The Woesian perspective suggests how several puzzling issues regarding the origins of radical innovation can be approached through further research: it is no longer necessary to invoke Lamarkian features (Ziman, 2000) to explain the rapid acquisition of novel functions, or even the sudden, unexpected emergence of radical innovation. Indeed, what in principle seems at odds with an evolutionary gradualist approach is on the contrary in perfect accordance with the Woesian perspective, since Horizontal Transfer can provide radical variations within one single generation. Moreover, albeit further historical research is needed, our micro-historical analysis suggests that micro-and macro levels can seamlessly coexist, and how the dilemma between intentionality and blindness can be reconciled (Paper 3).

Third, we proposed some implications for management and organizations. Since the three papers, have been written for different audiences, coping with different requests by the editors and reviewers, and are therefore conservative in their outcome, they are complemented with the next paragraphs, aimed at proposing some uncertain but promising implications and avenues of research that are missing or underdeveloped in the published papers.

Summarizing the theoretical framework

The departure point of the Woesian evolutionary approach to technological innovation from other extant evolutionary theories is the idea to consider the *modular artifact*, composed of *functional modules* (rather than other entities like for example the routine (Nelson and Winter 1982)), as the object of analysis and the evolving entity. We believe – and tried to demonstrate - that this perspective can provide a better understanding of the origins of many radical innovations, and in particular those that can be modeled as modular artifacts. The evolution of the modular artifact include the recombinant process of horizontal transfer which takes into account the transfer of *functional modules* across diverse technologies and industries, often involving processes of *preadaptation* (G. Cattani 2006) and *exaptation* (Dew, Sarasvathy, and Venkataraman 2004). Exaptive processes are associated to horizontal transfer – so the Woesian approach enables a clearer characterization of the phenomenon of modular exaptation (Andriani and Carignani 2014), conversely, *modular exaptation* could be considered a sub-process of a higher level evolutionary process, the emergence of *holistic superfunctions*, as discussed in Paper 3 and in the closing paragraph.

An Emergent Industry-Specific Pattern

By analogy with bacterial innovation, the emergence of a new Dominant Design (e.g., the bow and arrow, the turbojet, or the microwave oven) develops through a fluid phase dominated by the evolutionary mechanism of horizontal transfer, in which functional modules (often borrowed from other industries) are recombined into new 'evolutionary chimeras. This fluid phase is ended by the emergence of a novel artifact that could – if selected, initially in a niche - initiate a different evolutionary process dominated by vertical inheritance. (Figure 1)

Figure 1

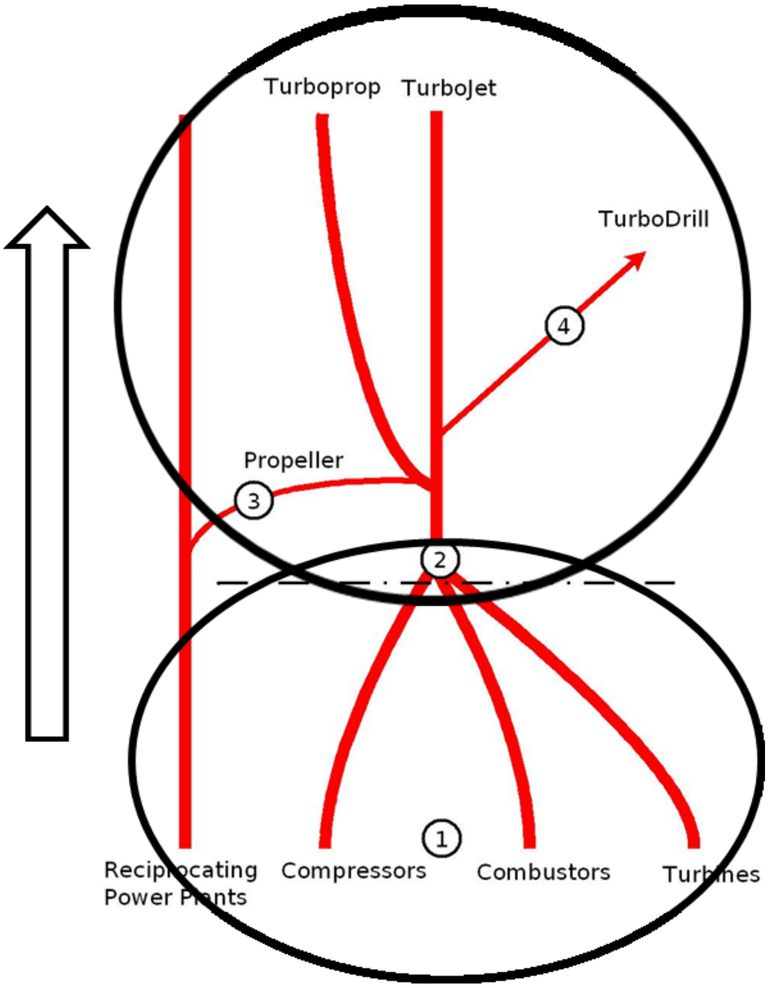

Figure 1: The emergence of the Dominant Design coincides with the Darwinian Threshold, separating the period in which Horizontal Transfer is the main evolutionary driver form the period in which Vertical Inheritance is Dominant, in good accordance with extant research. The novel analogy suggests the technological industry-specific Darwinian threshold as a separation between different innovation strategies, positing the necessity of sequential ambidexterity

This evolutionary pattern is in good accordance with extant research (e.g Anderson & Tushman, 1991, von Hippel 2016 (Figure 2), but the underlying complex analogy and the focus on the evolution of horizontally transferred functional modules provide the opportunity of developing not only descriptive, but even normative implications for management.

I propose in the following paragraphs some promising avenues of research undeveloped or only partially developed in the papers.

Figure 2

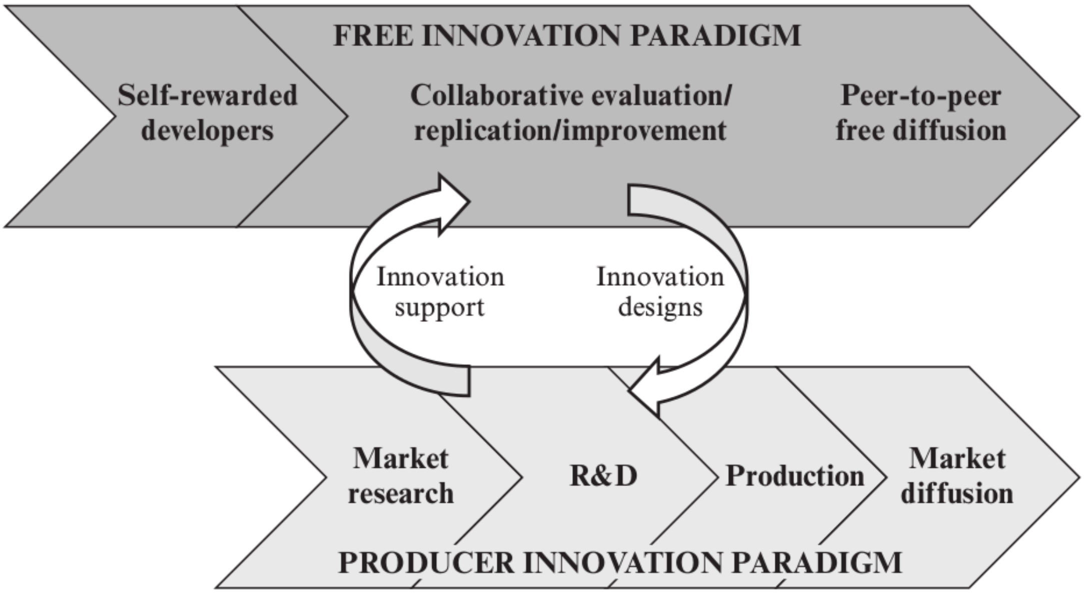

Figure 2: free innovation by 'self-rewarded developers' precedes producers innovation (top right). Within the Woesian model this is in accordance with the fluid phase in which developers (inventors, and entrepreneurs) external or peripheral to the industry recombine existing functional modules, until one of their Evolutionary Chimeras is selected by the producers. (adapted, from (Von Hippel 2016))

Sequential Ambidexterity

The pattern shown in Figure 1 and confirmed (from a different perspective, that of Free Innovation, by Figure 2) suggests that the dynamics of innovation before the Darwinian Threshold are radically different from those unfolding after it, i.e. after the emergence of the new Dominant Design. This radical change of regime suggests that organizations need a different strategy for effectively managing technological innovation in the two different phases. During the fluid phase preceding the emergence of the Common Ancestor (the new Dominant Design), incumbents should scout for existing functional modules that can be transferred horizontally both within and across organizational boundaries – e.g., through Open and User Innovation (OUI). This is in accordance with some results in OUI (Von Hippel 2016). Indeed, according with OUI literature, free innovation by 'self-rewarded developers' precedes producers' innovation (Figure 2).

The same process can be studied through the lens of the Woesian Model: acting as agents of variation, inventors and entrepreneurs (often external or peripheral to the industry, e.g. von Hippel, Paper 3) recombine existing functional modules, until one of their Evolutionary Chimeras is selected by the environment and consequently by the producers. Incumbents should therefore support rather than oppose OUI in their industry, possibly implementing counterintuitive policies like the opening of their modules to innovation communities, meanwhile getting ready for appropriating the recombinant novelties emerging. Following the emergence of a new Dominant Design, incumbents will be able to leverage their architectural knowledge, understanding of the market, as well as ability to design, prototype, improve and adapt functional modules, integrating them into a novel architecture – what we call *replicative/integrative capability* in Paper 3.

Replicative/integrative Capability and the Mirroring Hypothesis

Replicative/integrative capability[62], was defined in Paper 3 as the ability to 'replicate with modifications' existing functional modules integrating them into a novel architecture. The concept is clearly connected both with modular and architectural knowledge, and could lead to interesting implications for organizations. A radically new technical system is usually misaligned both with the existing knowledge and with the existing organizations, triggering a process of organizational evolution. The Woesian model suggests that technological radical change drives organizational change in this phase, opening interesting opportunities for the incumbents that are in the right position to *cross the abyss*. This chapter develops the idea and presents some initial historical evidence.

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[62] Simply replicative capability in Paper 3

Background: products build organizations

Modular products[63] are characterized by a technical architecture, usually described by a modular tree of functional modules. Ostensibly, products are designed and produced by organizations. There should be, therefore, a relation between the technical architecture and the organizational architecture, i.e. the hierarchical functional model of the firms (e.g. internal departments, property rights and contract structure). Indeed, in the cases of pervasive radical innovations impacting whole industries, like the Turbojet Revolution, the concept clearly extends to the 'Industry Architecture', involving the relations between firms in all related industries (C Y Baldwin 2015). The relation between technical structure and industry architecture, however, is not deterministic. On the contrary, it has the features of a complex system, including signature elements of the theories of complexity, like the butterfly effect and path dependency.

An early insight into the relations between technical architecture and industry architecture was proposed by Sanchez and Mahoney (Sanchez and Mahoney 1996). The authors provocatively suggest that 'although organizations ostensibly design products, it can be argued that *'product design organizations'*.

Sanchez and Mahoney build on the key concept of 'nearly decomposable systems' (Simon 1996) to investigate the ability of a modular technical architecture to coordinate an organization without the need of continually exercising authority. The authors explain how technological knowledge about components interaction (architectural knowledge) can be used to create a 'nearly decomposable system' of modules.

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[63] I often used the term 'artifact' rather than 'product' in this thesis, until this point. In this 'implications' section, instead, I use the term 'product' which is much more familiar in the field of management. The terms are nearly synonymous, in that most products are artifacts and vice-versa. The cases of artifacts that are not products and of products that are not artifacts are special cases that have no important impact of this theoretical quest.

The modular product architecture provides a form of 'embedded coordination' that reduces the need of external authority in coordinating the activities of an organization.

Product development is a form of 'programmed' innovation. Traditionally engineered New Product Development follows a methodology of 'constrained optimization' which leads to integral products composed by tightly coupled components requiring strong managerial authority. An alternative design methodology could create a loosely coupled design by specifying the components interfaces of an architectural product model. This could allow for effective coordination of the development of the product without the continuous need of central authority. The information structure of a modular product architecture is 'the glue' of embedded coordination of product development. Traditional New Product Development is strongly influenced by these concepts: in fact, while traditional development processes are sequential, the emergence of a radically new modular product design triggers a completely different development process, with disruptive consequences on organizational structures.

Background: the Mirroring Hypothesis and the concept of Strategic Bottleneck

A stream of recent academic studies argue that a relationship exists between the structure of an organization and the design of the products that this organization produces. Specifically, products tend to "mirror" the architectures of the organizations in which they are developed. This dynamics occurs because the organization's governance structures, problem-solving routines and communication patterns constrain the space in which it searches for new solutions (C Y Baldwin 2015).

The concept of Strategic Bottleneck, connected to that of Industry Architecture, is emerging as an important issue in Strategic Management. Strategic Bottlenecks are originated by important technical problems that, when solved, generate critical points in an industry. The control of these critical points (obtained for example through managerial action on organizational boundaries and property rights) can generate a stream of rents for the firm who is able to understand the complex technical system. (Baldwin 2015)

However, in the case of Radical Innovation whose inception and early development often takes place outside the established firms (like in the Turbojet case, Paper 3), the mirroring effect could also have the reverse origin. Extending to industry architectures the insight of Sanchez and Mahoney: Evolutionay Chimeras can build industries (or at least revolutionize their architecture), including they Strategic Bottlenecks.

A Woesian perspective of the mirroring hypothesis and strategic bottlenecks

The puzzling impact of the Turbojet revolution on the incumbent industry architecture
According to recent research, the Mirroring Hypothesis is in general sustained, but the direction of the arrow (from technological to organizational modularity, or vice-versa) is context-dependent (Colfer and Baldwin 2016).
The Woesian model could be the starting point in understanding the relation between technical and industry modular architectures in the all-important case of a pervasive Radical Innovation.

The impact of Radical Innovation on Industry Architectures and Strategic Bottlenecks

Radical Innovation creates novel artefacts, completely redefining the technical architecture, and therefore the Industry Architecture, or even generating new industries. The novel Dominant Design usually emerges in a niche (e.g. chasing small game on difficult terrain for the bow and arrow; chasing big bombers at high altitudes for the pure turbojet), diffusing only afterward to other environments and industries. These processes are jeopardized by incomplete architectural knowledge. Integrating different modular levels into the same organization can be the right initial strategy to build this (organizational and technical) knowledge. For example, at the beginning of civil transport in the late twenties Boeing (an aircraft builder) incorporated also an airline (the Boeing Air Transport, later to become United Airlines). De Havilland, a British aircraft builder who pioneered the first jetliner, the Comet, also designed and built the turbojet engines which equipped it. In both cases the company modular architectures ended up by mirroring the artifacts' 'natural' architecture. Significantly, the organizational architecture engine-airplane-airline had mirrored that of its technical counterpart by 1959, just after the Turbojet Revolution was completed also in civil aviation. [64]

Strategic Bottlenecks after the revolution

The aviation industry landscape had profoundly changed in comparison with the one preceding the revolution: as Hill and Rothaermel write, many important incumbents had declined and disappeared.

But the impact on the industry architecture shows also other unexpected features:

- first, the three winning British firms which were awarded by Sir Edward Hulton were all incumbents: Rolls Royce, de Havilland, BOAC. No new entrant had survived the Turbojet Revolution in a leading role. The same could be said of the American

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[64] In the turbojet case the mirroring of the turbojet technical architecture into the organizational architecture was completed in Britain (at that time the more advanced industry in turbojet building) by 1959, soon after the complete takeover of civil aviation by jet propulsion (the Jet Age). The event is epitomized by this incipit of short celebrative article published by Flight Magazine:*'On March 25 the Hulton Achievement Award for 1959 was handed by Sir Edward Hulton to Sir Geoffrey de Havilland. Sir Geoffrey was receiving it on behalf of the de Havilland Aircraft Co. Ltd., Rolls-Royce Ltd., and the British Overseas Airways Corporation, respectively responsible for building, powering and operating the Comet. In a brief speech Sir Edward Hulton said, "It is hoped this award will do something to tell the world that some of the features of modern life are British. The Comet 4 is a shining example of the British virtue of teamwork."* Interestingly, at that time the British airliner Comet, which had pioneered the path towards the jet age, was struggling under the burden of deadly catastrophes due to defective manufacturing and an already obsolete design, but the industry architecture was following the same path in the US and in other countries (e.g. France and the Soviet Union) manufacturing jet airliners.

counterparts, where General Electric (aeroengines), Boeing and Douglas (aircraft), Pan Am and TWA (airlines) were emerging as the winners;

- at a very high modular level, a clean and simple mirroring between technical modularity and industry modularity emerged: the hierarchy engine-aircraft-airline. The case for the mirroring hypothesis driven by technical architecture seems strong here, as discussed;
- at a lower modular level (aeroengines) a different picture appears: an integral rather than modular approach was the winning managerial choice. The dominant firms emerging from the Revolution were still incumbents (e.g Rolls Royce in the UK and general Electric in the USA) but their success can be traced to the control of a key functional module (the turbo-compressor) and an integral, rather than modular approach to other core modules, whose control, if not already possessed (Rolls Royce) was purposefully acquired (general Electric).

While it is of course a single – albeit important – case, certain regularities emerging from the historical record seem to promise a path of theoretical research for the Mirroring Hypothesis Of course, the Strategic Bottlenecks of the extant industry are destroyed as the industry architecture is recreated. The historical case of the Turbojet Revolution with its puzzling outcome in organizational terms suggests that incumbents has more than a chance of playing a role or even dominating the new post-revolution industrial world, thanks to their *replicative/integrative capability* but the intrinsic unpredictability of radical innovation requires novel managerial approaches in the fluid phase that often takes place at the periphery of the industry.

Conclusions: Holistic Function

The Woesian model proposed in this thesis highlights a different viewpoint explaining how new technologies, and particularly radical technologies, are originated. The horizontal transfer of functional modules and their recombination into a higher-level functional module could be seen (and it was in the cases discussed in the papers, from the Bow and Arrow to the Turbojet) as the crucial evolutionary process leading to radical innovation. While extant research emphasizes how innovations typically originate from the recombination of available knowledge, the specific processes by which recombination occurs and when (i.e., through which evolutionary phases) they are supposed to be at work were not examined explicitly. By exposing the nature of these processes, it is possible to distinguish between the case in which new functions emerge and then new artifacts are designed to perform those functions from the case in which (like in the bow and arrow, Paper 2, or the 'pure' turbojet, Paper 3) existing functional modules can be integrated into a radically new architecture generating a higher-level function (superfunction) that endows the novel artifact with extraordinary performances. Significantly, the emergence of the higher level *holistic function*[65] can integrate (as sub-processes) phenomena of *modular exaptation* (Andriani and Carignani 2014). For example, Paper 2 is built on the hypothesis (supported by recent archeological discoveries) that the exaptation of extant modules (snares or bow-drills) originated the Bow and Arrow. Paper 3 shows how existing functional modules (turbines and turbocompressor) underwent an exaptation process, in that their performances were insufficient for functioning into the new architecture, suggesting also the opportunity of defining and measuring the 'degree' of exaptation. The nature of technological exaptation – a concept now accepted in innovation studies – could possibly be further developed within the broader framework of a Woesian evolutionary model. Moreover, the complex analogy suggests that the knowledge acquired in bacterial evolution, where significant cases of holistic superfunctions have been ascertained[66], can be carefully but confidently transferred to innovation studies.

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[65] The term 'holistic' is used by Constant (1980) to characterize the turbojet

[66] For example, a case in which the acquisition and retention of number of modules with different functions, and the resulting innovation is not simply the sum of the different functions, but a *superfunction* is the case of the acquisition

The theory developed in the three papers suggests that any evolutionary approach based solely on vertical inheritance fails to recognize the central role of the horizontal transfer of functional modules and the underlying scientific, engineering and managerial knowledge. While these functional modules may be naively considered just engineering innovations (indeed, their short-sighted inventors often regarded them as such), their availability in the pool of transferable functional modules emerges as a necessary trigger enabling radical recombination, and could maybe be recognized as the real driver of Industrial Revolutions, including the one we are living through. Indeed, what Woese himself argued about microbiological evolution in the fluid era preceding the Darwinian Threshold can provide a beautiful yet precise description of the origins of technological radical change: "*only global invention arising in a diverse collection of primitive entities is capable of providing the requisite novelty*" (Woese 2002, p. 8746).

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of pathogenicity by not-virulent bacteria (Hacker and Kaper 2000). The superfunction is associated to a module of higher level, composed of the recombined modules, the so-called pathogenicity islands.

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