Mario Coccia

Technological Parasitism

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Preface

How does technology evolve? The book confronts this question here by developing *the theory of technological parasitism*, which endeavors to analyze and explain, with a new perspective, the relationships supporting the evolution of complex systems of technology in society.

This study is part of a large body of research on the evolution of technology started in 2016 at Arizona State University (Center for Social Dynamics and Complexity, Tempe AZ, USA), continued at Yale University in 2019 (School of medicine, New Haven CT, USA) and now is ongoing at National Research Council of Italy (Torino, Italy). This book is designed for students, undergraduates, graduates, managers in business and public administration, policymakers that wish to understand: critical characteristics of the evolution of technology, relationships between technologies in complex systems that clarify the driving forces of technical change, properties that explain which technologies are likely to evolve rapidly and, as well as also wish to expand their knowledge on these research fields that could aid management of firms and innovation strategy of nations to implement best practices of product/process design and development for supporting R&D investments, sustaining and safeguarding competitive advantage in markets.

In order to attain a reasonable depth, this book concentrates on critical topics of particular relevance in economics of innovation and technology that meet the needs of the intended audience. The book is divided in four inter-related chapters.

1. First of all, the chapter 1 of the book explains the main theories concerning the evolution of technologies, given by *a)* theories based on processes of competitive substitution of a new technology for the old one in markets; *b)* theories based on a multi-mode interaction between technologies.
2. The chapter 2 of this book proposes a new taxonomy of interactive technologies within a theoretical framework of Generalized Darwinism. This chapter supports the theory of technological parasitism that will be explained in next chapters.
3. The chapter 3 explains the evolution of technology with a new theory, called *technological parasitism*, which is based on the idea that parasite-host relationships between technologies and systems of technology with a high number of technological parasites have an accelerated evolution driven by long-run relationships of mutualistic symbioses. This theory may be useful for bringing a new perspective to explain and generalize, as far as possible, the evolution of technology directed to sustain competitive advantage of firms and nations in markets.
4. The final chapter 4 of the book focuses on a model of technometrics based on *theory of technological parasitism* to

measure the speed of technological evolution for supporting implications of innovations strategy and management of technology, as well as to monitor technological pathways during the transition from starting state of parasitic technology to final state of symbiosis that accelerates the technological evolution with a pervasive effect on economic and social change. This suggested model of technometrics, within the technological parasitism, also detects which technologies are likely to evolve rapidly for sustaining best practices of innovation management to safeguard competitive advantage of firms and nations.

Overall, then, no single book could hope to cover adequately all aspects of what is wide and essentially multi-disciplinary field of inquiry, and it is not the intention here to attempt to cover all aspects and topics of the evolution of technology and technological change in society. It is regrettable but inevitable therefore that some topics are excluded or given only limited coverage and it is not possible to meet fully the preferences of all readers. I hope that readers dealing with economics of innovation and technology, and in particular with topics of technological evolution, such as students, managers, policymakers, etc. are able to see this text as a starting point to understand the complex processes, characteristics, properties and relationships of the evolution of technology and technological change in society. Finally, this book's strengths and weaknesses are the responsibility of author.

M. Coccia
December 9, 2019

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Contents

Introduction

The evolution of technology is socioeconomic factor that plays an important role for the economic and social change of societies and the competitive advantage of firms and nations. In the context of social studies of science and technology, two vital concepts are: evolution and technology. *Evolution* is a stepwise and comprehensive development of a complex system in nature or in society. *Technology* is a complex system, made and/or used by living systems, that is composed of more than one entity or subsystem and a relationship that holds between each entity and at least one other entity in the system. Technology is selected considering practical, technical, social and/or economic characteristics to satisfy needs, achieve goals and/or solve problems of users for purposes of adaptation and/or survival in a highly differentiated and volatile environment. Technology changes current modes of cognition and action to enable makers and/or users to take advantage of important opportunities or to cope with consequential environmental threats. Technology is driven by *inventions* of new things, new ways of doing things, and transformation of inventions into usable *innovations* in markets, and the subsequent adoption, diffusion and evolution of such innovations in society. Technology, as a complex system, develops with four typology of innovation, generating technological change, especially: *incremental innovation* (progressive modifications of existing products and processes); *radical innovation* (a drastic change of existing products/processes, or new products to satisfy needs or solve problems in society); *technological systems* (a cluster of innovations that are technically and economically inter-related, e.g., nanotechnology); *technological revolution* (pervasive changes in technology affecting many branches of the economy, such as general purpose technologies of Information and Communication Technologies having a pervasive use in a wide range of sectors and technological dynamism). Technology also evolves with *learning*–by using, by doing, by interacting–of how to solve specific problems in a turbulent (complex and dynamic) environment. Sahal (1981), analyzing the patterns of technological innovation, argues that: "evolution…pertains to the very structure and function of the object (p.64) …. involves a process of equilibrium governed by the internal dynamics of the object system (p.69)". Kauffman & Macready (1995, p.26, original emphasis) state that: "technological evolution, like biological evolution, can be considered a search across a space of possibilities on complex, multipeaked 'fitness,' 'efficiency,' or 'cost' landscapes". Kauffman & Macready (1995, p. 27 and p.42) also point out that evolution, biological or technological, is actually a story of coevolution. In particular, the evolution of technology paves the way for other technologies in a process that Kauffman has called ''expanding the adjacent possible''.

Studies about technological evolution are dominated by approaches based on processes of competitive substitution of a new technology for the old one in a world of creative destruction of existing products (Calvano, 2006; Fisher & Pry, 1971; Sahal, 1981). These theories of competitive substitution between technologies show that the adoption of a new technology is associated with the nature of some comparable old technology in use (Sahal, 1981; Utterback *et al.,* 2019). In particular, when comparable technologies do exist, each technology tends to affect the character and evolutionary pathway of other technologies. The evolution of technology in these approaches is a process of actual substitution of new technology for the old technology in markets, such as the replacement of Compact Disk with Universal Serial Bus (USB) flash drive as device of data storage. In general, emerging technologies often substitute for more mature technologies. To put it differently, the competition between technologies implies a rivalry that is associated with the rate at which a new technology attempts of substituting for existing technologies in markets, generating technological change.

However, representations of the competition between technologies are in many respects unsatisfactory to explain the relationships underlying technological evolution. In fact, theories of competitive substitution between technologies have been criticized on a number of points because neglect many characteristics that are strongly related to the evolution of technology. Although the concept of competition is frequently used in diffusion and evolution of technology and innovation (Sahal, 1981), technological evolution is often not only a process of competitive substitution (cf., Utterback *et al.,* 2019). There are many cases where systems of technology evolve with a relationship of mutualistic symbiosis between inter-related technologies (Geels, 2005, pp.691-692; Raven & Verborg, 2009, pp.90-91;

Yang *et al.,* 2019). In fact, Utterback *et al.* (2019) suggest to abandon the approach that technology and innovations originate and evolve only in pure competition between emerging and established artifacts. These scholars argue that races between new and old products/processes have a behavior in which the growth of one innovative product/process or in general technology will often stimulate the growth of other inter-related products/processes, calling this interaction "symbiotic competition" (Utterback *et al.,* 2019, p.1; cf. also, Chi *et al.,* 2013). As a matter of fact, technologies can also interact in a relationship that is *not* a zero-sum game of pure competition (Utterback *et al.,* 2019). Hence, the theories of pure competition in the evolution of technology have been criticized because they do not clarify the understanding of all characteristics of *how* and *why* certain technologies evolve in relation to other inter-related technologies (Utterback *et al.,* 2019).

Current literature in economics of innovation and technology suggests approaches based on a multi-mode interaction between technologies because they provide a much richer and useful theoretical framework for technology analysis of technological evolution in markets with rapid change (Utterback *et al.,* 2019). These approaches are based on a broad analogy between technological evolution and biological evolution (Arthur, 2009; Basalla, 1988; Wagner & Rosen, 2014). In fact, the similarities between biological and technological evolution have generated a considerable literature (see reviews in Erwin & Krakauer, 2004; Schuster, 2016; Solé *et al.,* 2011, 2013). In particular, these approaches suggest that technological evolution, alongside biological evolution, displays radiations, stasis, extinctions, and novelty (Andriani & Cohen, 2013; Valverde *et al.,* 2007).

In this context of a new perspective to explain the evolution of technology based on multi-mode interaction between technologies, this book proposes a *new* conceptual scheme of the evolution of technology, the *theory of technological parasitism*. The scientific departure of this theory of technological parasitism is the approach of "Generalized Darwinism" (Hodgson & Knudsen, 2006; cf., Ziman, 2000) that provides a suitable theoretical framework for framing a broad analogy between evolutionary ecology of parasites and evolution of technologies (cf., Schuster, 2016, p.7; Coccia M. in additional references with studies from 2016 to 2019). In particular, the heuristic principles of "Generalized Darwinism" can underpin theoretical aspects of technological development considering analogies between evolution in the biological sense and similar-looking processes in the evolution of technology (Farrell, 1993). In fact, Schuster (2016, p.8) argues that: "technologies form complex networks of mutual dependences just as the different species do in the food webs of ecosystems" (cf., Iacopini *et al.*, 2018; Vespignani, 2009). The proposed *theory of technological parasitism is based on the idea that parasite-host relationships between technologies and systems of technology with a high number of technological parasites have an accelerated evolution driven by long-run relationships of mutualistic symbioses, providing the basis for extensive macroevolution and adaptive behavior of systems of interactive technologies in markets. This theory may be useful for bringing a new perspective to explain and generalize, whenever possible, the evolution of technology directed to sustain competitive advantage of firms and nations. In particular, technological parasitism explains the relationship of mutualistic symbiosis between a host (or master) technology and inter-related technologies to satisfy needs and/or to solve consequential problems of socioeconomic subjects over time.* In short, the concept of technological parasitism, based on technologies that depend on and interact within complex systems of host-master technologies, can explain general characteristics and relationships of the evolution of many technologies (e.g., smartphone, headphone, Blue toot technology, etc.).

In particular, the main goal of this book is to propose *this new theory of technological parasitism* that explains the relationships between technologies in complex systems that support the evolution of technology with consequences for economic, industrial and social change. This conceptual scheme here, based on the parasite-host relationships between technologies, is especially relevant in Schumpeterian markets with innovation-based competition to explain a major source of technological evolution and success. Especially, the book here focuses on new studies published on international journals that can explain the *relationships* underlying the evolution of systems of technology, *how* to measure the rate/speed of the evolution of technology within the theory of technological parasitism, and a theoretical framework towards a new taxonomy of interactive technologies that shows dynamic pathways of interactive technologies from initial state to advanced state of symbiosis. In fact, a parasite technology in a host system of technology is a starting state that can generate an evolution of overall technological host-parasite system towards states of commensalism, mutualism and finally symbiosis in the long run, such as the interaction between Bluetooth technology and mobile devices (cf., Chapter 2 and 4). New theory of technological parasitism, presented in this book, suggests *a new direction* for the development of more sophisticated concepts and theoretical frameworks to explain underlying dynamics of technological and industrial change in economic systems. Overall, then, this book, for the first time to our knowledge, present a theory of technological evolution that begins the process of clarifying and generalizing, as far as possible, the role of long-run coevolution between *host and parasitic technologies* in complex systems, suggesting to policymakers and managers fruitful implications for innovation management to support appropriate decision-making processes concerning the evolution and success of technologies in markets with rapid change. For in-depth analysis of specific topics discussed in this book, curious readers can refer to additional references indicated in this and other sections of the book.

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1 Theories of the evolution of technology: traditional and new perspectives

Introduction

The evolution of technology plays an important role in the economic and social change of societies and competitive advantage of firms and nations (Arthur, 2009; Basalla, 1988; Bryan *et al.*, 2007; Coccia, 2018; Coccia, 2018a, 2019; Hosler, 1994)[1]. In order to explain the evolution of technology, it is important to clarify the concept of evolution and of technology.

Firstly, evolution is a stepwise and comprehensive development of a complex system in nature and society. Sahal (1981), analyzing technical phenomena, argues that:

[1]For studies about measurement of technology, technological evolution and sources of technology, cf., Calabrese *et al.*, 2005; Coccia, 2003, 2005, 2005a, 2005b, 2005c, 2006, 2010, 2010a, 2013, 2013a, 2014, 2014a, 2014b, 2014c, 2014d, 2014e, 2015, 2015a, 2015b, 2016, 2016a, 2016b, 2017, 2017a, 2018, 2018a, 2018b, 2018c, 2018d, 2019; Coccia & Bozeman, 2016; Coccia & Cadario, 2014; Coccia *et al.*, 2015; Coccia & Rolfo, 2009, 2010, 2013; Coccia & Wang, 2016.

"evolution… pertains to the very structure and function of the object (p.64)…. involves a process of equilibrium governed by the internal dynamics of the object system (p.69)". Kauffman & Macready (1995, p.26, original emphasis) state that: "Technological evolution, like biological evolution, can be considered a search across a space of possibilities on complex, multipeaked 'fitness,' 'efficiency,' or 'cost' landscapes". Kauffman & Macready (1995, p.27 and p.42) also point out that evolution, biological or technological, is actually a story of coevolution.

Secondly, technology is a complex system that is composed of more than one entity or sub-system and a relationship that holds between each entity and at least one other entity in the system. The technology is selected and adapted in the environment to satisfy needs, achieve goals and/or solve problems of human society. Any technology is not independent from the behavior of other technologies (Coccia, 2018, 2018a). An important concept is the interaction between technologies: an interrelationship of information/resources/energy and other physical/chemical phenomena in inter-related complex systems for reciprocal adaptations within environment. In this context, another key concept is the coevolution of technologies: the evolution of reciprocal adaptations in a complex system, supporting the reciprocal enhancement of technologies' growth rate and innovation—i.e., a modification and/or improvement of technologies based on interaction and adaptation in a complex system to satisfy changing needs and solve consequential problems of people in society.

Technological evolution can be explained in economics and management with two different approaches (Figure 1):

- Traditional theories are based on processes of competitive substitution of a new technology for the old one (Fisher & Pry, 1971) or a competition between predator and prey technologies (Pistorius & Utterback, 1997).

- New theories consider a multi-mode interaction between technologies (Coccia, 2018; Pistorius & Utterback, 1997; Utterback *et al.*, 2019; Sandén & Hillman, 2011). The interaction between technologies can generate a mutual benefaction that reduces negative effects and favors positive effects directed to an evolution of reciprocal adaptations of technologies that fosters innovation over time (Coccia, 2018; 2019). A main theory in this new research stream is the theory of technological parasitism by Coccia (2019).

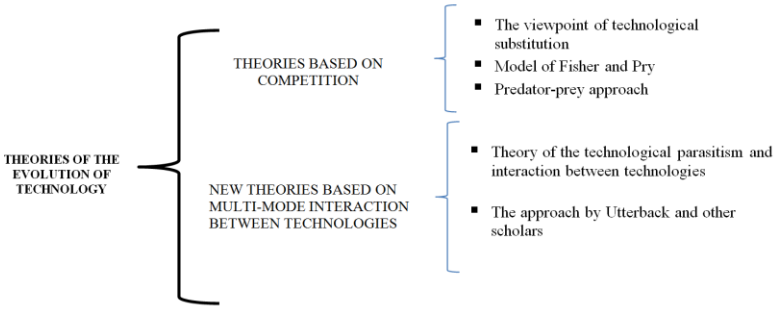

Figure 1. *Theories of the evolution of technology*

Theories of evolution of technologies based on comperirion between the new and the established technologies

Theories of competitive substitution between technologies, model of Fisher and Pry and predator-prey interaction.

An established technology improves when confronted with the prospect of being substituted by a new technology. In general, the adoption of a new technology is associated with the nature of some comparable older technology in use. When comparable technologies do exist, each technology tends to affect the character of the other. The evolution of technology does not take place in isolation. It is a process of actual substitution of new technology for the old one. More generally, the adoption of an innovation involves actual substitution of the new technology for the old. Pistorius & Utterback (1997) also argue that emerging technologies often substitute for more mature technologies. This interaction between technologies is typically referred to as competition, implying a confrontational interaction. The interaction is manifested in the degree and rate at which the new technology is adopted when it attempts, and often succeeds, in substituting for the existing technologies. Pistorius & Utterback (1997, p.72) claim: "Pure competition, where an emerging technology has a negative influence on the growth of a mature technology, and the mature technology has a negative influence on the growth of the emerging technology". Porter (1980) considers substitutes as one of the five forces in his model of industrial competition.

The growth in the use of new and old technology can follow some S-shaped patters (Sahal, 1981). An attempt to operationalize thisapproach, focusing on temporal aspect of the evolution of technology, was originally presented by Fisher & Pry (1971, p.75) that argue how technological evolution consists of substituting a new technology for the old one, such as the substitution of coal for wood, hydrocarbons for coal, robotics technologies for humans, etc. To put it differently, technological advances are represented by competitive substitutions of one method of satisfying a need for another. Fisher & Pry (1971, p.88) also state that: "The speed with which a substitution takes place is not a simple measure of the pace of technical advance … it is, rather a measure of the unbalance in these factors between the competitive elements of the substitution".

Farrell (1993, 1993a), instead, used a model based on Lotka-Volterra equations to examine pure competition between various technologies, such as nylon versus rayon tire cords, and telephone versus telegraph usage. Competition is often embodied insubstitutes, which have been recognized as a powerfulforce in competition. In this context, the interaction between technologies can generate a predator-prey interaction, where one technology enhances the growth rate of the other but the second inhibits the growth rate of the first (Pistorius & Utterback, 1997, p.74). In fact, a predator-prey relationship can exist between an emerging technology and a mature technology where the emerging technology enters a niche market that is not served by the mature technology. In this case the emerging technology will benefit from the presence of the mature technology. At the same time, the emerging technology may slowly be stealing market share from the mature technology. Overall, then, a predator-prey interaction has emerging technology in the role of predator and the mature technology as the prey. On the other hand, one can also visualize a situation where the mature technology is the predator and the emerging technology is the prey (Pistorius & Utterback, 1997, p.78).

New theories of evolution based on interacting technologies

Utterback *et al.* (2019) suggest to abandon the idea that technology and innovation originate only in pure competition between the new and the established practices. These scholars believe that more likely the races between new and older products, processes and services, growth of one will often stimulate growth of the others, calling this interaction *symbiotic competition* (Utterback *et al.*, 2019). As a matter of fact, there are many cases where technologies interactin a relationship that is not confrontational andwhere the interaction between technologies is thereforenot one of competition in the strict sense of theword. In this context, the theory of technological parasitism by Coccia (2018, 2019) is an interesting theoretical framework to explain how interaction between technologies generate coevolution of complex systems of artifacts.

Theory of Technological Parasitism

The theoretical background of this theory is based on a "Generalized Darwinism" (Hodgson & Knudsen, 2006) for framing a broad analogy between technologies and evolutionary ecology of parasites that provides a logical structure of scientific inquiry (cf., Coccia, 2018). Basalla (1988) also suggested that the evolution of technology can profitably be seen as analogous to biological evolution. Technological evolution, alongside biological evolution, displays radiations, stasis, extinctions, and novelty (Solé*et al.*, 2013). In this context, Pistorius & Utterback (1997, p.72ff) suggest different interactions among technologies in analogy with biology. Sandén & Hillman (2011, p.407) point out a further refinement of these topics by the introduction of a six-mode typology, using similarity with the interaction of species, in which they differentiate the following technological interactions: neutralism, commensalism, amensalism, symbiosis, competition and parasitism (and predation into one category). This theoretical framework is the background of the theory of technological parasitism by Coccia (2019, 2018) to explain the evolution of technology in society.

The crux of the theory is rooted in evolutionary ecology of parasites and since this approach is uncommon in the social sciences some concepts are useful to understand and clarify it. In the evolutionary ecology, parasites (from Greek para = near; sitos = food) are any life form finding their ecological niche in another living system (host). Parasites have a range of traits that evolve to locate in available hosts, survive and disperse among hosts, reproduce and persist. Coccia (2019,

2018) argues that technologies can have a behavior similar to parasites because technologies cannot survive and develop as independent systems *per se*, but they can function and evolve in markets if associated with other host or master technologies, such as audio headphones, speakers, software apps, etc. that function if and only if they are associated with host or master electronic devices, such as smartphone, radio receiver, television, etc.In particular, a parasitic technology P in a host or master technology H is atechnology P that during its life cycle is able to interact and adapt into the complex system of H, generating coevolutionary processes to satisfy needs and human desires and/or solve problems in society. Parasitic technologies are often sub-systems embedded within and primarily functional in the ecological system of other host (or master) technologies. For instance, audio headphones are parasitic technologies of many electronic/audio devices. A technology can be a parasite of different host or master technologies, as well as a technology can be a host or master of different parasitic technologies(e.g., mobile devices are host of software applications, headphones, Bluetooth technology, etc.; cf., Coccia, 2018). In general, many technologies do not function as independent systems themselves, but *de facto* they depend, as parasites, on other technologies (hosts or masters) to form a complex system of parts that interact in a non-simple way. This behavior of technologies can be generalized with the *theorem of not independence of any technology* (Coccia, 2018a): the long-run behavior and evolution of any technological innovation Ti is not independent from the behavior and evolution of the other technological innovations Tj, $\forall i = 1, \ldots, n$ and $j = 1, \ldots, m$

This theory proposes a model to analyze the interaction between a host technology (system) and a parasitic technology (subsystem) to explain evolutionary pathways of technologies as complex systems. The logarithmic form of the model (Coccia, 2019) is a simple linear relationship:

$$\log P = \log A + B \ \log H$$

B is the evolutionary coefficient of growth that measures the evolution of technology P (Parasite) in relation to H (host or master technology). The value of B measures the relative growth of P in relation to the growth of H and it suggests different patterns of technological evolution: B<1 (underdevelopment of host-parasite technological system), B> 1 (development of host-parasite technological system), B=1 (growth of host-parasite technological system).

This theory of technological parasitism suggests the following findings and predictions in the evolution of technology (Coccia, 2018, 2019):

1. The long-run behavior and evolution of any technology depend on behavior and evolution of inter-related technologies; in particular, the long-run behavior and evolution of any technology are driven by interactions with other technologies within and between complex systems. To put it differently, long-run evolution of a specific technology is enhanced by the integration of two or more parasitic/symbiotic technologies that generate co-evolution of the overall complex system of technology (Coccia, 2019).
2. The long-run evolution of an established technology is due to interaction with new (parasitic) technologies.
3. Technological host or master systems with many parasitic technologies generate a rapid stepwise evolution of technological host-parasite systems. Technological systems with fewer parasitic technologies and a low level of interaction with associated technologies improve slowly.
4. Technology having an accelerated growth of its parasitic technologies advances rapidly, whereas technology

with low growth of its parasitic technologies enhances slowly.

5. Interaction within technological host-parasite systems generates coevolution with the shift from technological parasitism to technological symbiosis over the course of time (see figure 2). The *property of mutual benefaction* argues that the interaction between technologies reduces negative effects and favors positive effects directed to an evolution of reciprocal adaptations of technologies in complex systems of technology over time and space (Coccia, 2018).

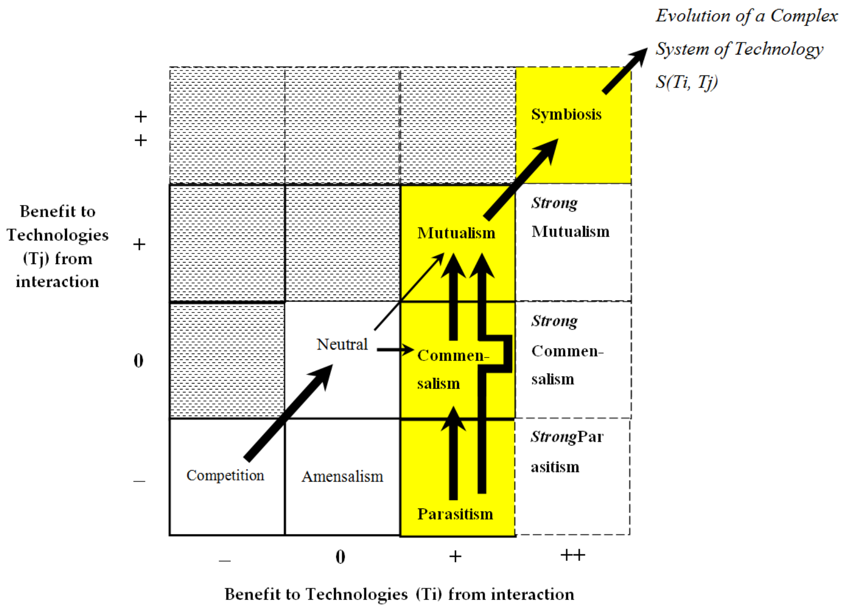

Figure 2. *Types of relationships between technologies and evolutionary pathways in a complex system. Note. The notions of positive, negative and neutral benefit to technologies Ti and Tj in S from mutual interaction are represented with following symbols of logic: +, –, 0 (zero); ++ is a strong positive benefit to technologies Ti and Tj in S from long-run mutual- symbiotic interaction (i.e., coevolution of Ti and Tj in S, ∀i=1,…,n; ∀j=1,…,m).*

The idea of a "technological parasitism" should not necessarily be considered as a general behavior, because it is adequate in some cases but less in others because of the diversity of technologies and their interaction in complex systems and socioeconomic environments (cf., Coccia, 2018; Pistorius & Utterback, 1997; Sandén & Hillman, 2011). Nevertheless, the analogy keeps its validity in explaining several phenomena of the coevolution of technology in markets and society. The theory of technological parasitism suggests some general properties that are a reasonable starting point for understanding the universal features of the coevolution of technologies that leads to technological and economic change, though the model of course cannot predict any given paths and characteristics of the evolution of technologies with precision. We know, *de facto*, that other things are often not equal over time and space in the domain of technology.

Conclusion

The evolution of technology is associated with the idea of human progress. The distal factor of the evolution of technology is a progressive satisfaction of human wants, such as the improvement of health, the growth of wealth, the creation of new knowledge, the solution of complex problems, etc. In general, determinants of technological evolution and, as a consequence, of human progress seem to be human wants and human control of nature through science advances and new technology (cf., Coccia, 2010, 2018). Moreover, the evolution of technologies runs in appropriate social structures with strong democracy, good economic governance, widespread higher education system, specific culture, predominant religion, growth rates of population, purposeful of socioeconomic systems, etc. (Coccia, 2010, 2014, 2015, 2018). These elements support the acquisition by humanity of better and more complex forms of life.

To conclude, evolution of technology is a result of human activity and human nature in order to take advantage of important opportunities, to cope with and/or adapt to environmental threats and/or changing contexts. Overall, then, evolution of technologyis mainly linked to the question of what human beings truly need and how they seek to satisfy needs, solve social issues and adapt to new social, political and economic conditions. As a matter of fact, these theories described here can encourage further theoretical and empirical exploration in the *terra incognita* of the evolution of technology to explain economic and social change in human society. However, Wright (1997, p.1562) properly claims that: “In the world of technological change, bounded rationality is the rule.”

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2 Towards a taxonomy and theory of interactive technologies and evolutionary pathways

Introduction

Patterns of technological innovation have also been analyzed using analogies with biological phenomena over the last century (Basalla, 1988; Nelson & Winter, 1982; Solé *et al.*, 2013; Sahal, 1981; Veblen, 1904; Wagner, 2011; Ziman, 2000). Wagner & Rosen (2014) argue that the application of Darwinian and evolutionary biological thinking to different research fields has reduced the distance between life sciences and social sciences generating new approaches, such as the evolutionary theory of economic change (Nelson & Winter, 1982; cf., Dosi, 1988). Basalla (1988) suggests the similarity between history of technology and biological evolution. Usher (1954), within these research fields, analyzed the nature of technological processes and the forces that influenced events at technical level (cf., Ruttan, 2001). In general, technological evolution, as biological evolution, displays radiations, stasis, extinctions, and novelty (Valverde *et al.*, 2007).

Scholars of the economics of technical change have tried of defining, explaining and measuring innovation in its many forms as well as of providing classifications of technical change and progress (Asimakopulos & Weldon, 1963; Bigman, 1979; Coccia, 2006; Freeman & Soete, 1987; Pavitt, 1984; Robinson, 1971). As a matter of fact, the study and classification of technological innovations are a central and enduring research theme in the economics of technical change (Bowker, 2000; Jones *et al.,* 2012). Although the concepts of "classification" and "taxonomy" are almost synonyms, they have different meaning. The term taxonomy (from ancient Greek word taxon=arrangement, array) refers to a branch of systematics based on the theory and practice of producing classification schemes with the aim of maximizing the differences among groups. Thus, a taxonomic process provides rules on how to form and represent groups with classification. Instead, classification in science is a product of the taxonomic process that represents classes of entities with a matrix, a table, a dendrogram, etc. (McKelvey, 1982). For instance, the biological classification by Linnaeus, the periodic classification of chemical elements by Mendeleev, the Mercalli scale in seismology, the Beaufort wind force scale, etc. (Coccia, 2006). Taxonomy has usefulness in natural and social sciences if it is able to reduce the complexity of the population studied into simple classes, which are represented by a classification (Archibugi, 2001). In particular, social sciences have two general approaches to create a classification: the empirical and theoretical one (Rich, 1992; Doty & Glick, 1994). Theoretical classifications in social sciences begin by developing a theory of differences which then results in a classification of typologies. The empirical approach begins by gathering data about the entities under study. These data are then processed using statistical techniques to produce groups with measures of similarity (e.g., Minkowski distance, Manhattan distance, Euclidean distance, Weighted Euclidean distance, Mahalanobis distance, Chord distance, etc.).

The subject matter of this study here is taxonomy of technologies. In general, technology studies present severaltaxonomies of technical change (Coccia, 2006; Freeman & Soete, 1987; Pavitt, 1984). However, a taxonomy that considers the interaction between technologies in complex systems is unknown.

This paper here has two goals. The first is to propose a new taxonomy of technologies based on a taxonomic characteristic of interaction between technologies within complex systems. The second is to explain and generalize, whenever possible this theory that may clarify the typologies of interactive technologies that support paths of technological evolution over time. Overall, then, this theoretical framework here can systematize and predict behaviour of interactive technologies and their evolutionary pathways in complex systems, and encourage further theoretical exploration in this *terra incognita* of the interaction between technologies during technological and economic change.

Theoretical background

Economics of technical change presents many classifications of technological innovation (Coccia, 2006)[2]. De

[2] For studies of technology and sources of innovation, such as research labs, cf., Calabrese *et al.*, 2005; Cariola & Coccia, 2004; Cavallo *et al.*, 2014, 2014a, 2015; Coccia, 2001, 2003, 2004, 2005, 2005a, 2005b, 2005c, 2006, 2006a, 2007, 2008, 2008a, 2008b, 2009, 2009a, 2010, 2010a, 2010b, 2010c, 2010d, 2010e, 2011, 2012, 2012a, 2012b, 2012c, 2012d, 2013, 2013a, 2014, 2014a, 2014b, 2014c, 2014d, 2014e, 2014f, 2014g, 2015, 2015a, 2015b, 2015c, 2015d, 2016, 2016a, 2016b, 2016c, 2017, 2017a, 2017b, 2017c, 2017d, 2018, Coccia & Bozeman, 2016; Coccia & Finardi, 2012, 2013; Coccia & Wang, 2015, 2016; Coccia & Cadario, 2014; Coccia *et al.*, 2015, 2012, Coccia & Rolfo, 2000, 2002, 2009, 2012, 2007, 2010, 2010, 2013; Coccia & Wang, 2015, 2016; Rolfo & Coccia, 2005.

Marchi (2016, p. 983) argues that The Frascati and Oslo manuals assemble technological activities without attempting to propose a cogent organization of the categories. In these research fields, Rosenberg (1982) introduces the distinction between technology directed to new product development, and technology that generates cost reducing–process innovation. Hicks (1932) argued that technological progress is naturally directed to reducing the utilization of a factor that is becoming expansive. Archibugi & Simonetti (1998) suggest that each technological innovation can be classified considering:

1. *Technological nature of innovation* that is a technical description of technological innovation. This classification considers the objects of technological change;
2. *The sector of activity of the producing organization.* This is a classification by subject that promotes technological innovation;
3. *The product group where the innovation is used.* Here, it is considered the economic object of technological innovation;
4. *The using organization.* Here too, as in point 2, it is considered the economic subject of technological innovation;
5. *The human needs* which the technological innovation is designed to address.

Freeman & Soete (1987, pp. 55-62, original italics and emphasis) propose a taxonomy to categorize various types of technical change and distinguish:

> *Incremental Innovations.* These occur more or less continuously in any industry or service activity, although at a varying rate in different industries and over different time periods. They may often occur, as the outcome of improvements suggested by engineers and others directly engaged in the production process, or as a result of initiatives and proposals by users…. They are particularly important in the follow-through period after a radical breakthrough

innovation and frequently associated with the scaling up of plant and equipment and quality improvements to products and services for a variety of specific applications. Although their combined effect is extremely important in the growth of productivity, no single incremental innovation has dramatic effects, and they may sometimes pass unnoticed and unrecorded….

Radical Innovations. These are discontinuous events and in recent times is usually the result of a deliberate research and development activity in enterprises and/or in university and government laboratories. They are unevenly distributed over sectors and over time.... big improvements in the cost and quality of existing products.... in terms of their economic impact they are relatively small and localized…. Strictly speaking… radical innovations would constantly require the addition of new rows and columns in an input-output table….

New Technological Systems. Keirstead (1948)… introduced the concept of 'constellations' of innovations, which were technically and economically inter-related. Obvious examples are the clusters of synthetic materials innovations and petrochemical innovations in the thirties, forties and fifties…. They include numerous radical and incremental innovations in both products and processes (Freeman *et al.,* 1982).

Changes of 'Techno-Economic Paradigm' (Technological Revolutions). These are far-reaching and pervasive changes in technology, affecting many (or even all) branches of the economy, as well as giving rise to entirely new sectors. Examples given by Schumpeter were the steam engine and electric power. Characteristic of this type of technical change is that it affects the input cost structure and the conditions of production and distribution for almost every branch of the economy. A change in techno-economic

> paradigm thus comprises clusters of radical and incremental innovations and embraces several 'new technological systems'.

Sahal (1985, p.64, original Italics) argues that technological innovations can be: "*structural innovations* that arise from a process of differential growth; whereby the parts and the whole of a system do not grow at the same rate. Second, we have what may be called the *material innovations* that are necessitated in an attempt to meet the requisite changes in the criteria of technological construction as a consequence of changes in the scale of the object. Finally, we have what may be called the *systems innovations* that arise from integration of two or more symbiotic technologies in an attempt to simplify the outline of the overall structure". This trilogy can generate the emergence of various techniques including revolutionary innovations in a variety of technological and scientific fields (cf., Sahal, 1981; Coccia, 2016, 2016a).

Abernathy & Clark (1985, p.3) introduce the concept of transilience: "the capacity of an innovation to influence the established systems of production and marketing. Application of the concept results in a categorization of innovation into four types". In particular, the four typologies of innovation by Abernathy & Clark (1985, p.7ff, original italics) are:

> *Architectural innovation*. New technology that departs from established systems of production, and in turn opens up new linkages to markets and users, is characteristic of the creation of new industries as well as the reformation of old ones. Innovation of this sort defines the basic configuration of product and process, and establishes the technical and marketing agendas that will guide subsequent development. In effect, it lays down the architecture of the industry, the broad framework within which competition will occur and develop….

Innovation in the market niche…. Opening new market opportunities through the use of existing technology is central to the kind of innovation that they have labelled "Niche Creation", but here the effect on production and technical systems is to conserve and strengthen established designs…. In some instances, niche creation involves a truly trivial change in technology, in which the impact on productive systems and technical knowledge is incremental. But this type of innovation may also appear in concert with significant new product introductions, vigorous competition on the basis of features, technical refinements, and even technological shifts. The important point is that these changes build on established technical competence, and improve its applicability in emerging market segments….

Regular innovation…. is often almost invisible, yet can have a dramatic cumulative effect on product cost and performance. Regular innovation involves change that builds on established technical and production competence and that is applied to existing markets and customers. The effect of these changes is to entrench existing skills and resources…. can have dramatic effect on production costs, reliability and performance…. Regular innovation can have a significant effect on product characteristics and thus can serve to strengthen and entrench not only competence in production, but linkages to customers and markets….

*Revolution innovation.*Innovation that disrupts and renders established technical and production competence obsolete, yet is applied to existing markets and customers…. The reciprocating engine in aircraft, vacuum tubes, and mechanical calculators are recent examples of established technologies that have been over thrown through a revolutionary design. Yet the classic case of revolutionary innovation is the competitive duel between Ford and GM in the late

1920s and early 1930s.

Anderson & Tushman (1986) distinguish, in patterns of technological innovation, two types of discontinuous change: competence-enhancing and competence-destroying discontinuities. Competence-enhancing discontinuities are based on existing skills and know-how. Competence-destroying discontinuities, instead, require fundamentally new skills and cause obsolescence of existing products and knowledge. In general, technological shifts are due toboth competence-destroying and competence-enhancing because some firms can either destroy or enhance the competence existing in industries (*cf.*,Tushman & Anderson, 1986). Usher (1954), in this context, argues that technological innovation is driven by a cumulative significance in the inventive process (cf., Rosenberg, 1982).

Grodal *et al.*, (2015), in management of technology, propose that the evolution of both technological designs and categories follows a similar pattern, characterized by an early period of divergence followed by a period of convergence. Grodal *et al.*, (2015, p. 426) identify the following mechanisms within coevolutionary processes of technology:

- Design recombination is the creative synthesis of two or more previously separate designs that results in the creation of a new design to address an existing or potential need.
- Path dependence is the mechanism through which the cumulative effects of prior technological design choices increasingly determine and constrain subsequent design recombinations.
- Design competition is the mechanism by which producers and users make design investment choices about which designs to retain and which to abandon.

Garcia & Calantone (2002) apply Boolean logic to identify three labels in product innovation management: radical, really new and incremental innovation. The radical innovations cause discontinuity of marketing and technology, both at a macro and a micro level. Incremental innovations occur only at micro level and cause either discontinuity of marketing, or discontinuity of technology, but not both. Really new innovations include combinations of these two extremes. These three definitions of product innovation also indicatea reduction in the degree of innovativeness as follows: radical→ really new → incremental innovation.

An alternative approach to categorize technical change is the scale of technological innovation intensity by Coccia (2005) that measures and classifies technical change according to effects generated by technological innovations on geo-economic space, in analogy with the effects of seismic waves (cf., also Coccia, 2005a).

Pavitt (1984, p.343ff) proposed a taxonomy of sectoral patterns of technical change based on innovating firms: "(1) supplier dominated; (2) production intensive; (3) science based. They can be explained by sources of technology, requirements of users and possibilities for appropriation. This explanation has implications for our understanding of the sources and directions of technical change, firms' diversification behaviour, the dynamic relationship between technology and industrial structure, and the formation of technological skills and advantages at the level of the firm, the region and the country".

De Marchi (2016, p.984), instead, suggests a classification based on general characteristics of scientific discovery and technological innovation. The features of these two activities can be described with oppositions between pairings of aspects of ''real oppositions'', graphically represented by pairs of semi axes. The first real opposition would be between problems and solutions. The second real opposition adopted is that countering specificity and generality of problems and solutions (cf., Arthur, 2009). Since these two oppositions are simultaneously applicable to science and technology, the study categorizes the activities of both research and innovation in a matrix 2×2, where each cell is defined by a pair of semi axes (cf., De Marchi, 2016, pp. 984-985).

In short, the vast literature has suggested many approaches for classification of innovation, though studies described above are not a comprehensive review in these research fields (Clark, 1985; Coccia, 2016; Hargadon, 2003; Nelson & Winter, 1982; Nelson 2008; Rosenberg, 1969; cf., Anadon *et al.*, 2016)[3]. However, studies of technical change have given little systematic attention to the different characteristics of interaction between technologies that can generate coevolution of technological systems and technological change in society. The crux of the study here is to categorize technologies considering their interaction with other technologies, in a broad analogy with the ecology[4]. The suggested interpretation here can provide a theoretical framework to clarify typologies of interactive technologies that support evolutionary pathways of complex systems of technology over time and space. At the same time, we are aware of the vast differences between biological and technological processes (cf., Braun, 1990; Hodgson, 2002; Ziman, 2000).

Study Design

In order to lay the foundations for a new taxonomy of

3 See Coccia (2006) for further approaches of classifications of innovation in economics of technical change and management of technology.

4 Ecology is the scientific study of interactions between organisms of the same or different species, and between organisms and their non-living environment (Poulin, 2006). The scope of the ecology is to explain the number and distribution of organisms over time and space and all sorts of interactions.

technologies here, it is important to clarify the concept of complexity and complex systems. Simon (1962, p.468) states that: "a complex system [is]… one made up of a large number of parts that interact in a non simple way…. complexity frequently takes the form of hierarchy, and…. a hierarchic system… is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until we reach some lowest level of elementary subsystem." McNerney *et al.*, (2011, p. 9008) argue that: "The technology can be decomposed into *n* components, each of which interacts with a cluster of $d-1$ other components" (cf., Arthur, 2009). A characteristic of complex systems is the interaction *between* systems and the interaction *within* systems—i.e., among the parts of those systems. This philosophical background of the architecture of complexity by Simon (1982), shortly described, is important to support theoretically the taxonomy of interactive technologies proposed by the study here.

Taxonomy of interactive technologies is based on following concepts:

* A technology is a complex system that is composed of more than one component or sub-system and a relationship that holds between each component and at least one other element in the set. The technology is selected and adapted in the Environment *E* with a natural selection operated by market forces and artificial selection operated by human beings to satisfy needs, achieve goals and/or solve problems in human society.

* Interaction between technologies *T1* and *T2* or more associated technologies *Ti* (*i*=1, …, n) is a reciprocal adaptation between technologies in a complex system *S* with inter-relationships of information/resources/energy and other physical phenomena to satisfy needs, achieve goals and/or solve problems in human society. *Ti* is called interactive technology in S.

The proposed taxonomy (TX) here is established to respect the following conditions of (Brandon, 1978, pp. 188-192):

i. independence: the taxonomy to play its explanatory role cannot be a tautology.

ii. generality: it must apply to the whole elements of technological change. It must be general and universally applicable throughout the domain of technical and economic change.

iii. epistemological applicability: TX has to be testable and can be applied to particular cases of systems of technology.

iv. and empirical correctness: TX must not be false.

Overall, then, the taxonomy suggested here has the goal to categorize and generalize the typologies of interactive technologies and clarify, whenever possible their role in evolutionary pathways of complex systems over time and space.

A proposed classification of interactive technologies in complex systems

The basic unit of technology analysis, in the proposed taxonomy and theory, is interactive technologies. In general, technologies do not function as independent systems *per se*, but they depend on other (host) technologies to form a complex system of parts that interact in a non-simple way (*e.g.*, batteries and antennas in mobile devices, etc.; cf., Coccia, 2017). Coccia (2017a) states the theorem of *not* independence of *any* technology that in the long run, the behaviour and evolution of *any* technology is *not* independent from the behaviour and evolution of the other technologies. In general, technologies are not autonomous systems *per se*, but they form complex systems composed of inclusive and interrelated sub-systems of technologies until the lowest level of technological unit (*cf.*,Simon, 1962, p. 468; Oswalt, 1976; cf., Coccia, 2017, 2017a). To put it differently, technologies can function in ecological niches of other technologies and the interaction between technologies can be an important taxonomic characteristic to categorize technologies that support the coevolution of technological systems (i.e., the evolution of reciprocal adaptations of technologies in a complex system S).

Suppose that the simplest possible case involves only two interactive technologies, *T1* and *T2* in a Complex System *S*(T1, T2); of course, the theory can be generalized for complex systems including many sub-systems of technology, such as *S*(T1, T2, …, T*i*, …T_N). Table 1, based on theoretical framework above, categorizes four types of interactive technologies within a complex system S, in a broad analogy with ecology.

Table 1. *A classification of technologies in complex systems*

Grade	Typology of interactive technology	Examples
1	*Technological parasitism* is a relationship between two technologies T1 and T2 in a complex system S where one technology T1 benefits (+) from the interaction with T2, whereas T2 has a negative side (–) from interaction with T1. The interaction between T1 and T2 in mathematical symbols is indicated here (+, –) to represent the benefits (positive or negative) to technologies from interaction in a complex system S(T1,T2).	An example of parasite technology is audio headphones, speakers, software apps, etc. of many electronic devices. These technologies are parasites of different technologies because they can function, if and only if (iff) associated with other technologies. Plus sign (+) indicates the fruitful benefit to parasitic technologies from interaction. In Information and Communication Technologies, host technology decreases its energy from interaction with parasitic technologies, such as electric power of battery; the sign –(minus) here indicates the negative side of interaction for host technology.
2	*Technological commensalism* is a relationship between two technologies where one technology T1 benefits (+) from the other without affecting it (0). The commensal relation is often between a larger host or master technology and a smaller commensal	An example of commensal technologies is the connection of a single mobile device to a large Wi-Fi network; the connection of an electric appliance to national electricity network; etc.

	technology; host or master technology is unmodified from this interaction, whereas commensal technologies may show great structural adaptation consonant with their systems. The interactive technologies (T1, T2) have a relation (+, 0) in a complex system S. 0 (zero) indicates here no benefits from interaction.	
3	*Technological mutualism* is a relationship in which each technology benefits from the activity of the other technology. The interaction between T1 and T2 has mutual benefits in S indicated with symbols (+, +).	An example of mutual technologies is the relation between battery and mobile devices, antenna and mobile devices, HD displays and mobile devices, etc. The interaction here generates mutual benefits between technologies (+,+) in S.
4	*Technological symbiosis* is a long-term interaction between two technologies (T1,T2) that evolve together in a complex system S. The symbiotic technologies have a long-run interaction that generates continuous and mutual benefits and, as a consequence, coevolution of complex systems in which these technologies function and adapt themselves. The interaction between T1 and T2 in S is indicated with (++, ++) to represent benefits of the long-run mutual symbiotic relationship between host and parasitic technologies (coevolution of technological systems).	For instance, symbiotic technologies are the continuous interaction between Bluetooth technology and mobile devices that has improved both technologies and increased their effectiveness and technical performance, such as Bluetooth 2.0 with an Enhanced Data Rate for faster data transfer, Bluetooth 4.0 with low energy to save battery of mobile devices, etc. This technological evolution of Bluetooth technology is associated with new generations of mobile devices–e.g. *i*Phone 6,7,8, etc.– in order to better interact with this and other technologies and generate coevolution of complex systems in which these technologies function (Apple Inc., 2016; Bluetooth, 2017).

Note: +(Plus) is a positive benefit to technology Ti from interaction with technology Tj in a complex system S($\forall i=1,\ldots,n$; $\forall j=1,\ldots,m$); –(minus) is a negative benefit to technology Ti from interaction with technology T$j$in S; 0 (zero) indicates a neutral effect from interaction between technologies Ti and T$j$in S; ++ is a strong positive benefit from long-run mutual symbiotic interaction between technologies Ti and Tj in S (i.e., coevolution of Ti and Tj in S).

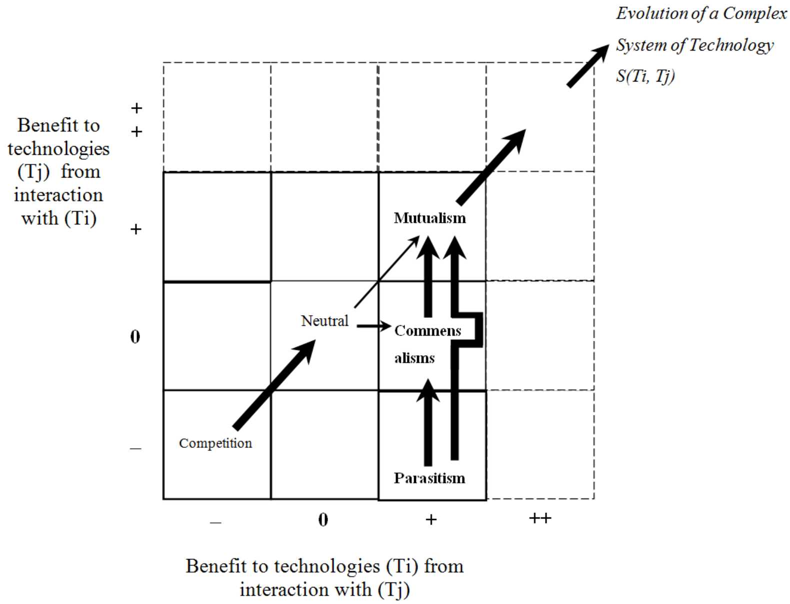

Figure1. Types and evolutionary pathways of interactive technologies in a complex system S.

Note. The notions of positive, negative and neutral benefit from interaction between technologies *Ti* and *Tj*in S are represented with mathematical symbols +, –, 0 (zero), ++ is a strong positive benefit from long-run mutual symbiotic interaction between technologies T*i* and T*j* in S (i.e., coevolution of T*i* and T*j* in S). Thick solid arrows indicate the probable evolutionary route of interactive technologies in a complex system S: the possibilities for parasitic technologies to become commensals, mutualists, and symbiotic; thin arrows show other possible evolutionary pathways of technologies T*i* and T*j* during the interaction in a complex system S($\forall i=1,\dots,n$; $\forall j=1,\dots,m$).

In general, parasitism, mutualism, commensalism and symbiosis between technologies do not establish clear cut-offs of these concepts and each relationship represents an end-point of an evolutionary development of interactive technologiesin a complex system *S*(cf., Poulin, 2006 for ecological interaction). In particular, parasitism is an interaction that may evolve over time towards commensalism, mutualism and symbiosis to support evolutionary innovations (cf., Price, 1991). The symbiosis is also increasingly recognized as an important selective force behind interdependent coevolution of complex systems (cf., Smith, 1991). In short, the interaction between technologies tends to generate stepwise coevolutionary processes of complex systems (cf., Price, 1991). Figure 1 represents evolutionary pathways of the four typologies of interactive technologies in S (Table 1).

The proposed taxonomy here has the following properties:

1). *Property of increasing interaction of technology in S over time.* Interactive technologies increase the grade of interaction over time directed to evolution of an overall system of technology S along the following evolutionary route: technological parasitism→ commensalism → mutualism → technological symbiosis ⇒ evolution of technology (see, Figure 1).

2) *Property of inclusion of interactive technologies*. Interactive technologies can be of four types (Tab. 1):

TS= Technological Symbiosis; TM= Technological Mutualism; TC=Technological Commensalism; TP= Technological Parasitism.

TS, TM, TC and TP are sets within a complex system S.

The set theory indicates with the symbol $\subset$ a subset. A derived binary relation between two sets is the set inclusion. In particular, interactive technologies of proposed taxonomy have the following property of inclusion in S:

$[(TP \subset TC) \subset TM] \subset TS$

Overall, then, this taxonomy can systematize the typologies of interactive technologies and predicts their evolutionary pathways that generate stepwise coevolutionary processes within a system of technology S (e.g., devices, new products, etc.).

Predictions based on interactive technologies

Technologies are complex systems composed of interrelated technological subsystems until the lowest level of technological unit (cf., Oswalt, 1976). Interaction is proposed here to be one of the mechanisms driving the evolution of technology and a critical taxonomic characteristic for a classification of technology (cf., Coccia, 2017). On the basis of the suggested taxonomy here, it is possible to make some predictions about evolutionary paths of interactive technologies within complex systems S.

a) The short-run behaviour and evolution of interactive technologies is approximately independent from the other technologies in S. In particular, the short-run evolution of a specific interactive technology (e.g., parasite technology) is due to advances or mutations in the technology itself.

b) The long-run behaviour and evolution of any interactive technologies (i.e., *technological parasitism, commensalism, mutualism and symbiosis*) depends on the behaviour and evolution of associated technologies; in particular, the long-run behaviour and evolution of any interactive technology is due to interaction with other technologies within and between complex systems.

c) Symbiotic, mutualistic, commensal and parasitic technologies tend to generate a rapidevolution of a complex system of technology S in comparison with complex systems without interactive technologies.

Discussion

The proposed taxonomy and theory here have a number of implications for the analysis of nature, source and evolution of technical change. Some of the most obvious implications, without pretending to be comprehensive are as follows.

Contribution to the literature on taxonomy of technical change

This study contributes to the literature on taxonomy of technical change by detailing the importance of specific typologies of interactive technologies during the evolutionary patterns of technological innovation. Current literature categorizes technical change with *static* characteristic considering objects and/or subjects of technological innovation (Archibugi & Simonetti, 1998; Freeman & Soete, 1987). In fact, technology can be classified according to: a) the nature of technological innovation-*object*-, such as incremental and radical innovation, product and process innovation, etc. (cf., Freeman & Soete, 1987); b) The sector of activity of innovative firms-*subject*-, such as supplier-dominated, scale-intensive, specialized suppliers and science- based (Pavitt, 1984).

The study here extends this specific literature by identifying typologies of technologies with a *dynamic*characteristic represented by interaction between technologies in complex systems over time. The theoretical framework here categorizes the interaction between technologies in technological parasitism, commensalism, mutualism and symbiosis. These typologies of interactive technologies have specific characteristics that drive the evolutionary pathways of complex systems of technology and technological diversification over time and space. The dynamic characteristic underlying the proposed taxonomy here may also help better understand the linkages between technologies that explain directions of technical development of complex systems of technology. In general, the taxonomy and theory here, borrowing concepts from ecology, it can extend economics of technical change with a new research stream to theorize and categorize interactive technologies that can explain the process through which these technologies become meaningful, and their role for processes of evolution of complex systems of technology.

Contribution to the literature on evolution of technology

This theory here also extends the literature on technological evolution identifying some important but overlooked typologies of technology within the nature of technology (Arthur, 2009; Dosi, 1988). Arthur (2009, pp.18-19) argues that the evolution in technology is due to combinatorial evolution: "Technologies somehow must come into being as fresh combinations of what already exists". This combination of components and assemblies is organized into systems to some human purpose and has a hierarchical and recursive structure: "technologies … consist of component building blocks that are also technologies, and these consist of subparts that are also technologies, in a repeating (or recurring) pattern" (Arthur, 2009, p.38). In short, Arthur (2009) claims that a source of change in technology evolution is the combination based on supply of new technologies assembling existing components and on demand for means to fulfil purposes, the need for novel technologies. The suggested taxonomy of technologies here is consistent with this well-established literature by Arthur (2009) as well as with studies that consider structural innovations and systems innovations based on integration of two or more symbiotic technologies (Sahal, 1985). However, the study here extends this research field by detailing how different typologies of technologies interact in complex systems and guide the evolution of technology. One of the most important implications of this work is also that specific interactive technologies, such as symbiotic technologies, can generate fruitful evolutionary routes for complex systems of technology S in evolving industries. Kalogerakis *et al.*, (2010, p. 418) argue that new technology can also be due to 'inventive analogical transfer' from experience of a specific technology in one knowledge field – *source domain* – to other scientific fields – *target domains*. This theory adds to this body of literature a new perspective represented by the interaction between technologies from source domain to other target domains of systems of technology to satisfy needs and/or to solve problems in human society. *Overall, then, the theoretical framework developed here opens the black box of the interaction between technologies that affects, with different types of technologies, the evolutionary pathways of complex systems of technology over time and space.*

Concluding remarks

Manifold dimensions in the analysis and evolution of technology are hardly known. Researchers should be ready to open the debate regarding the nature and types of interaction between technologies that may explain the evolution of technology and technical change in human society (cf., De Marchi, 2016). Some scholars argue that technologies and technological change display numerous life-like features, suggesting a deep connection with biological evolution (Basalla, 1988; Erwin & Krakauer, 2004; Solé *et al.*, 2011; Wagner & Rosen, 2014). This study extends the broad analogy between technological and biological evolution to more specifically focus on the potential of a taxonomy and theory of interactive technologies in complex systems, but fully acknowledge that interaction between technologies is not a perfect analogy of biological/ecological interaction; of course, there are differences (Ziman, 2000; Jacob, 1977; Solé *et al.*, 2013). For studying technical change, though, the analogy with biology and ecology is a source of inspiration and ideas because it has been studied in such depth and provides a logical structure of scientific inquiry in these research fields. The study here proposes a taxonomy of technology based on four typologies represented by technological parasitism, commensalism, mutualism and symbiosis that can guide evolutionary pathways of technology within and between complex systems. These types of interactive technologies seem to be general driving components for the evolution of new technology across time and space (cf., Smith, 1991; Prince, 1991; Coccia, 2017). The characteristics and dynamics of interactive technologies, described in table 1 and figure 1, are also affected by learning processes and technological capability of firms in markets with rapid change (cf., Teece *et al.,* 1997; Zollo & Winter, 2002).

On the basis of arguments presented in this study, the taxonomy here categorizes general typologies of interactive technologies that can explain, whenever possible, some characteristics of the interaction between technologies for the evolution of complex systems of technology and technical change in human society.

In particular, the results here suggest that:

1. Technological parasitism, commensalism, mutualism and symbiosis can help explain aspects of evolutionary pathways of complex systems within technical change in society.
2. Evolution of complex systems of technology may be rapid in the presence of subsystems of technological symbiosis and/or mutualism, rather than technological parasitism and commensalism (*see,* Fig. 1).

Hence, the study here provides an appropriate theoretical framework to classify interactive technologies and explain possible evolutionary pathways of complex systems of technology. Moreover, taxonomy here suggests a general prediction that it may be possible to influence (support) the long-run evolution of technical change by increasing mutual symbiotic interactions between technologies. This finding could aid technology policy and management of technology to design best practices to support technological interaction in complex systems for industrial and economic change, and technological progress of human society. Valverde (2016, p.5) in this context also states that: "Technological progress is associated with more complex human-machine interactions". As a matter of fact, human activity acts as ecosystem engineers able to change social and technological systems (Solé *et al.*, 2013).

In short, the study here makes a unique contribution, by showing how technology can be classified in critical typologies considering the concept of interaction between technologies. This idea of a "taxonomy of interactive technologies" suggested in the study here is adequate in some cases but less in others because of the vast diversity of technologies and their interaction in complex systems and environments. Nevertheless, the analogy keeps its validity in classifying and explaining general interaction and coevolution of technology in complex systems. The taxonomy here also suggests some properties of interactive technologies that are a reasonable starting point for understanding the universal features of the technology and coevolution of complex systems of technology that leads to technical change and progress in society, though the model here of course cannot predict any given characteristics of technologies with precision.

These typologies of interactive technologies can create theoretically, methodological and empirical challenges. In particular, scholars studying technology and technological evolution might have to take the interaction between technologies into account and begin data collection to explain with comprehensive model the role of interactive technologies for the emergence and evolution of technological paradigms and trajectories (Nelson & Winter, 1982; Dosi, 1988). Future efforts in this research stream will be directed to provide empirical evidence of the interaction between technologies in complex systems to better classify and evaluate their role during the process of evolution of new technology and, in general, of technical change. Other directions for the future of this research topic, which is not a studied field, are: firstly, the proposed taxonomy needs to be tested on the basis of complete coverage of different technologies belonging to many sectors; secondly, this taxonomy needs to be extended; thirdly, the taxonomy may be studied to provide a variety of uses for designing best-practices of innovation policy and management of technology; finally, the taxonomy and the theory here may be studied to shed light on a number of important aspects of technical change, such as new types, directions and routes of interactive technologies in different industries, accumulation of technological skills and dynamic capabilities of firms from interaction between technologies in markets with rapid change, emerging technologies from interactive technologies, etc. (cf., Teece *et al.,* 1997).

Overall, then, this taxonomy may support a better understanding of the role played by interactive technologies in evolutionary patterns of technological innovation and in general social and technical change. In addition, given the variety of technologies in current patterns of technological change, the taxonomy here can support a generalization and systematization of typologies of interactive technologies during the evolution of technology. Although, we know that other things are often not equal over time and space in the domain of technology.

To conclude, the proposed taxonomy here based on the ecology-like interaction between technologies—may lay the foundation for development of more sophisticated concepts and theoretical frameworks in economics of technical change. In particular, this study constitutes an initial significant step in categorizing technologies considering the interaction between technologies in complex systems and evolution of technology inexorably interlinked. However, identifying generalizable taxonomy and theory is a non-trivial exercise. Wright (1997, p. 1562) properly claims that:

"In the world of technological change, bounded rationality is the rule."

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3 Theory of technological parasitism to explain the evolution of technology

Introduction

The evolution of technology plays an important role in the economic and social change of human societies (Basalla, 1988; Freeman & Soete, 1987; Hosler, 1994; Nelson & Winter, 1982). In 2009, Brian Arthur claimed that one of the most important problems to understand regarding technology is to explain how it evolves (p.15ff). In this context, technological evolution has been compared to biological evolution by many scholars (Arthur, 2009; Basalla, 1988; Solé *et al.*, 2013; Wagner, 2011). The similarities between biological and technological evolution have generated a considerable literature (see reviews in Erwin & Krakauer, 2004; Solé *et al.*, 2011). Wagner & Rosen (2014) argued that biological thinking has reduced the distance between life sciences and social sciences (cf., Nelson & Winter, 1982; Dosi, 1988; Solé *et al.*, 2013, 2011). Basalla (1988) suggested that the history of technology can profitably be seen as analogous to biological evolution. Technological evolution, alongside biological evolution, displays radiations, stasis, extinctions, and novelty (Valverde *et al.*, 2007). In general, patterns of technological innovation emerge and evolve with technological paradigms and trajectories in specific economic, institutional and social environments (Dosi, 1988). Hosler (1994, p.3, original italics) argues that the development of technology is, at least to some extent, influenced by "technical *choices*", which express social and political factors, and "technical *requirements*", imposed by material properties. Arthur & Polak (2006, p.23) claim that: "Technology … evolves by constructing new devices and methods from ones that previously exist, and in turn offering these as possible components—building blocks—for the construction of further new devices and elements". In particular, Arthur (2009, pp.18-19) argues that the evolution of technology is due to combinatorial evolution: "Technologies somehow must come into being as fresh combinations of what already exists."This combination of components and assemblies is organized into systems or modules to some human purpose and has a hierarchical and recursive structure: "technologies … consist of component building blocks that are also technologies, and these consist of subparts that are also technologies, in a repeating (or recurring) pattern" (Arthur, 2009, p.38). In addition, Arthur (2009) claims that technology evolution is based on "supply" of new technologies assembling existing components and on "demand for means to fulfill purposes, the need for novel technologies."

Other scholars suggest that technological evolution is driven by solving consequential problems during the engineering process (Coccia, 2014e, 2016, 2017e; Dosi, 1988; Usher, 1954) andby supporting leadership of distinct purposeful organizations -for instance firms- to achieve the prospect of a (temporary) profit monopoly and/or competitive advantage (Coccia, 2015, 2017a)[5]. However, it is clear that there are at least some aspects of the evolution of technology that these studies have trouble explaining. In particular, little is known about how technologies interact and create systems in which each component (sub-system) and overall system can continue to evolve in socio-ecological environments. In this research context, our study has two goals. The first is to define the concept of technological host-parasites coevolution, a new perspective that may explain and generalize aspects of technological evolution in human societies. The second is to provide an empirical test based on historical data of the evolution of four example technologies to substantiate the theoretical framework. Statistical evidence hint at general properties of technological evolution, and, in particular, provide some insights into which technologies have greater potential to advance rapidly. This new theoretical framework of technological host-parasites coevolution lays a foundation for the development of more sophisticated concepts and theories to predict technological coevolution and explain economic change in human society.

[5] For other studies concerning source, diffusion and evolution of technology and science, cf., Calabrese *et al.*, 2005; Coccia, 2003, 2005, 2005a, 2005b, 2005c, 2005d, 2006, 2006a, 2007, 2008, 2008a, 2008b, 2008c, 2009, 2010, 2010a, 2012, 2013, 2013a, 2014, 2014a, 2014b, 2014c, 2014d, 2014e, 2015, 2015a, 2015b, 2015c, 2016, 2016a, 2016b, 2017, 2017a, 2017b, 2017c, 2017e, 2017f, 2018, 2018a, 2018b, 2018c, 2018d, 2018e, 2018g, 2018h, 2018i, 2018l, 2018m, 2018n, 2018o, 2018p, 2019, 2019a, 2019b, 2019c, 2019d, 2019e, 2019f, 2019g, 2019h; Coccia & Cadario, 2014; Coccia *et al.*, 2015; Coccia & Finardi, 2012, 2013; Coccia & Rolfo, 2009, 2010, 2013; Coccia & Wang, 2015, 2016.

Theoretical framework

Basic concepts

This study analyzes the interaction between technological breakthroughs in host-parasite systems, in a broad analogy with ecology. Parasites (from Greek para = near; sitos = food) are defined as any life form that finds their ecological niche in another living form. Host–parasite interactions can be of different types. Under certain conditions, a host–parasite relationship results in commensalism (a class of relationships between two organisms where one organism benefits from the other without affecting it), in mutualism (two organisms of different species exist in a relationship in which each individual benefits from the activity of the other) orin symbiosis (long-term interaction between two different biological species that live and evolve together). In other conditions, the relationship may result in parasitism. Mutualism, commensalism, and symbiosis represent a spectrum of interactions without clear cut-offs that distinguish them from parasitism, and each relationship represents an end-point of an evolutionary development (Poulin, 2006). In particular, parasitism is an interaction that evolves over time towards commensalism, mutualism and symbiosis (Price, 1991). The symbiosis is also increasingly recognized as an important selective force behind interdependent coevolution (Smith, 1991). Some scholars argue that the host-parasite interaction tends to generate stepwise coevolutionary processes within systems (cf., Price, 1991; Coccia, 2018).

Philosophical foundations of the theory of technological parasitism

Although models of technological evolution exist to explain the patterns of technological innovations (Sahal, 1981), there is no unified theory of coevolution that can explain the emergence of complex interaction patterns of different technologies. Interactions between technologies have profound effects on technological evolution, but despite their importance, little is known on the general structure and properties of this process. An important step towards explaining the fundamental interactions between and within systems of technology with technological host-parasites coevolution or technological parasitism is to first clarify the concept of complexity and complex systems. Simon (1962, p.468) states that: "a complex system [is]… one made up of a large number of parts that interact in a non simple way …. complexity frequently takes the form of hierarchy, and …. a hierarchic system … is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until we reach some lowest level of elementary subsystem." McNerney *et al.* (2011, p.9008) argue that: "The technology can be decomposed into n components, each of which interacts with a cluster of d−1 other components." This modularity can be one of the most important features of complex adaptive systems (cf., Arthur, 2009). Another characteristic of complex systems is the interaction between systems and sub-systems such that the hierarchy can be defined in terms of the intensity of interaction of the elements of the system. A distinction in hierarchic systems is the interactions between systems and the interactions within systems—i.e., among the parts of those systems. In this context, Simon (1962, p.474) points out that hierarchies have the property of nearly decomposable systems: "(a) in a nearly decomposable system, the short run behavior of each of the component subsystems is approximately independent of the short-run behavior of the other components; (b) in the long run, the behavior of any one of the components depends in only an aggregate way on the behavior of the other components."

The primary goal of this study, based on theoretical background discussed above, is to define the concept of technological host-parasites coevolution or technological parasitism; and that definition should meet the conditions of independence, generality, epistemological applicability and empirical correctness.

A proposed definition of technological host-parasites coevolution

i. Suppose that:

a) Technology is defined as a complex system that is composed of more than one component and a relationship that holds between each component and at least one other element in the system. The technology is selected and adapted in the Environment *E* to satisfy needs, achieve goals, and/or solve problems in human society.

b) Interaction between technologies is a reciprocal adaptation between technologies with interrelationship of information/resources/energy and other physical phenomena to satisfy needs, achieve goals, and/or solve problems in human society.

c) Coevolution of technologies *is* the evolution of reciprocal adaptations in a complex system that generates innovation—i.e., a modification and/or improvement of technologies that interact and adapt in a complex system to satisfy needs, achieve goals, and/or solve problems of human society over space and time.

d) The simplest possible case involves only two technologies; of course, the concept can be generalized for a complex system including a finite number of technologies.

Definition of the technological host-parasites coevolution ('iff' is shorthand for 'if and only if'):

P is a parasitic technology in **H** (host or master technology) iff during its life cycle ***P*** is able to interact and adapt into the complex system of ***H***, generating coevolutionary processes to satisfy needs, achieve goals, and/or solve problems in human society.

Remark: if host or master technology H*i* can fulfill needs and purposes in society without P*j*, and P*j* can fulfill purposes if and only if it interacts with other technological systems *Hi*, then P*j* is a parasitic technology ($\forall i$=1, …, n; $\forall j$=1, …, m).

Parasitic technologies P*j* are often sub-systems embedded within and primarily functional in the ecological system of host (or master) technologies H*i*. For instance, the dynamo (electric generator) is a parasitic technology when installed as an accessory to bicycles and other machines. Audio headphones are parasitic technologies of many electronic/audio devices. Technology *Pj*can be a parasite of different technologies *Hi*; technology *Hi* can be a host of different parasitic technologies *Pj* (e.g., mobile devices are host of software applications, headphones, Bluetooth technology, etc.). A technological innovation with many parasitic technologies can be considered a complex system with a high hierarchy (as defined by Simon, 1962) in comparison to a technological innovation with low number of parasitic technologies (i.e., less associated sub-systems of technology). To put it differently, a technology with a high hierarchy is associated with a higher number of technological parasites than technologies with less hierarchy in their system, such as aircraft vs. bicycle technology. In general, many technologies P*j* do not function as independent systems themselves, but *de facto* they depend on other technologies H*i* to form a complex system of parts that interact in a non-simple way (cf., Coccia, 2018m). Moreover, the diffusion and adaptation of parasitic technologies as complex adaptive systems depend on market forces, social networks, institutions, technical choices, and technical requirements over time and space (cf., Anadon *et al.,* 2016; Coccia, 2010, 2017; Dosi, 1988; Kreindler & Peyton Young, 2014; Hosler, 1994). Figure 1 visualizes a technological host-parasite system.

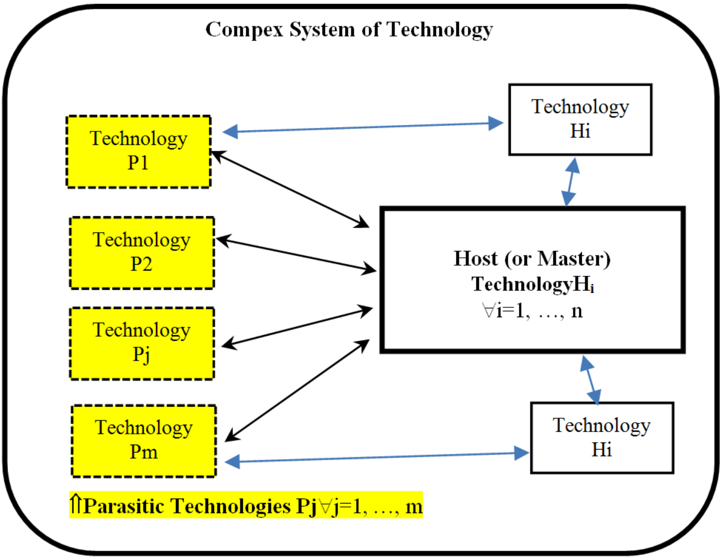

Figure 1. *Atechnological host-parasite system*

Study design

The statistical evidence here offers a preliminary assessment of the theory of technological host-parasites coevolution, considering historical data from the developmental trajectory of four technologies:

- Passenger aircraft, 1932-1965 CE (Current Era) and 2014-2017 CE
- Farm tractors, 1920-1968 CE
- Freight locomotives, 1904-1967 CE
- Road racing bicycles, 1901-2017 CE

Sources of aircraft, tractor, and locomotive data are tables published by Sahal (1981, pp.341-346; cf. also pp.321-330, originally sourced from trade literature; additional data for aircraft technology are from Lufthansa magazine, 2014; 2017. These data are also documented in supporting information here). The cycling data were archived by McGann & McGann (2006; Bicycle race data, 2017). In particular, this study compares aircraft technology (that is assumed to be a complex technological system with many interactions intra- and inter- parasitic technologies within a host technology) to other less complex technological innovations, such as the racing bicycle, farm tractor and freights locomotive. In particular, the high complexity of aircraft technology is due to the integration of many technology components and interaction between parasitic technologies necessary to safely meet the requirements—i.e., meet human needs or solve problems—of manned heavier-than-air flight. In fact, aircraft are characterized by several subsystems and associated air-to-air and air-to-ground systems of technology with intra- and inter-component interaction to be able to fly and satisfy human needs (main component technologies in aircraft are: jet engine, cockpit, slats, spoiler, aileron, flaps, elevator, rudder, radar, vertical and horizontal stabilizer, etc.; cf., NASA, 2017). Moreover, in the initial stage of development many of the components, particularly electronics, were not essential to tractor and locomotive technology (cf., Sahal, 1981). Evolution of these technologies is measured with Functional Measures of Technology (FMT) over time to take into account both major and minor innovations supporting technical performance and efficiency of technology (Sahal, 1981, pp.27-29). FMTs applied here are:

– for passenger aircraft: maximum sustained airspeed in miles per hour over 1932-1965 CE and 2014-2017 CE

– for farm tractors: mechanical efficiency (ratio of drawbar horsepower to belt or power take-off –PTO- horsepower) over 1920-1968 CE

– for freight locomotives: tractive effort in pounds over 1904-1967 CE

– for road racing bicycles: the increase in efficiency[6], over 1901-2017 CE (cf., Appendix)

The Functional Measures of Technology *i* in *t* (FMT*i, t*) are systematized in a comparable framework by applying the following standardization formula for the technology *i* in *t*:

$$\varphi_{it} = \frac{FMT_{it} - \mu_t}{\sigma_t} \quad (1)$$

where:

φ_{it} = standardized FMT_{it} (Functional Measures of Technology *i* at *t*=time)

FMT_{it}= Functional Measures of Technology*i* at the year *t*

μ_t = arithmetic mean of the FMT over a period *t*

σ_t = standard deviation of the FMT over *t*

Remark: φ_{it} is negative when the raw score is below the arithmetic mean, positive when it is above. A zero value of φ_{it} indicates that the raw value is equal to the arithmetic mean.

This approach compares the technologies described above considering similar patterns of technological development from the initial stage for each technology. Aircraft data are 34 years (1932-1965 CE), and for the purpose of comparing these different technologies, we have focused our statistical analysis on trends of the first 34 years available for the other

[6] Efficiency is a metric of how much power generated by the cyclist is translated to forward motion. Because the bicycle is the only example of human-powered equipment discussed here, and because of improvements in athletes' training (and performance-enhancing drugs) it was necessary to try and isolate the innovation in racing bicycles from the performance of the rider. A detailed explanation of the bicycle FMT is offered in the additional materials (supporting information) section, but briefly this measure is derived from average speeds of world-class races while using data from contemporaneous running events (marathons) to control for rider performance improvement.

three datasets. The statistical analysis also presents a comparison of aircraft *vs.* bicycle technology for a long run represented by 117 years for bicycle technology and 85 years for aircraft technology (data sparse after 1967 for latter technology; long-run data for freight locomotive and farm tractor were not available). Note that in all of these examples, the first year represented is not the year of invention; instead these data all come from a time period approximately thirty years after the original invention, when data from established (but nascent) industries and FMT metrics are available (cf., Sahal, 1981).

The time series of each technology are estimated with a simple regression analysis to assess the coefficients of regression of the evolution of these technologies under study here.

Specification of the linear model is:

$$y_{i,t}= \beta_0+ \beta_1\, t + \varepsilon_{i,t} \qquad (2)$$

$y_{i,t}$= Standardized FMT_{it} Functional Measures of Technology i, t

t = Time

$\varepsilon_{i,t}$=error term

i=technology=1, 2, 3, 4

In the presence of a specific scatter of empirical data for a technology, the study design here estimates the most appropriate relation, such as cubic, power, compound or exponential model. These models of simple regression are estimated with Ordinary Least Squares (OLS). Statistical analyses are performed with the Statistics Software SPSS® version 24. The expectation here (per the theory and the computational model introduced) is that aircraft technology, as a complex technology with many parasitic technologies, will show more technological development than the other technologies with less parasitic technologies.

Results

The second priority of this study is to explore empirical, historical data on the evolution of four example technologies. In particular, the results of the historical data for the development of four technologies data assess the theory of technological host-parasites coevolution. The results of this study, based on aircraft, tractor, locomotive, and bicycle technologies are shown in Figure 2. In particular, the results reveal that the passenger aircraft technology, a more complex technology with many parasitic technologies and considerable interaction between associated technologies, has the fastest rate of evolution. This empirical finding of faster evolution of technology associated with high number of parasitic technologies is also confirmed in the long run when aircraft technology is compared with bicycle technology (Figure 3)[7].

The statistical evidence here suggests that host (or master) technologies with more technological parasites (and technological interactions, e.g., aircraft technology) have a rapid evolution of technology in the long run. Technologies with fewer parasitic technologies and a low level of interaction with associated technologies improve more slowly, such as racing bicycles (Fig. 2 and 3). Overall, this empirical evidence is consistent with the theory of technological host-parasites coevolution. Properties and predictions of the evolution of technology with technological parasitism are as follows.

[7]Data of bicycle technology are from 1901 to 2017, whereas data of aircraft technology are from 1932-1965. In order to analyze the long-run evolution of these two technologies with a higher (aircraft) and lower (bicycle) complexity and number of parasitic technologies, data of aircraft technology are integrated with cruising speed of Lufthansa Fleet of Airbus, Boing, Boing BBJ, Embraer and Bombardier from 2014 to 2017 (Lufthansa magazine n. 12/2014; p. 88; n. 05/2017, p. 74).

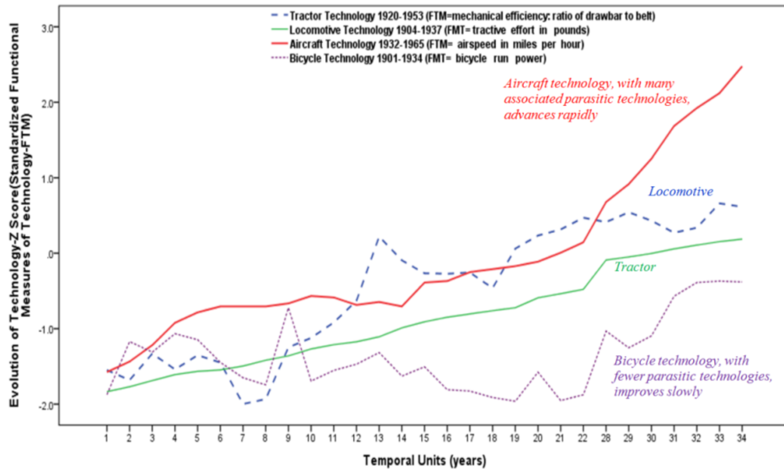

Figure 2. *Evolution of racing bicycle, farm tractor, freight locomotive and passenger aircraft technology over medium run (based on empirical data).*

Note: The bicycle is a less complex technology with fewer parasitic technologies than aircraft technology. The temporal units (years) on x-axis are from *1* to m, where *1* is the initial year of data of the technology (i.e., 1920 for tractor technology; 1904 for locomotive technology, 1901 for bicycle and 1932 for aircraft technology). Period under study here is 34 years for having a similar time span of data between technologies. y-axis indicates the Functional Measures of Technology standardized. For the tractor, locomotive and bicycle technologies, the estimated relationships of linear models ($y_{i,t}= \beta_0+ \beta_1 \times t + \varepsilon_{i,t}$), based on empirical data, reveal: for farm tractor technology (1920-1953) unstandardized coefficient beta is $\beta_1=0.71$, standardized coefficient is 0.899 (p-$value < 0.001$, F=114.10, $sig.$=0.001, Adjusted R^2=0.80); for freight locomotive technology (1904-1937), unstandardized β_1=840.11, standardized coefficient = 0.998 (p-$value< 0.001$, F=9444.85, $sig.$= 0.001, Adjusted R^2=0.997); for racing bicycle technology (1901-1934) unstandardized β_1=1.35, standardized coefficient is 0.392 (p-$value < 0.05$, F=5.82, $sig.$= 0.022, Adjusted R^2=0.13). The trend of passenger aircraft technology (1932-1965), a complex technology with many parasitic and associated technologies, fits a compound model ($\ln y_{i,t}= \ln \beta_0+ \beta_1 \ln$ time $+ \varepsilon_{i,t}$). Results of the estimated relation of aircraft technology are: unstandardized β_1=1.03 (p-$value < 0.001$, F=457.66, $sig.$= 0.001, Adjusted R^2=0.93). Aircraft technology has also a standardized coefficient beta higher than other technologies: β_1=2.629. Empirical evidence here shows the rapid evolution of aircraft technology compared to other technologies. This result in aircraft technology can be explained by the high number of parasitic technologies (and interaction) within and between this specific system of technology.

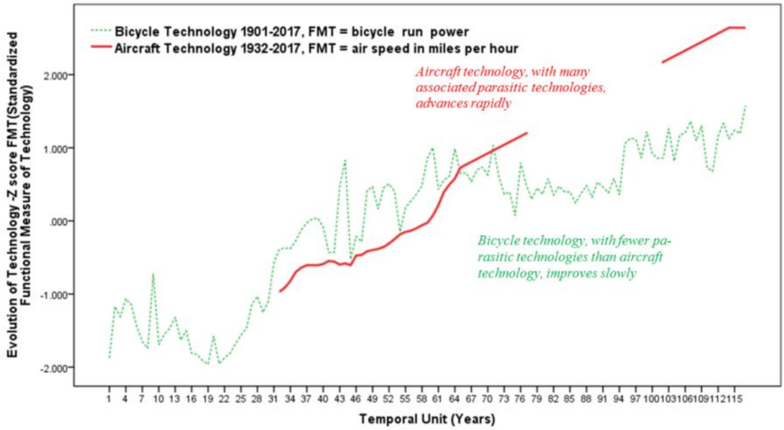

Figure 3. *Long-run evolution of racing bicycle and passenger aircraft technology based on empirical data*

Note: The racing bicycle is a less complex technology with fewer parasitic technologies than aircraft technology. The temporal units on x-axis are years. Period under study is 117 years for bicycle technology (1901-2017) and 85 years for aircraft technology (1932-2017). y-axis indicates the Functional Measures of Technology standardized. For the aircraft and bicycle technologies, the estimated relationships of linear models reveal: for passenger aircraft technology, unstandardized coefficient beta β_1=0.99, standardized coefficient is β_1=5.23 (*p-value* < 0.001, F=1855.24, *sig*.=0.001, Adjusted R^2=0.98); for racing bicycle technology, unstandardized coefficient is β_1=0.89, standardized coefficient is β_1=1.92 (*p-value* < 0.001, F=429.72, *sig*.= 0.001, Adjusted R^2=0.79). Empirical evidence here also confirms the faster long-run evolution of aircraft technology than bicycle technology. Note that in 1932 aircraft is an emerging technology in comparison to bicycle that had a higher technological evolution started in 1901 and in a growing phase. Subsequently, the higher number of parasitic technologies and technological interaction in aircraft technology than bicycle technology explains the high long-run rate of evolution of aircraft technology: i.e., $\beta_{\text{passenger aircraft technology}}$ =5.23 >$\beta_{\text{racing bicycle technology}}$=1.92

Predictions of the theory

Technologies are complex systems composed of interrelated sub-systems of technology until the lowest level of technological unit (cf., Oswalt, 1976; Coccia, 2018; 2019g). Our study of technological host-parasites coevolution, starting with theory that was further refined with a computational model, and finally compared to empirical data and statistical analyses, suggests the following predictions:

1. Higher-level host technologies with many parasitic technologies advance rapidly. Technologies with fewer parasitic technologies and a low level of interaction with associated technologies improve slowly.

2. The long-run evolution of a technology depends on the behaviorand evolution of associated parasitic technologies; the long-run evolution of any technology is *not* independent of the other technologies (*technological symbiosis*). To put it differently, long-run evolution of a specific technology is due to interaction with new parasitic technologies. In brief, technological innovation is enhanced by the integration of two or more parasitic technologies that generateco-evolution of system innovations (cf., Theorem of not independence of any technological innovation by Coccia, 2018m).

Discussion and conclusion

Scholars argue that technologies and technological change display numerous life-like features, suggesting a deep connection with biological evolution (Basalla, 1988; Coccia, 2018, 2019g; Erwin & Krakauer, 2004; Solé *et al.*, 2011; Wagner & Rosen, 2014). We extend the broad analogy between technological and biological evolution to more specifically focus onthe potential of technological parasitism, but fully acknowledge it is not a perfect analogy; of course there are differences (Ziman, 2000). For studying technical change, though, the analogy with parasite biology and ecology is a source of inspiration and ideas because it has been studied in such depth and provides a logical structure of scientific inquiry.

The study here proposes that the interactions between technologies in complex systems are similar to the biological interaction of host-parasite dynamics. In particular, technological host-parasites coevolution is a dynamic process that can predict evolutionary pathways of interactive technologies in complex systems.

On the basis of statistical evidence presented in this study, technological host-parasites coevolution can explain and generalize, whenever possible, some characteristics of the evolution of technology in human society. In particular, the results of the analyses here suggest:

3. Technological host systems with many parasitic technologies generate a rapid stepwise evolution of technological host-parasite systems not seen in technologies with fewer associated parasitic technologies and a low level of technological interaction.

4. The long-run behavior and evolution of any technology is *not* independent of the other associated parasitic technologies (cf., Coccia, 2018m).

5. Studying inter-related or more symbiotic technologies as complex systems can help explain aspects of technological and economic change in human societies.

The study documented here makes a unique contribution, for the first time to our knowledge, by showing how technologies co-evolve by interacting in complex systems of devices and artifacts in a context of host-parasitic dynamic process. In particular, the theory here suggests a general prediction that it may be possible to influence (improve) the long-term evolution of technical change by increasing the fundamental interactions between parasitic and host technologies. This finding could aid technology policy and management of technology to design best practices to support mutual symbiotic relationships between a specific host technology and associated parasitic technologies directed to enhance the technological progress in human society.

Hence, the analogy of the study here provides an appropriate theoretical framework to explain one of the characteristics of the evolution of technology. However, the concept of technological evolution departs from biological evolution in fundamental ways. In general, technological innovations and their evolution are due to entrepreneurs that seek optimality, typically under economic criteria, such as minimization of cost, maximization of profit, etc. to achieve the prospect of a monopoly power and/or sustain a competitive advantage of firms in markets (cf., Coccia, 2017e; McNerney *et al.,* 2011; Solé *et al.,* 2013). In contrast to technology, living organisms are the result of tinkering that is undirected mutation plus a widespread reuse and combination of available elements to build new structures (Jacob, 1977).

In this research context, Valverde (2016, p.5) states that: “Technological progress is associated with more complex human-machine interactions.” As a matter of fact, humans act as ecosystem engineers, able to change the socioeconomic environment and support progress (cf., Solé *et al.,* 2013).

The idea of a "technological parasitism” or in general of technological host-parasites coevolution presented in the study here should not necessarily be considered as a general behavior, because it is adequate in some cases but less in others because of the vast diversity of technological innovations and their interaction in complex systems and socioeconomic environments. Nevertheless, the analogy keeps its validity in explaining several phenomena of the coevolution of technology in human society. The theory of technological host-parasites coevolution suggests some properties that are a reasonable starting point for understanding the universal features of the coevolution of technologies that leads to technological and economic change, though the model of course cannot predict any given paths and characteristics of the evolution of technologies with precision. We know, *de facto*, that other things are often not equal over time and space in the domain of technology

Overall, then, the proposed theory here—technological parasitism based on the ecology-like interaction between technologies and innovations—may lay the foundation for development of more sophisticated concepts and theoretical frameworks. Future efforts in this study will be directed to provide further empirical evidence to better evaluate this new approach and to refine the computational model. However, identifying generalizable theory at the intersection of engineering, economics, sociology, anthropology, and perhaps biology is a non-trivial exercise. Wright (1997, p.1562) properly claims that: "In the world of technological change, bounded rationality is the rule."

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Appendix

Bicycle innovation data and calculation of the Functional Measure of Technology FMT in racing bicycle technology (bicycle efficiency)

The raw data underlying the assessment of bicycle efficiency improvements is the average speeds of several long-running top-level races. Specifically, we have included data from eight races: the three grand tours (Giro d'Italia, Tour de France, Vuelta a España), and the five one-day classics (Milano-San Remo, Flanders, Paris-Roubaix, Liege-Baston-Liege, Tour de Romandie). The oldest of these races was first held in 1892, but recognizably modern formats and rules were not used until the early 20th century. Also, the grand tours consist of multiple stages (over 20 stages in recent decades), different formats (e.g., individual time trials, team time trials, and regular road races), and courses that vary significantly over the years (e.g., some years include more climbing). Taken altogether though, the average speeds of the winners across the three grand tours (and the one-day classics, which are raced on consistent courses) minimizes any effect of year-to-year course and weather variations. Note that data from the earliest years and also the war years are sparse. Average speeds have improved in the years since 1901 (about 64% faster) due to improvements in rider training, faster bicycles –new materials (e.g., carbon fiber) for components– (and yes, in some cases, performance-enhancing drugs; Bicycle race data, 2017). Our intent with this data was to isolate insofar as possible the technological development of the bicycle. Importantly, though, average speeds of race winners are the outcome of many, many factors—and some of those factors that may contribute to faster racing through time (such as team tactics) are difficult or impossible to quantify. But it is possible to largely control for the most relevant parameter other than the bicycle itself: the athlete. For comparison, we also collected data on winning speeds of the Boston Marathon data (2017), a running event held since the late 19th century. Marathon speeds have also improved, but much more modestly compared to cycling (15% for running). Weighting the cycling race speeds by removing the effect of the athlete (using the running data) provides a much cleaner assessment of the innovations in bicycle technology. Because cycling speeds are generally 2.5-3 times faster than marathon runners, further transformation of the speed data was necessary to compare the two sports. First, the power generated by the athlete to either run or pedal a bicycle can be reduced to a function of the oxygen metabolized to generate that power. If you can calculate the power necessary to run a certain speed, you can likewise calculate the speed of a cyclist generating the same power (assuming slope and winds are non-factors; those other parameters can be accounted for in the math, but it is much more complicated). For example, in 2016, winning cyclists averaged

40.4 km/h, and a simplified estimate of the power required to maintain that speed is 355 watts (equation below, note the non-linear relationship between power and speed; because of air resistance, large gains in power are necessary for even modest gains in speed). Alternately, in that same year the marathon winner ran 19.1 km/h and generated power around 339 watts.

For the early years, cycling speeds and related power estimates were low (e.g., 26 km/h, or less than 100 w). Importantly, early 20th century cyclists were not pushing much lower power compared to modern cyclists (perhaps 15% less, not almost four times less!). Instead, their bikes were less efficient. The difference in power generated by the marathon runner and the cyclist any given year provides a reasonable assessment of the efficiency of the bicycle. To that end, to generate our metric of bike innovations, we simply subtracted the running power from cycling power each year 1901-2017 as follows.

How to transform bicycle race speeds into Functional Measures of Technology FMT (bicycle efficiency):

Bicycle Speed	Average km/h of the 3 grand tours and 5 one-day Classics (*Giro d'Italia, Tour de France, Vuelta a España; Milano-San Remo, Flanders, Paris-Roubaix, Liege-Baston-Liege, Tour de Romandie*).Note: data sparse during war years.
Bicycle Power *Calculated*:	Power (watts) needed to maintain speed given drag coefficient of 0.25 $P_b = C \times s^3$ where: P_b= Bicyclepower (watts) C = drag coefficient, set to 0.25 s= speed converted to meters per second (simplified from Puget, 2015)
Run Speed	km/h of *Boston Marathon* winner
Run Power *Calculated*:	Pace converted to watts for 150 lb (68.2 kg) athlete $P_r = \frac{210}{p} \times \frac{W}{1000} \times 75$ where: P_r= run power (watts) p = pace in minutes/km W= weight in kg *Note*: given economy numbers of 75W/L on the Bicycle and 210ml/kg/km on the run (O_2 consumption). Converts running pace to O_2 consumption, then O_2 to Bicycle power (Hawley and Noakes, 1992).

Hence, the difference between $\boxed{P_b - P_r = \text{FMT}}$ and indicates the bicycle efficiency, i.e. the evolution of bicycle technology, without the human improvements.

Data of technologies and their sources for empirical analyses

Year Tractor *	Farm Tractor (mechanical efficiency) *	Year Locomotive *	Freight locomotive tractive effort in pounds *	Year Aircraft *	Passenger aircraft airspeed in miles per hour *	Year Bicycle/ Marathon ♦†	Racing bicycle speed (km/h) ♦	Run speed Boston Marathon (km/h) †
1920	52.17	1904	22804	1932	109	1901	25.862	16.94767
1921	50.95	1905	23666	1933	116	1902	28.088	15.51287
1922	54.19	1906	24741	1934	127	1903	27.3915	15.67778
1923	52.25	1907	25781	1935	142	1904	28.8915	16.01666
1924	53.99	1908	26356	1936	149	1905	28.43767	15.98127
1925	53.09	1909	26601	1937	153	1906	25.96567	15.27421
1926	48.03	1910	27282	1938	153	1907	28.01275	17.53255
1927	48.62	1911	28291	1939	153	1908	27.252	17.37413
1928	54.95	1912	29049	1940	155	1909	29.26617	14.58353
1929	56.1	1913	30258	1941	160	1910	26.9586	17.00649
1930	57.99	1914	31006	1942	159	1911	29.03783	17.87293
1931	60.64	1915	31501	1943	154	1912	29.561	17.9172
1932	68.49	1916	32380	1944	156	1913	29.47467	17.43195
1933	65.58	1917	33932	1945	153	1914	27.85083	17.43195
1934	63.99	1918	34995	1946	169	1915	27.795	16.69069
1935	63.94	1919	35789	1947	170	1916	26.69	17.19126
1936	64.09	1920	36365	1948	176	1917	25.89	17.0351
1937	62.19	1921	36935	1949	178	1918	25.46	16.89114
1938	67.01	1922	37441	1950	180	1919	25.22757	16.9666
1939	68.61	1923	39177	1951	183	1920	27.49457	16.93256
1940	69.35	1924	39891	1952	189	1921	27.21343	18.22022
1941	70.79	1925	40666	1953	196	1922	27.68514	18.32352
1942		1926	41886	1954	204	1923	27.18371	17.60774
1943		1927	42798	1955	208	1924	26.924	16.91559
1944		1928	43838	1956	210	1925	27.17057	16.54706
1945		1929	44801	1957	214	1926	28.47829	17.38009
1946		1930	45225	1958	219	1927	28.56157	15.78695
1947	70.25	1931	45764	1959	223	1928	29.32543	16.1135
1948	71.45	1932	46299	1960	235	1929	28.90957	16.53265
1949	70.42	1933	46916	1961	252	1930	29.49114	16.35465
1950	68.95	1934	47712	1962	274	1931	30.54386	15.18261
1951	69.56	1935	48367	1963	286	1932	32.81586	16.48242
1952	72.54	1936	48972	1964	296	1933	33.22914	16.76437
1953	72.12	1937	49412	1965	314	1934	33.02329	16.55969
1954	69.57	1938	49803			1935	33.42913	16.64315
1955	71.77	1939	50395			1936	33.86475	16.47527
1956	72.54	1940	50905			1937	34.38257	16.51109
1957	74.22	1941	51217			1938	34.30471	16.27405
1958	74.08	1942	51811			1939	35.11286	17.0084
1959	73.12	1943	52451			1940	34.7425	17.05231
1960	74.55	1944	52822			1941	32.742	16.80704
1961	79.55	1945	53217			1942	33.29125	17.24004

Table of the data and their sources of technologies (continued from previous page)

Year Tractor *	Farm Tractor (mechanical efficiency) *	Year Locomotive *	Freight locomotive tractive effort in pounds *	Year Aircraft *	Passenger aircraft airspeed in miles per hour *	Year Bicycle/ Marathon ♦†	Racing bicycle speed (km/h) ♦	Run speed Boston Marathon (km/h) †
1962	75.41	1946	53735			1943	36.493	17.05806
1963	76.03	1947	54506			1944	37.4935	16.6742
1964	82.26	1948	55170			1945	32.538	16.80332
1965	83.09	1949	56333			1946	33.97471	16.94011
1966	75.34	1950	57075			1947	34.07475	17.38208
1967	66.06	1951	58476			1948	35.70538	16.76252
1968	73.97	1952	59966			1949	36.22757	16.6742
1969		1953	61339			1950	34.99938	16.585
1970		1954	63152			1951	36.62014	17.13503
1971		1955	65005			1952	36.33157	16.66872
1972		1956	68745			1953	37.15643	18.23335
1973		1957	61515			1954	35.276	18
1974		1958	61312			1955	36.63963	18.29704
1975		1959	61408			1956	37.3525	18.86044
1976		1960	61314			1957	37.07075	18.07281
1977		1961	61969			1958	36.83288	17.3523
1978		1962	61415			1959	38.35038	17.74142
1979		1963	61533			1960	38.93425	17.96806
1980		1964	62311			1961	36.99463	17.62409
1981		1965	63096			1962	37.34988	17.6057
		1966	70900			1963	38.02814	18.21804
		1967	65267			1964	38.827	18.08572
		1968				1965	38.30375	18.54046
		1969				1966	38.31588	18.45487
						1967	37.998	18.64972

Note. Sources of data.
*Sahal (1981, pp. 341-346; cf. also originally sourced from trade literature pp. 321-330)
♦Bicycle race data (2017). [Retrieved from].
†Boston Marathon data (2017) from the race organizer's Boston Athletic Association website [Retrieved from].
For complete dataset see sources of data above.

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4 Technometrics to measure and detect pathways of interactive technologies within theory of technological parasitism

Introduction

This book has two goals. The first is to propose a new perspective to measure and assess the evolution of technology, using a broad analogy with the evolutionary ecology of parasites. The second is to suggest properties that explain and generalize, whenever possible characteristics of the evolution of technology to predict which innovations are likely to evolve rapidly.

The analysis of the technology change and evolution of technology plays an important role in social studies of technology to explain the nature of innovation and predict patterns of technological innovation directed to solve problems and satisfy needs in society (Anadon *et al.*, 2016; Andriani & Cohen, 2013; Angus & Newnham, 2013; Basalla, 1988; Freeman & Soete, 1987; Grodal *et al.*, 2015; Hosler, 1994; Nelson & Winter, 1982; Rosenberg, 1969). In particular, measurement of the evolution of technology is an increasing challenge faced by governments, agencies and public research labs for improving technological forecasting and, as a consequence, supporting new technology for economic progress in society (cf., Coccia, 2005; Daim *et al*., 2018; Hall & Jaffe, 2018; Linstone, 2004; Tran & Daim, 2008). Scholars in this field of research endeavor of measuring technological advances of products and processes and technical performance of innovations with different approaches to explain determinants and directions of technological progress8. For instance, Nordhaus (1996, p.29ff) applies an economic approach to estimate changes in lighting efficiency with a price index based on changes over the last two centuries, showing that the growth of real wages and real output in economic systems may have been significantly understated during the period since the Industrial Revolution. Other scholars apply engineering approaches to measure the advances of technical characteristics of innovations and explain different technological pathways (Dodson, 1985; Fisher & Pry, 1971; Knight, 1985; Martino, 1985; Sahal, 1981).

Although many studies of technology analysis, a technometrics that measures and assesses the evolution of technology as a complex system of interacting technologies is, at author's knowledge, unknown. The study here confronts this problem by developing a new approach to measure and assess the evolution of technology within theoretical framework of "Generalized Darwinism" (Hodgson & Knudsen, 2006, 2008). Wagner & Rosen (2014) argue that the application of evolutionary biology to different research fields has reduced the distance between life sciences and social sciences (cf., Nelson & Winter, 1982;

8 cf., Angus & Newnham, 2013; Coccia, 2005; Daim *et al*., 2018; Farrell, 1993; Farmer & Lafond, 2016; Faust, 1990; Koh & Magee, 2006, 2008; Magee *et al*., 2016; Nagy *et al*., 2013; Ruttan, 2001; Tran & Daim, 2008; Wang *et al*., 2016.

Dosi, 1988). In general, analogies[9] derived from Darwinian evolutionary biology have provided meta-theoretical frameworks for interdisciplinary studies of the nature and evolution of technology (cf., Arthur, 2009; Arthur & Polak, 2006; Basalla, 1988; Coccia, 2018; Kauffman & Macready, 1995; Nelson, 2006). In fact, evolutionary biology, applied in economics of technical change, provides a logical structure of scientific inquiry to analyze and explain, in a broad analogy, characteristics and evolutionary pathways of technology (cf., Andriani & Cohen, 2013; Coccia, 2018; Wagner, 2011).

In general, technological change can be explained by a process of competitive substitution of a new technology for the old one (Fisher & Pry, 1971). However, technological progress is due to various aspects and dynamics of technological innovation (Coccia, 2005, 2018). Pistorius & Utterback (1997, p.67) argue that a multi-mode interaction between technologies provides a much richer theoretical framework for technology analysis. In particular, Pistorius & Utterback (1997, p.72ff) suggest different interactions among technologies in analogy with biology, more precisely: pure competition, symbiosis and predator-prey. Sandén & Hillman (2011, p.407) discuss a further refinement of technological interactions by introducing a six-mode typology, using similarity with the interaction of species: neutralism, commensalism, amensalism, symbiosis, competition, and parasitism and predation into one category. A research challenge in this research field is the development of technometrics to measure different modes of technological interaction and transition between modes to explain the evolution of technology.

In this context, the study here suggests a new conceptual framework for measuring and predicting technological evolution, applying a broad analogy with evolutionary

9 cf., Oppenheimer, 1955.

ecology of parasites (cf., Coccia, 2018). In particular, the evolution of technology is analyzed here in simple way in terms of morphological changes between a host technology and a main technological parasitic subsystem. The proposed model assesses the types of interaction supporting the evolution of technology to suggest a technological forecasting of innovations that grow rapidly. This new perspective is verified on different technologies, using historical data. Overall, then, the theoretical framework here, borrowing conceptual insights from evolutionary ecology of parasites can extend the economics of technical change with a new approach that explains and generalizes evolutionary processes of innovation through interaction between technologies in a complex system. Moreover, results of this study here could aid policymakers and managers to predict which technologies are likely to evolve rapidly in order to design best practices of management of technology for accelerating industrial and economic change in society. In order to position this study within existing literature, next section describes different approaches for measuring technological advances.

Theoretical background of the measurement of technological evolution

The central issue for a theory of measurement is two basic problems: the first is the justification of assignment of the numbers to objects or phenomena (called representational theorem); the second is the specification of degree to which this assignment is unique (uniqueness theorem; cf., Luce *et al.,* 1963; Suppes & Zinnes, 1963; Stevens, 1959). In the research field of the measurement of technology, technometrics is a theoretical framework for the measurement of technological advances and technological change with policy implications (Sahal, 1985; cf. also Sahal, 1981). Some approaches of the measurement of technological advances are described as follows, without pretending to present a comprehensive overview of the methods of technometrics (Coccia, 2005, p.948ff).

Hedonic approach

The assumption of this approach is a positive relationship between market price of a good or service and its quality. In particular, it is assumed that a particular product can be represented by a set of characteristics and by their value; hence, the quality of product Qj is function of defining characteristics:

$$Q_j = f(a_1,\dots,a_n, X_{1j},\dots, X_{2j},\dots, X_{kj})$$

where ai is the relative importance of the i-th characteristics and Xij is the qualitative level of characteristics in product j. Technological progress can be defined here as the change in quality during a given period of time:

$$TC_j = \frac{\Delta Q_j}{\Delta t}$$

Moreover, the observed changes in the price of a product can be decomposed into a "quality/technological change effect" and "pure price effect" (cf., Coccia, 2005, pp.948-949; Saviotti, 1985).

RAND[10] approach

A technological device has many technical parameters that measure its characteristics and characterize the state-of-

10 RAND Corporation ("Research and Development") is an U.S. research organization that develops researches to support the security, health and economic growth of the USA, allied countries and in general the world.

the-art (SOA). Dodson (1985) proposes a planar and an ellipsoidal surface of SOA to measure technical advances of products:

Planar

$$\sum_{i=1}^{n}\left(\frac{x_i}{a_i}\right)=1$$

Ellipsoidal

$$\sum_{i=1}^{n}\left(\frac{x_i}{a_i}\right)^2=1$$

where xiis the i-th technological characteristic and ai is the i-thparameter (a constant). Alexander & Nelson (1973) suggest hyperplanes for the surface of SOA, instead of ellipses. In brief, Hedonic and RAND techniques for measuring technological advances are similar and differ only in the choice of dependent variable, which is price in the former and calendar year in the latter (Coccia, 2005, pp.949-952).

Functional and Structural approach

The technique by Knight (1985) is based on a functional and a structural description of a given technology to detect its evolution. In regard to the functional description of a new computer over an earlier one, this technique can indicate how technological advancement has taken place, but it does not specify the details of new development. In order to explain technological issues, it is also necessary the structural description between technologies by comparing the structure of new systems with that of earlier ones (cf., Coccia, 2005, pp.955-957). The structural approach was originated by Burks *et al.*, (1946) that describe the "logical design for a general-purpose digital computer", showing key information needed to determine its functional performance and computing power (as quoted by Knight, 1985, p.109).

Wholistic and Holistic approaches

Sahal (1985) suggests two ideas of technometrics. In the first approach called Wholistic, the state-of-the-art (SOA) is specified in terms of a surface of constant probability density given the distribution of technological characteristics. The SOA at any given point in time is represented by a probability mountain, rising above the geometric plane. The level of technological capability is given by the height of mountain. Instead, the magnitude of technological change can be estimated by the difference in heights of successive mountains. In the second approach called Holistic, a technological characteristic is specified as a vector in an N-dimensional space generated by a set of N linearly independent elements, such as mass, length, and time. The length of the vector represents the magnitude of a technological characteristic, whereas the type of characteristic is represented by direction. In this case, the SOA reduces to a point. The successive points at various times constitute a general pattern of technological evolution that evinces a series of S-shaped curves. These two approaches are distinct but related (Coccia, 2005, p.955).

Model of technological substitution for measuring technological evolution

Fisher & Pry (1971, p.75) argue that technological evolution consists of substituting a new technology for the old one, such as the substitution of coal for wood, hydrocarbons for coal, robotics technologies for humans (cf., Daim *et al.,* 2018), etc. Technological advances are represented by competitive substitutions of one method of satisfying a need for another. Fisher & Pry (1971, p.88) state that: "The speed with which a substitution takes place is not a simple measure of the pace of technical advance… it is, rather a measure of the unbalance in these factors between the competitive elements of the substitution".

Technological advances measured with patent data

Faust (1990, p.473) argues that patent indicators allow for a differentiated observation of technological advances before the actual emergence of an innovation, such as technological development in the scientific field of superconductivity. Wang *et al.*, (2016, p.537ff) investigate technological evolution using US Patent Classification (USPC) reclassification. Results suggest that: "patents with Inter-field Mobilized Codes, related to the topics of 'Data processing: measuring, calibrating, or testing' and 'Optical communications', involved broader technology topics but had a low speed of innovation. Patents with Intra-field Mobilized Codes, mostly in the Computers & Communications and Drugs & Medical fields, tended to have little novelty and a small innovative scope" (Wang *et al.,* 2016, p.537, original emphasis). Future research in this research field should extend the patent sample to subclasses or reclassified secondary USPCs in order to explain in-depth technological evolution within a specific scientific field.

Other approaches for measuring technological evolution

New criteria of technological assessment apply technology development envelope (extension of hierarchical decision modeling and analytical hierarchy process into the future) to detect multiple pathways for technological evolution and construct strategic roadmapping, as illustrated by Daim *et al.*, (2018, p. 49ff) for robotics technologies.

Koh & Magee (2006; 2008) suggest an approach for studying technological progress based on three functional operations—storage, transportation and transformation. Results for information and energy technology indicate a continuous progress for each functional category independent of the specific underlying technological artifacts dominating at different times. However, some differences between energy and information technology are seen (cf. also, Valverde, 2016 for transitions in information technology). Magee *et al.*, (2016) show that Moore's law is a better description of long-term technological change when the performance data come from various designs, whereas experience curves may be more relevant when a singular design in a given factory is considered. In particular, Magee *et al.*, (2016, p.245) argue that: "Moore's exponential law appears to be more fundamental than Wright's power law for these 28 domains (where performance data are record breakers from numerous designs and different factories)". Moreover, Wright's approach shows that the cost of technology decreases as a power law of cumulative production, whereas generalized Moore's law shows that technologies improve performance exponentially with time. Nagy *et al.*, (2013, p.1)–using a statistical model to rank the performance of the postulated laws applied on cost and production of 62 different technologies–claim that:

Wright's law produces the best forecasts, but Moore's law is not far behind…. results show that technological progress is forecastable, with the square root of the logarithmic error growing linearly with the forecasting horizon at a typical rate of 2.5% per year. These results have implications for theories of technological change, and assessments of candidate technologies and policies for climate change mitigation.

In this context, for predicting technological progress, Farmer & Lafond (2016, p.647): "formulate Moore's law as a correlated geometric random walk with drift, and apply it to historical data on 53 technologies… to make forecasts for any given technology with a clear understanding of the quality of the forecasts. … to estimate the probability that a given technology will outperform another technology at a given point in the future”.

Table 1. *Strengths and weaknesses of some technometric approaches*

Technometrics	Strengths	Weaknesses
Hedonic	Hedonic function estimates a price surface. Hedonic method considers both economic and technical information.	First, the technique works best in cases of a distinct product technology. It cannot easily be applied to cases of a process technology. Second, the Hedonic approach is unsuitable for international comparisons because of significant differences in factor prices among countries. Third, it cannot be used in an ‘unskilled’ way to measure changes in technology. Finally, its theoretical status is still not clear.
RAND	State of the art (SOA) surfaces can reveal whether technological changes are “biased” toward increasing the relative availability (decreasing the relative cost) of one characteristic, or a group of them, relative to others.	First, the estimation procedure is arbitrary and difficult. Second, it does not take into account the correlations between technological characteristics, thereby seriously obscuring if not distorting the real rate and extent of technical progress.
Functional and Structural	The methodology has excellent potential application for most product and production technologies.	The full use of the functional/structural analysis to isolate and describe specific technologic advances and their values has found limited successful use.
Wholistic and Holistic	Wholistic. The framework provides an objective basis for determining the critical variables in the evolution of technology. The reproducibility of the results is excellent. Holistic. It provides an a priori theoretical basis for the selection of relevant variables, the choice of a functional form, and the quantification of weights assigned to each of the variables. It is possible to identify the sources underlying the observed advances in technology.	Methodological issues (e.g., data collection, etc.).

Fisher and Pry's Model	Technological advances are represented by competitive substitutions between new and old products.	Technological progress is due to multi-mode interaction among technologies rather than mere competition.

Table 1 synthetizes some approaches of the measurement of technological advances with pros and cons. Many techniques of the analysis of technological advances focus on competition between technologies, such as substitution model by Fisher & Pry (1971) and predator-prey interaction by Pistorius & Utterback (1997). This study here endeavors to measure the evolution of technology considering an alternative perspective based on interactions between a host-master technology and its main parasitic subsystem of technology to predict long-term development of the complex system of technology (cf., Coccia, 2018). Next section presents the conceptual framework of the suggested technometrics here.

Evolutionary ecology of technology within a Generalized Darwinism

The scientific departure of the proposed technometrics here is principles of the "Generalized Darwinism" (Hodgson & Knudsen, 2006, 2008) that provide suitable concepts for framing a broad analogy between evolution of technologies and evolutionary ecology of parasites to measure and explain different evolutionary pathways of technology itself. In economics of technical change, the generalization of Darwinian principles ("Generalized Darwinism") can assist in explaining the multidisciplinary nature of many innovation processes (cf., Basalla, 1988; Farrell, 1993; Hodgson & Knudsen, 2006; Levit *et al.*, 2011; Nelson, 2006; Schubert, 2014; Wagner & Rosen, 2014). In this context, Arthur (2009) argues that sociocultural evolution is related to the evolution of technology and Darwinism can explain technology development as it has done for species development (cf., Schuster, 2016, p.7). In general, technological evolution, as biological evolution, displays radiations, stasis, extinctions, and novelty (Valverde *et al.*, 2007). Kauffman & Macready (1995, p.26, original emphasis) state that: "Technological evolution, like biological evolution, can be considered a search across a space of possibilities on complex, multipeaked 'fitness,' 'efficiency,' or 'cost' landscapes". Schuster (2016, p.8) argues that: "Technologies form complex networks of mutual dependences just as the different species do in the food webs of ecosystems". Kauffman & Macready (1995, p.27 and p. 42) also point out that:

Evolution, biological or technological, is actually a story of coevolution. Adaptive alterations by the predatory bat alter the adaptive landscape of its frog prey. Alterations in the maximum power of the engine of an automobile alter optimal tire, suspension, and even highway design. Coevolution is a process of coupled, deforming landscapes where the adaptive moves of each entity alter the landscapes of its neighbours in the ecology or technological economy (p.27)…. Biological and technological evolution are both characterized by the requirement to solve hard combinatorial optimization problems… These interrelated features of many hard combinatorial optimization problems are therefore likely to underlie features of biological and technological evolution (p.42).

Nelson (2006, p.491) claims that a broad approach of Universal Darwinism in social sciences is: "a roomy intellectual tent welcoming scholars studying a variety of topics".

The crux of the study here is to measure and assess the evolution of technologies in a broad analogy with evolutionary ecology of parasites within a setting of Generalized Darwinism. Some brief backgrounds of the evolutionary ecology of parasites are useful to clarify the technometrics proposed here. Firstly, ecology studies the relationship functions and interactions between organisms of the same or different species and environment in which they live (cf., Poulin, 2006). In particular, the scope of the ecology is to explain all sorts of interaction of organisms to one another and to their environment. Secondly, the evolutionary ecology of parasites focuses on parasites (from Greek para = near; sitos = food) that are any life form finding their ecological niche in another living system (host). Parasites have a range of traits that evolve to locate in available hosts, survive and disperse among hosts, reproduce and persist (cf., Janouskovec & Keeling, 2016). Coccia (2018) argues that technologies can have a behavior similar to parasites because technologies cannot survive and develop as independent systems per se, but they can function and evolve in markets if associated with other host technologies, such as audio headphones, speakers, software apps, etc. that function if and only if they are associated with host electronic devices (e.g., smartphone, radio receiver, television, etc.).

This study endeavors to measure the effect that one host technology has on growth rate of parasitic technology to explain the evolution of the overall complex system of technology.

Model for the evolution of technology in complex systems

Evolution is a stepwise and comprehensive development [it originates from Latin evolution –onis, der. of evolvĕre = act of carrying out (the papyrus)]. In general, the process of development generates the formation of complex systems in nature and society (cf., Barton, 2014). The theoretical framework of "Universal Darwinism" (Dawkins, 1983; Nelson, 2006) claims that: "Darwinism involves a general theory of all open, complex systems” (Hodgson 2002, p.260; cf., Levit *et al.,* 2011). Hodgson & Knudsen (2006) suggest a generalization of the Darwinian concepts of selection, variation and retention to explain how complex systems evolve (cf. also, Hodgson, 2002; Stoelhorst, 2008). Hence, in order to show the proposed metrics of the evolution of technology here, it is important to clarify the concept of complex system. Simon (1962, p.468) in the study of complexity states that: “a complex system [is]… one made up of a large number of parts that interact in a nonsimple way... complexity frequently takes the form of hierarchy, and... a hierarchic system… is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until we reach some lowest level of elementary subsystem.” In the field of technology, McNerney *et al.* (2011, p. 9008) argue that: “The technology can be decomposed into n components, each of which interacts with a cluster of d − 1 other components” (cf., Gherardi & Rotondo, 2016; Oswalt, 1976; Magee, 2012, p.16ff. for materials innovation). Arthur (2009, pp.18-19) claims that: “Technologies somehow must come into being as fresh combinations of what already exists”. This combination of components and assemblies is organized into systems to some human purpose and has a hierarchical and recursive structure. In particular, the evolution of technology is due to major innovations and numerous minor innovations that interact in a complex system of technology (cf., Coccia, 2018; Sahal, 1981, p.37). Sahal (1981) points out that: “evolution… pertains to the very structure and function of the object (p.64)… involves a process of equilibrium governed by the internal dynamics of the object system (p.69)”. Moreover, the short-term evolution of technology is due to changes within system, whereas the long-term evolution is possible by forming an integrated system (Sahal, 1981, pp.73-74). This study here endeavors, starting from theoretical background discussed above, to measure and assess interaction between technologies within a host-parasite system for forecasting evolutionary pathways over time [11]. The following premises support the technometrics here (Coccia, 2018):

Technology is a complex system composed of more than one entity or sub-system and a relationship that holds between each entity and at least one other entity in the system. The technology is adapted in the Environment E with a natural selection operated by market forces and/or artificial selection operated by human beings (based on efficiency, technical, environmental and economic characteristics) to satisfy needs, achieve goals and/or solve problems in human society.

In the long run, the behavior and evolution of any technology is not independent from the behavior and evolution of the other technologies (Coccia, 2018).

Interaction between technologies is an interrelationship of information/resources/energy and other physical/chemical phenomena for reciprocal adaptations in inter-related complex systems.

Coevolution of technologies is the evolution of reciprocal adaptations in a complex system supporting the reciprocal enhancement of technologies' growth rate—i.e., a modification and/or improvement of technologies based on interaction and adaptation in complex systems and markets to satisfy changing needs and solve consequential problems in society.

P is a parasitic technology in H (host or master technology) if and only if during its life cycle, technology P is able to interact and adapt into the complex system of

11 Barabási *et al.*, (2001) suggested a parasitic computer to solve the nondeterministic polynomial time-complete satisfiability problem by engaging different web servers physically located in three continents (America, Europe and Asia).

technology H, generating coevolutionary processes to satisfy needs, achieve goals, and/or solve problems in society.

In general, technologies form complex systems based on subsystems of technology that interact in a non-simple way (e.g., batteries and antennas in electronic devices; cf., Coccia, 2018). Overall, then, the interaction between technologies in a complex system tends to generate stepwise coevolutionary processes within "space of the possible" (Wagner & Rosen, 2014, passim).

In order to operationalize the approach here to measure, assess and predict the evolution of technology here, this study proposes a simple model of technological interaction between a host technology H and an interrelated parasitic subsystem of technology. This model measures changes in a subsystem of parasitic technology in relation to proportional changes in the overall host system of technology. In particular, this model measures the effect that one host technology has on parasitic technology's growth rate. This approach is based on the biological principle of allometry that was originated to study the differential growth rates of the parts of a living organism's body in relation to the whole body (cf., Reeve & Huxley, 1945 for evolutionary biology studies; Sahal, 1981 for patterns of technological innovation).

The general model is based on following assumptions.

Suppose the simplest possible case of only two technologies, H (a host or master technology) and P (a parasitic subsystem of technology in H), forming a Complex System S(H, P); of course, the model can be generalized for complex systems including many subsystems of technology.

Let P(t) be the extent of technological advances of a technology P at the time t and H(t) be the extent of technological advances of a technology H (master or host system) that interacts with P at the same time (cf., Sahal, 1981, pp. 79-89). Suppose that both P and H evolve according to some S-shaped pattern of technological growth, such a pattern can be represented analytically in terms of the differential equation of logistic function. For H, Host technology, the starting equation is:

$$\frac{1}{H}\frac{dH}{dt}=\frac{b_1}{K_1}\left(K_1-H\right)$$

The equation can be rewritten as:

$$\frac{K_1}{H}\frac{1}{\left(K_1-H\right)}dH=b_1 dt$$

The integral of this equation is:

$$\log H-\log\left(K_1-H\right)=A\ +b_1 t$$
$$\log\frac{K_1-H}{H}=a_1-b_1 t$$
$$H=\frac{K_1}{1+\exp\left(a_1-b_1 t\right)}$$

$a_1=b_1 t$ and t = abscissa of the point of inflection.

The growth of H(t) can be described respectively as:

$$\log\frac{K_1-H}{H}=a_1-b_1 t \tag{1}$$

Mutatis mutandis, for Parasitic technology P(t) the equation is:

$$\log\frac{K_2-P}{P}=a_2-b_2 t \tag{2}$$

The logistic curve here is a symmetrical S-shaped curve with a point of inflection at 0.5K with $a_{1,2}$ are constants depending on the initial conditions, $K_{1,2}$ are equilibrium levels of growth, and $b_{1,2}$ are rate-of-growth parameters (1=Host technological system, 2=Parasitic technological subsystem).

Solving equations [1] and [2] for t, the result is:

$$t = \frac{a_1}{b_1} - \frac{1}{b_1}\log\frac{K_1 - H}{H} = \frac{a_2}{b_2} - \frac{1}{b_2}\log\frac{K_2 - P}{P}$$

The expression generated is:

$$\frac{H}{K_1 - H} = C_1\left(\frac{P}{K_2 - P}\right)^{\frac{b_1}{b_2}} \tag{3}$$

Equation [3] in a simplified form is C1=exp[b1(t2-t1)] with a1=b1t1 and a2=b2t2 (cf. Eqs. [1] and [2]); when P and H are small in comparison with their final value, the model of technological evolution of the host-parasite system is given by:

$$P = A\,(H)^B \tag{4}$$

where $A = \frac{K_2}{(K_1)^{\frac{b_2}{b_1}}} C_1$ and $B = \frac{b_2}{b_1}$

The logarithmic form of the equation [4] is a simple linear relationship:

$$\log P = \log A + B\ \log H \tag{5}$$

B is the evolutionary coefficient of growth that measures the evolution of technology P (Parasite) in relation to H (Host or Master technology).

This model of the evolution of technology [5] has linear parameters that are estimated with the Ordinary Least-Squares Method. The value of $B \gtreqless 1$ in the model [5] measures the relative growth of P in relation to the growth of H and it indicates different patterns of technological evolution: B<1 (underdevelopment), B ≥ 1 (growth or development of technology P). In particular,

$B<1$, whether technology P (a subsystem of H) evolves at a lower relative rate of change than technology H; the whole system of technology S(H, T) has a slowed evolution (underdevelopment) over the course of time.

B has a unit value: $B=1$, then the two technologies P and H have proportional change during their evolution: i.e., a symmetrical coevolution between a system of technology (H)and its interacting subsystem P. In short, when B=1, the whole system of technology S(H, T) here has a proportional evolution (growth) of its sub-systems of technology.

$B>1$, whether P evolves at greater relative rate of change than H; this pattern denotes disproportionate technological advances in the structure of a subsystem P as a consequence of change in the overall structure of a host technological system H. The whole system of technology S(H,T) has an accelerated evolution (development) over the course of time.

The coefficient B of evolutionary growth can be a metric for classifying the modes of interaction between technologies. Moreover, this coefficient B is systematized in an ordinal scale that indicates typologies of the evolution of technology and grade of how a host technology can enhance or inhibit the growth rate of parasitic technology (table 2).

Table 2. *Scale of the evolution of technological subsystem P in relation to Host technology H*

Grade of evolution of the system of technology	Coefficient of evolutionary growth of the subsystem of technology P	Type of the evolution of subsystem of technology P in relation to H (Symbol)	Mode of technological interactions between technologies H and P	Evolution of overall complex system of technology (Symbol)	Predictions of the evolution of overall system of technology
1 Low	B<1	Reduced /	Parasitism	Underdevelopment /	Complex system of technology evolves slowly over time
2 Average	B=1	Proportional +	Mutualism	Growth +	Complex system of technology has a steady-state growth
3 High	B>1	Accelerated !	Symbiosis	Development !	Complex system of technology is likely to evolve rapidly

Note: Symbols /, +, ! indicate in brief the type of technological evolution: underdevelopment, growth and development respectively.

Table 2 also suggests some symbols to indicate the intensity of growth rate of complex system of technology, measured with the coefficient of evolutionary growth B in model [5]: \ = underdevelopment, +=growth, and != development.

Properties of the scale of the evolution of technology are (table 2):

Technology of higher rank-order on the scale (with B>1) has higher technological advances of lower rank-order technologies (with B<1).

If a technology has the highest ranking on the scale (i.e., with B>1), it evolves rapidly (development) over the course of time. Vice versa, if a technology has the lowest ranking on the scale (with B<1), it evolves slowly (underdevelopment).

Technology of the highest rank order on the scale (with B>1) has accumulated all previous evolutionary stages of low rank order and generates a symbiotic growth between a system of technology H and its interacting subsystem of technology P.

The logical relation of interactions between technologies is: technological parasitism $\subseteq$ technological mutualism $\subseteq$ technological symbiosis (the symbol $\subseteq$ indicates subset in the set theory).

The model here suggests different grades of technological evolution of the subsystem of technology P supporting the evolution of overall complex system of technology. In particular, the initial stage of technological interaction is a technological parasitism between host and parasitic subsystem of technology (B<1). The change of coefficient B indicates the shift towards modes of stronger interaction between technologies within a complex system, such as technological mutualism (B=1) and technological symbiosis (B>1) that lead to a coevolution of the overall system of technology (cf., Coccia, 2018). Hence,

B<1 indicates mainly a Technologicalparasitism: any type of relationships between two technologies where one technology P (subsystem technology) benefits from the other (Host) that, instead, has a negative benefit from this interaction. This relationship can generate a low development of the subsystem technology and, as a consequence, of the overall complex system of technology (cf., Coccia, 2018). The low growth of the complex system of technology is due to an unidirectional and asymmetrical effect from H $\rightarrow$P

B=1 indicates a Technologicalmutualism: any type of relationships in which each technology benefits from the activity of the other technology. This interaction between technologies supports mutual benefits with symmetric and proportion evolutionary growth both of host system of technology H and of parasitic subsystem of technology P. The bi-directional relation of growth is given by: H$\leftrightarrow$P.

B>1indicates a Technologicalsymbiosis: any type of long-term relationships between technologies that interact and evolve together in a complex system. The technological interaction between H and P is: H⇔(strong) P.

Materials and method

Data and their sources

The evolution of technology is measured here using historical data of five example technologies (four for US market and one for Italian market); farm tractor, freight locomotive, generation of electricity in steam-powered and internal-combustion plants in the United States of America. In fact, US national system of innovation is a vital case study that shows general patterns of the evolution of technology across advanced market economies (Steil *et al.*, 2002). Sources of data for these technologies are tables published by Sahal (1981, pp.319-350, originally sourced from trade literature; cf. also Coccia, 2018). Note that data from the earliest years and also the war years are sparse for some technologies. In addition, this study also considers data of a main Information and Communication Technology (ICT): smartphone. Data of smartphone here are originally sourced from trade literature of Italian market, one of the largest economy in Europe (Punto Cellulare, 2018). Historical data of these technologies are important to verify applicability, effectiveness, generality, precision, correctness and robustness of the proposed model of technological evolution.

Measures

Functional Measures of Technology (FMT) are the technical characteristics of innovations and their change can indicate the evolution of technology over the course of time based on major and minor innovations, such as fuel-consumption efficiency of vehicles (cf., Sahal, 1981, pp.27-

29). The following FMTs are associated with a main subsystem of technology that indicates a parasitic technology P, and a host system H in which the parasitic technology P operates and interacts. FMTs per each technology seem to be the most appropriate variables to apply the suggested model of host-parasitic system for measuring and predicting the evolution of technology. Other measures are not considered here because they do not provide complete information of technical characteristics of technologies under study, such as index of tractor price in relation to price of labor, number of locomotive in service, cumulated production quantities, etc.

Functional Measures of Technologies (FMTs) for farm tractor over 1920-1968 CE (Common Era) in US market are:

fuel-consumption efficiency in horsepower-hours indicates the technological advances of engine (a parasitic technology P) within farm tractors. This FMT represents the dependent variable P in the model [5].

mechanical efficiency (ratio of drawbar horsepower to belt or power take-off –PTO- horsepower) is a proxy of the technological advances of farm tractor (H=Host technology). This FMT represents the explanatory variable H in the model [5].

For freight locomotive, FMTs over 1904-1932 CE in US market are:

Tractive efforts in pound indicate the technological advances of locomotive (Parasitic technology P). This FMT represents the dependent variable P in the model [5].

Total railroad mileage indicates the evolution of the infrastructure system of railroad (Host technology). This FMT represents the explanatory variable H in the model [5].

For electricity generated by steam-powered plants, FMTs over 1920-1970 CE in US market are:

Average fuel-consumption efficiency in kilowatt-hours per pound of coal indicates the technological advances of boiler, turbines and electrical generator (parasitic technology P of steam-powered plant). This FMT represents the dependent variable P in the model [5].

Average scale of plant utilization (the ratio of net production of steam-powered electrical energy in millions of kilowatt-hours to number of steam powered plants) indicates a proxy of technological advances of the steam-powered plant (Host technology). This FMT represents the explanatory variable H in the model [5].

For electricity generated by internal-combustion plants, FMTs over 1920-1970 CE in US market are:

Average fuel-consumption efficiency in kilowatt-hours per cubic foot of gas indicates the technological advances of boiler, turbines and electrical generator (a parasitic subsystem of internal combustion plant). This FMT represents the dependent variable P in the model [5].

Average scale of plant utilization (the ratio of net production of electrical energy by internal-combustion type plants in millions of kilowatt-hours to total number of these plants) indicates a proxy of technological advances of plants with internal-combustion technology. This FMT represents the explanatory variable of the host technology H in the model [5].

This study also considers smartphone technologies by using a sample of N=738 models of famous brands (Apple, ASUS, HTC, Huawei, LG Electronics, Motorola, Nokia, Samsung, Sony, ZTE, etc.) from 2008 to 2018, sold in Italy during the years 2012 and 2018. Functional Measures of Technological characteristics (FMTs) in smartphone technology over 2008-2018 CE in Italian market are given by:

Main Camera in megapixel (Mpx) indicates the technological advances of camera technology (Parasitic technology P) in smartphone. This FMT represents the dependent variable P in the model [5].

Processor GHz (Giga Hertz, GHz) indicates a proxy of the technological advances of overall smartphone technology (Host technology H). This FMT represents the explanatory variable H in the model [5].

In addition, in order to assess the multidimensional process of interaction between host technology and parasitic technologies, this case study of smartphone technology also considers further FMTs over 2008-2018 period given by:

Display resolution in total pixels12= display size row × display size column

Second Camera Mpx (megapixel)

Memory Gb (Giga byte)

RAM Gb (Giga byte)

Battery mAh (milliAmpere hour)

Model and data analysis procedure

Model [5] of the technological evolution is specified as follows:

$$\log P_t = \log a + B \log H_t + u_t \tag{6}$$

a is a constant; log has base e= 2.7182818; t=time; ut = error term.

Ptwill be the extent of technological advances of technology P (a parasitic subsystem of the Host technology H at time t).

Htwill be the extent of technological advances of host technology H in which the parasitic subsystem of technology P interacts at time t; H technology as a complex system is the driving force of the evolutionary growth of overall interrelated subsystems of technology Pi (i=1, . . . , n).

12 The display resolution is usually quoted as width × height, with the units in pixels: for example, "1024 × 768" means the width is 1024 pixels and the height is 768 pixels. Total pixels= 1024 × 768=786,432 pixels.

The multidimensionality is considered with the following model:

$\log P1t = \log a + B1 \log Ht + B2 \log P2t + Bi \log Pit + \ldots + Bm \log Pmt + \varepsilon t$ [7]

Ht=Host technology; Pit= Parasitic technology i (i=1, …, n); t=time; εt = error term.

The equations of simple regression [6] and multiple regression [7] are estimated using the Ordinary Least Squares method. Statistical analyses are performed with the Statistics Software SPSS® version 24.

Case studies of the evolution of technology in agriculture, rail transport, electricity generation and smartphone

Results of the evolution of farm tractor technology (1920-1968 period in US market)

Table 3 shows that the evolutionary coefficient of growth of farm tractor technology, from model [6], is B = 1.74, i.e., B >1:the subsystem technology of engine (P) has a disproportionate technological growth in comparison with overall farm tractor (H). This coefficient indicates a high grade of the evolution of technology P and a development of the whole system of farm tractor technology (cf., Figure 1).

Table 3. *Estimated relationship for farm tractor technology (1920-1968 period in US market)*

Dependent variable: log fuel consumption efficiency in horsepower hours (P=technological advances of engine within tractor)				
	Constant α (St. Err.)	Evolutionary coefficient β=B (St. Err.)	R2 adj. (St. Err. of the Estimate)	F (sign.)
Farm tractor	–5.14*** (0.45)	1.74*** (0.11)	0.85 (0.10)	256.44 (0.001)

Note: ***Coefficient β is significant at 1‰; Explanatory variable is log mechanical efficiency ratio of drawbar horsepower to belt (technological advances of farm tractor –Host technology H)

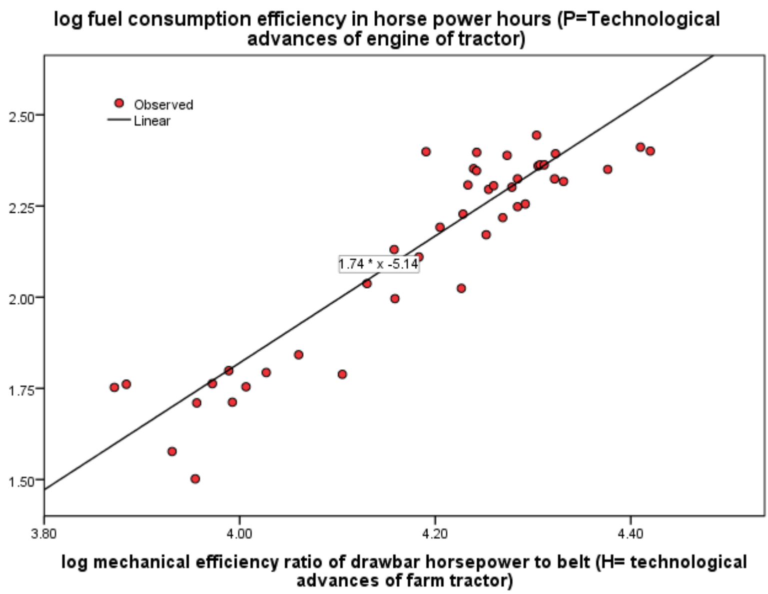

Figure 1. *Trend and estimated relationship of the evolution of farm tractor technology (1920-1968 period in US market)*

This result confirms the study by Sahal (1981) that the rapid evolution of farm tractor technology is due to numerous incremental and radical innovations over time, such as the diesel-powered track-type tractor in 1931, low-pressure rubber tires in 1934 and the introduction of remote control in 1947 that made possible improved control of large drawn implements. The development of the continuous running power takeoff (PTO) also in 1947 allowed the tractor's clutch to be disengaged without impeding power to the implements. Moreover, in 1950 it is introduced the 1000-rpm PTO for transmission of higher power, whereas in 1953 power steering was applied in new generations of tractor. In addition, the PTO horsepower of tractor has more than doubled from about 27hp to 69hp over 1948-1968; finally, dual rear wheels in 1965, auxiliary front-wheel drive and four-wheel drive in 1967 have improved the overall technological performance of tractor (Sahal, 1981, p. 132ff). These radical and incremental innovations have supported the accelerated evolution of farm tractor technology over time as confirmed by the statistical evidence here with the coefficient of evolutionary growth B>1 (grade 3=high in table 2).

Results of the evolution of freight locomotive technology (1904–1932 period in US market)

Table 4 shows that the evolutionary coefficient of freight locomotive technology is B = 1.89, i.e., B> 1: this coefficient of growth indicates a process of development of freight locomotive technology P in the host system of rail transportation (see, Figure 2).

Table 4. *Estimated relationship for freight locomotive technology (1904–1932 period in US market)*

Dependent variable: log Tractive efforts in pound (P=technological advances of locomotive)				
	Constant α (St. Err.)	Evolutionary coefficient β=B (St. Err.)	R2 adj. (St. Err. of the Estimate)	F (sign.)
Locomotive technology	−13.87*** (1.48)	1.89*** (0.12)	0.91 (0.07)	270.15 (0.001)

Note: ***Coefficient β is significant at 1‰; Explanatory variable is log Total railroad mileage (technological advances of the infrastructure –Host technology H)

This development of freight locomotive technology can be explained with a number of technological advances, such as the introduction of compound engine in 1906 that improved tractive effort (Sahal, 1981). In 1912 the first mechanical stoker to use steam-jet overfeed system of coal distribution was perfected. In 1913, another technological advance was the substitution of pneumatically operated power reverse gear for the hand lever. In 1916, the introduction of the unit drawbar and radial buffer eliminated the need for a safety chain in coupling the engine and tender together. Further technological advances are due to the adoption of cast-steel frames integral with the cylinder, the chemical treatment of the locomotive boiler water supply and the introduction of roller bearings over 1930s. In particular, these technical developments reduced the frequency of maintenance work in locomotives. Subsequently, the continuous modification of steam locomotive with reciprocating engine has led to diesel-electric locomotive by the mid-1940s (Sahal, 1981, p.154ff). These and other technological developments have supported the accelerated evolution of freight locomotive technology over time as confirmed by the coefficient of evolutionary growth B>1 calculated in table 4.

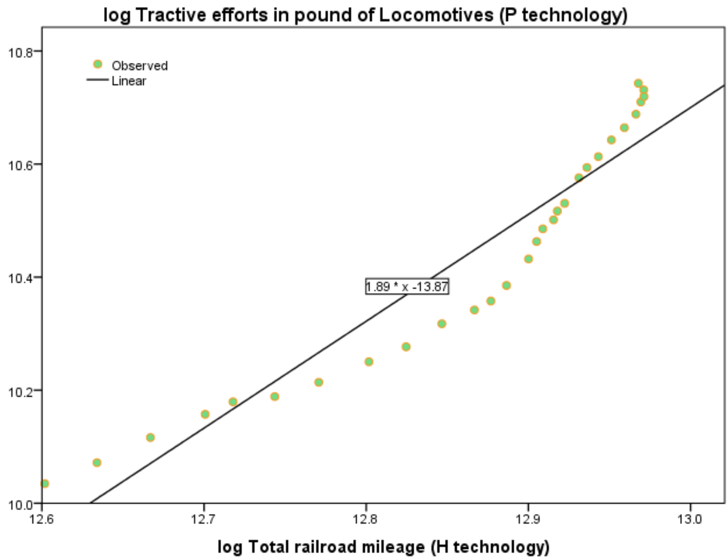

Figure 2. *Trend and estimated relationship of the evolution of freight locomotive technology (1904–1932 period in US market)*

Results of the evolution of electricity generation technology (1920-1970 period in US market)

Electricity is generated in different types of plants: 1. Steam-powered plants, which may be either fossil fueled or nuclear plant; 2. Internal-combustion plants, including gas turbines and diesel engines; 3. hydroelectric plants. This study focuses on 1st and 2nd type of plants. Table 5 shows that the steam-powered electricity, with plants that are fossil (coal) fueled, has B = 0.23, i.e., B < 1 (see also Figure 3).

Table 5. *Estimated relationship for steam-powered plants that are fossil (coal) fueled (1920-1970 period in US market)*

Dependent variable: log Average fuel consumption efficiency in kwh per pound of coal (P=technological advances of turbine and various equipment)				
	Constant α (St. Err.)	Evolutionary Coefficient β=B (St. Err.)	R2 adj. (St. Err. of the Estimate)	F (sign.)
Turbine and various equipment (coal fueled)	−1.35*** (0.04)	0.23*** (0.01)	0.93 (0.09)	675.12 (0.001)

Note: ***Coefficient β is significant at 1‰; Explanatory variable is log Average scale of steam-powered plants (Host technology H)

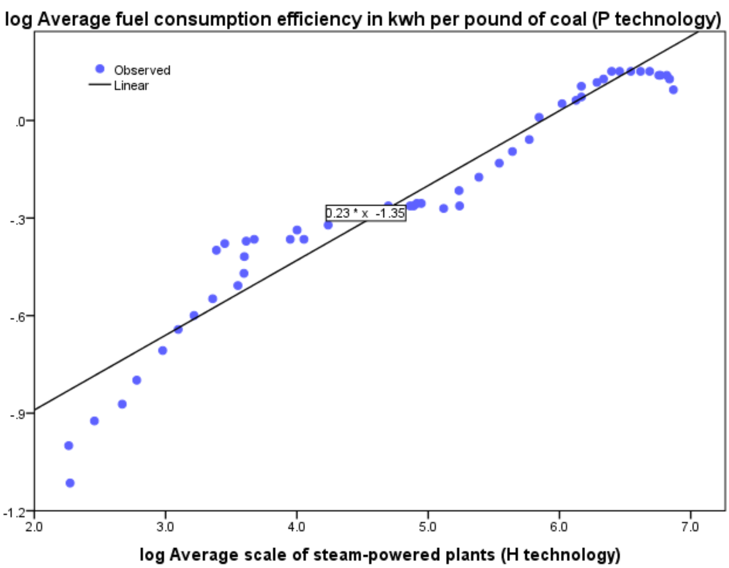

Figure 3. *Trend and estimated relationship of the evolution of steam-powered electricity with plants that are fossil (coal) fueled (1920-1970 period in US market)*

Table 6 shows results of electricity generation with internal-combustion plants having gas turbines; the coefficient of evolutionary growth of this technology is B = 0.35, i.e., B < 1. In short, the evolution of technology in the generation of electricity both in steam-powered plants and internal-combustion plants is low and driven by an evolutionary route of underdevelopment over the course of time (see, Figure 3 and 4).

Table 6. *Estimated relationship for internal-combustion plants with gas turbines (1920-1970 period in US market)*

Dependent variable: log Average fuel consumption efficiency in kwh per cubic feet of gas (P=technological advances of turbine and various equipment)

	Constant α (St. Err.)	Evolutionary coefficient β=B (St. Err.)	R2 adj. (St. Err. of the Estimate)	F (sign.)
Gas turbine and various equipment	–2.93*** (0.02)	0.35*** (0.02)	0.81 (0.14)	213.63 (0.001)

Note: ***Coefficient β is significant at 1‰; Explanatory variable is log Average scale of internal-combustion plants (Host technology H)

In general, the evolution of technology in the generation of electricity is associated with available natural resources (fossil and gas), the increase in steam pressure and temperature made possible by advances in metallurgy, the use of double reheat units and improvements in the integrated system man-machine interactions to optimize the operation of overall plants, etc. (cf., Sahal, 1981, pp.183ff). Low rate of technological evolution in the electricity generation technology (underdevelopment with B<1 in tables 5-6) can be due to: "the deterioration in the quality of fuel and of constraints imposed by environmental conditions…. other main reasons: First, increased steam temperature requires the use of more costly alloys, which in turn entail maintenance problems of their own…. Thus there has been a decrease in the maximum throttle temperature from 1200 °F in 1962, to about 1000 °F in 1970. Second, there has been lack of motivation to increase the efficiency in the use of gas in both steam-powered and internal-combustion plants because of the artificially low price of fuel due to

Federal Power Commission's wellhead gas price regulation. Finally, … there has been a slowdown in generation efficiency due to heavy use of low-efficiency gas turbines necessitated by delays in the construction of nuclear power plant" (Sahal, 1981, p.184).

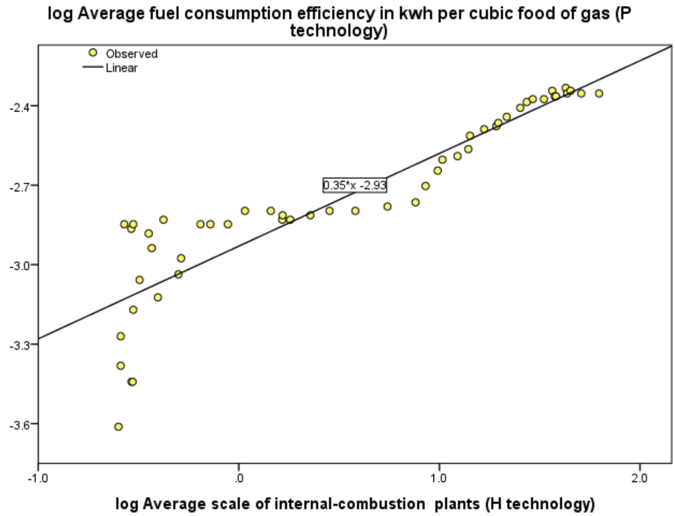

Figure 4. *Trend and estimated relationship of the evolution of internal-combustion plants with gas turbines (1920-1970 period in US market)*

Results of the evolution of smartphone technology (2008-2018 period in Italian market)

Table 7 shows that the evolutionary coefficient of growth of smartphone technology is B = 1.19, i.e., B >1. Technical characteristics of main camera (Parasitic technology P) have a disproportionate technological growth in comparison with overall smartphone (Host technology H). This coefficient indicates a high grade of the evolution of camera technology supporting a development of complex system of smartphone technology (cf., Figure 5).

Table 7. *Estimated relationship for smartphone technology (2008-2018 period in Italian market)*

Dependent variable:	log Main Camera in megapixel (P technology)			
	Constant α (St. Err.)	Evolutionary coefficient β=B (St. Err.)	R2 adj. (St. Err. of the Estimate)	F (sign.)
Main Camera technology	2.07*** (0.03)	1.19*** (0.04)	0.97 (0.18)	897.483 (0.001)

Note: ***Coefficient β is significant at 1‰; Explanatory variable is log Processor GHz (technological advances of smartphone–Host technology H)

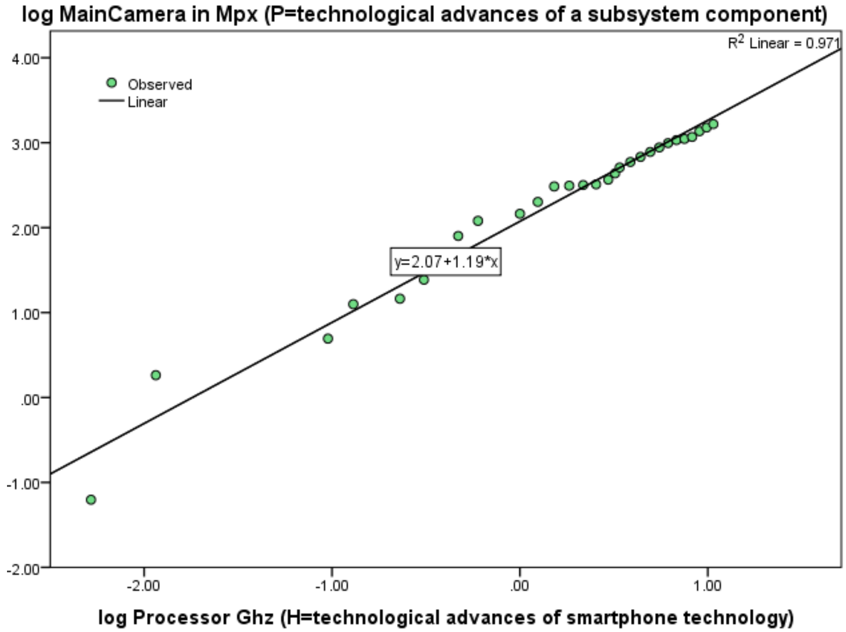

Figure 5. *Trend and estimated relationship of the evolution of main camera in smartphone technology (2008-2018 period in Italian market)*

Table 8. *Estimated relationship for the evolution of smartphone technology considering multidimensional interaction between host system and subsystems of parasitic technologies (log-log model, 2008-2018 period in Italian market)*

Dependent variable: log Main Camera in megapixel (P1 technology) at t =2008, …, 2018

Smartphone	Unstandardized Coefficient	Standardized Coefficient	t-test
Constant. α	–1.19		–1.83
(St. Err.)	(0.65)		
Predictors ⇓			
Coefficient log P2 technology	0.09***		4.65
2nd Camera megapixel		0.17	
(St. Err.)	(0.02)		
Coefficient log P3 technology	0.14***		4.12
Resolution Display in pixels		0.19	
(St. Err.)	(0.03)		
Coefficient log P4 technology	0.20***		3.84
RAM Gb		0.24	
(St. Err.)	(0.05)		
Coefficient log P5 technology	0.12***		4.38
Memory Gb		0.20	
(St. Err.)	(0.03)		
Coefficient log P6 technology	0.14*		1.97
Battery mAh		0.07	
(St. Err.)	(0.07)		
Coefficient log H technology	0.12		1.46
Processor GHz		0.06	
(St. Err.)	(0.08)		
R2 adj. adj.	0.70		
(St. Err. of the Estimate)	(0.29)		
F	233.81		
(sign.)	(0.001)		

Note: Pi=Parasitic technology i=1, …, 6; H=Host technology (smartphone); *** p-value< .001; ** p-value< .010; * p-value< .050

Table 8 shows that the evolutionary pathways of camera technology in smartphone is mainly driven by advances of RAM in Gb, memory in Gb and display resolution in pixels, as showed by standardized coefficients of regression (see, highlighted cell in the third column of table 8). R2 adjusted of the model [7] indicates that about 70% of the variation in megapixels of main camera can be attributed (linearly) to predictors indicated in table 8. Figure 6 shows that the coevolution of technical characteristics of host system and parasitic technologies in smartphone technology. Table 9 reveals that main camera has a very high coefficient of correlation with other parasitic technologies and with processor GHz (a proxy of the technical advances of overall smartphone-host technology): in general, r>.78 (p-value 0.001), except for battery mAh. This result suggests that the evolution of smartphone technology is due to coevolutionary processes of different parasitic technologies in a complex system of technology.

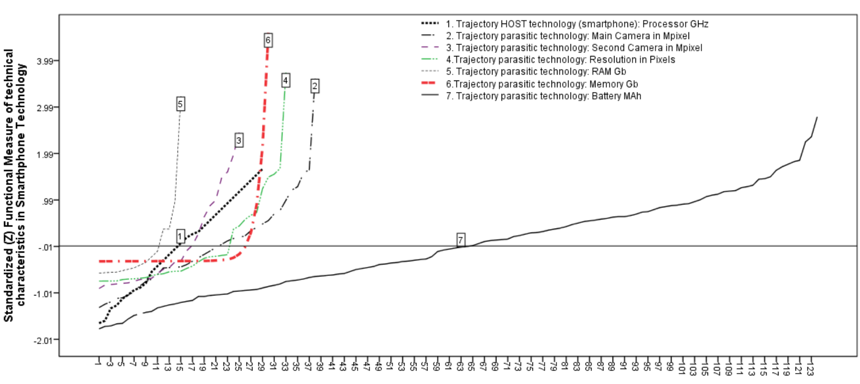

Figure 6. *Coevolution of technical characteristics of host and subsystem parasitic technologies in smartphone (2008-2018 period).*

Note: The Functional Measures of Technology *i* in *t* (FMT*i, t*) of *y*-axis are systematized in a comparable framework by applying the following standardization formula for the technology *i* in *t=time*: $Z(FMT)_{it} = \frac{FMT_{it} - \mu_t}{\sigma_t}$; where: $Z(FMT)_{it}$= standardized FMT_{it} (Functional Measures of Technology *i* at *t*); FMT_{it}= Functional Measures of Technology*i* at the year *t*; μ_t= arithmetic mean of the FMT over *t*; σ_t = standard deviation of the FMT over *t*. *Remark*: FMT_{it} is negative when the raw score is below the arithmetic mean, positive when it is above. A zero value of FMT_{it} indicates that the raw value is equal to the arithmetic mean.

Table 9. *Correlation between advances of technical characteristics of main camera, host and other parasitic technologies in smartphone (2008-2018 period)*

		HOST Log Processor GHz	Parasitic 2 Log Second Camera MP	Parasitic 3 Log Resolution Pixels	Parasitic 4 Log RAM Gb	Parasitic 5 Log Memory Gb	Parasitic 6 Log Battery MAh
Log Parasitic 1	Pearson Correlation	.985**	.903**	.929**	.933**	.781**	.295
Main Camera	Sig. (2-tailed)	.001	.001	.001	.001	.001	.072
Mpx	N	29	25	33	15	30	38

Note: **. Correlation is significant at the 0.01 level (2-tailed). N=technical improvements from 2008 to 2018

In particular, the rapid evolution of smartphone technology (B>1 in table 7) is due to numerous innovations over time, such as Bluetooth for wireless communication in 2002, touchscreen in 2007, app store and android market in 2008 that have generated many parasitic technologies given by software applications for mobile devices, Siri and fingerprint scanners in 2011, 4G in 2012, waterproof phone in 2013, dual camera in 2014, 4K HDR resolution display in 2015, modular phones in 2016, and facial recognition in 2017, etc. This finding indicates that the long-run evolution of smartphone technology depends on the behavior and coevolution of inter-related parasitic technologies (cf., Coccia, 2018). Moreover, learning effects, based on learning by doing and learning by using, are fostering the assimilation of new technology in smartphone devices from many parasitic technologies to support the evolutionary pathway of overall complex system of technology (Cohen & Levinthal, 1990). Sahal (1981, p.82, original italics) argues that: "the role of learning in the evolution of a technique has profound implications for its diffusion as well". In the context of smartphone technology, Watanabe *et al.*, (2012, pp.1293-1294) argue that learning effects in ICTs can be the sources of its self-propagating development of technology, acquiring new functionality from digital industry, wireless communications and software applications (cf., Carranza, 2010; Coccia, 2018).

Overall, then, this statistical analysis shows that the proposed models here can assist in assessing explaining the evolution of different technologies based on interaction between host system and its subsystem of technology that guides evolutionary pathways and technological diversification over time and space (cf., Coccia, 2018).

Discussionand conclusion

Many characteristics in the nature and evolution of technology are hardly known. Scientists should open the debate regarding the nature and types of interaction between host technologies and its subsystem technologies that may explain and generalize aspects of the evolution of technology and technical change in society (cf., Coccia, 2018; Pistorius & Utterback, 1997; Sandén & Hillman, 2011). Some scholars argue that technologies and technological change display numerous life-like features, suggesting a deep connection with biological evolution[13]. The analogy between biological processes and technological evolution is a source of ideas because biological evolution has been studied in-depth and provides a logical structure of scientific inquiry for the evolution of technology.

This study applies a broad analogy between evolutionary ecology of parasites and technological evolution, within a theoretical framework of Generalized Darwinism, to propose a theory to measure, assess and predict the evolutionary pathways of technology. The evolution of technology here is

13 Basalla, 1988; Coccia, 2018; Erwin & Krakauer, 2004; Jacob, 1977; Kreindler *et al.,* 2014; Kyriazis, 2015; Nelson & Winter,1982; Solé *et al.,* 2011, 2013; Wagner & Rosen, 2014; Valverde *et al.,* 2007; Ziman, 2000.

based on an assumption that technologies are complex systems that interact in a nonsimple way with other technologies and inter-related subsystems of technology. In particular, this study analyses the evolution of technology considering the interaction between host technology (system) and parasitic technology (subsystem). The approach here is operationalized with a simple model that contains only two parameters and provides the coefficient of evolutionary growth, which is useful to measure and assess the effect that host technology can have on parasitic technology's growth rate, predicting which technologies are likely to evolve rapidly. The technometrics here suggests three simple grades of the evolution of technology, based on the coefficient of evolutionary growth, according to host technology H can enhance or inhibit the growth rate of parasitic technology P: B<1 (underdevelopment of P), B=1 (growth of P) and B>1 (development of P and of the whole system of technology). The proposed technometrics, tested in five example technologies, provides consistent results of the evolution of technologies with empirical data and the history of specific technologies under study.

In general, the evolution of technology has universals based on mutualistic and symbiotic interaction, similar to many phenomena in nature and society. In fact, Szathmáry (2011) argues thatbenefits of cooperation can drive the evolution of a system that supports cooperative behavior. Technological interaction based on cooperation between technologies (e.g., mutualism and symbiosis) must pay off in the long run, even if it is immediately costly to cooperative technologies due to switching costs for adapting to evolving host technology (e.g., the transition of headphones from wired to wireless technology with new generations of electronic devices without jack) .

Coefficient of evolutionary growth B here is a metric for classifying the modes of technological interaction and for predicting the long-term development of complex system of technology, namely:

Coefficient B<1 suggests low interaction between host system and its subsystem of technology (technological parasitism), whereas B>1 suggests a high interaction between host system and subsystem of technology (technological symbiosis).

Technology having an accelerated growth of its parasitic technologies (B>1) advances rapidly, whereas technology with low growth of its parasitic technologies (B<1) enhances slowly.

High development of technology is governed by a process of disproportionate growth in its parasitic technologies (B>1), such as the technological development of farm tractor, smartphone and freight locomotive technologies described here.

Evolution of technology is inhibited when its parasitic subsystem P has low changes in relation to changes of host technology (B<1), generating underdevelopment of the whole system of technology over the course of time (e.g., the generation of electricity in steam-powered and internal-combustion plants).

Long-run evolution of a technology depends on the behavior and evolution of associated parasitic technologies. To put it differently, long-run evolution of a specific technology is enhanced by the integration of two or more parasitic/symbiotic technologies that generate co-evolution of the overall complex system of technology.

Overall, then, one of the most important findings of the proposed theoretical framework here is two general properties of the evolution of technology as a complex system:

(a) the disproportionate growth of technological subsystems in a host technology generates the development of overall complex system of technology

(b) Interaction between technologies can generate coevolution within complex system of technology with the shift from technological parasitism (indicated with B<1) to technological symbiosis (B>1) over the course of time. This transition dynamics is due to natural selection of technical characteristics during the interaction between technologies that reduces negative effects and favors positive effects directed to an evolution of reciprocal adaptations of technologies in complex systems of technology over time and space (cf., property of mutual benefaction by Coccia, 2018).

The finding of this study could aid policymakers and managers to design best practices of technology policy and management of technology for supporting development of new technology, and as a consequence, industrial and economic change in society. One of the main limitations of this approach is the lack of useful data in sufficient quality for different technologies. Future efforts in this research field require a gathering of substantial amount of technological characteristics for different technologies to provide further empirical evidence of the evolutionary pathways of technology over time and space. Moreover, future study will be also directed to support the theory here with practical policy and management implications to guide funding for R&D towards specific technologies (having B>1) that are likely to evolve rapidly in society.

Overall, then, the idea presented in the study here to measure, analyze and predict evolution of technology is adequate in some cases but less in others because of the diversity of technological innovations and their relationships in different complex systems and socioeconomic environments. Nevertheless, the broad analogy between evolutionary ecology of parasites and technological evolution, based on Generalized Darwinism, keeps its validity here in explaining and predicting general evolutionary pathways of technology. In particular, the proposed approach here based on the ecology-like interaction between technologies—may lay the foundation for development of more sophisticated concepts and theoretical frameworks in technometrics and technological forecasting. As a matter of fact, these findings here can encourage further theoretical and empirical exploration in the terra incognita of the interaction between different technologies during economic change to measure, explain and predict the aspects of the evolution of technology. To conclude, this study constitutes an initial significant step in measuring the evolution of technology considering the interaction between technologies in complex systems to predict the long-run behavior of technology in society. However, the identification of a comprehensive technometrics for technological forecasting in different domains of technology, having a technological diversification in markets, is a non-trivial exercise. In fact, Wright (1997, p. 1562) properly claims that: "In the world of technological change, bounded rationality is the rule."

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Appendix

	log Fuel consumption efficiency in horsepower hours (Engine of Tractor P)	log Mechanical efficiency ratio of drawbar horsepower to belt (Tractor efficiency H)	log Tractive efforts in pound (Locomotive power P)	log Total railroad mileage (Infrastructure for locomotive H)
Years	44	44	29	29
Mean	2.13	4.19	10.43	12.86
Std. Deviation	0.27	0.146	0.22	0.11
Skewness	-0.76	-0.68	-0.21	-1.04
Kurtosis	-0.83	-0.56	-1.19	-0.06
	log Average fuel consumption efficiency in kwh per pound of coal (turbine and various equipment in steam-powered plants P)	log Average scale of steam-powered Plants H	log Average fuel consumption efficiency in kwh per cubic feet of gas (turbine and various equipment in internal-combustion plants P)	log Average scale of internal-combustion plants H
Years	51	51	51	51
Mean	-0.25	4.85	-2.75	0.51
Std. Deviation	0.34	1.43	0.33	0.85
Skewness	-0.67	-0.17	-0.67	0.02
Kurtosis	-0.09	-1.26	0.04	-1.64
	log Main Camera megapixel in smartphone P1	log Processor Giga Hertz in smartphone H	log Second Camera megapixel in smartphone P2	log Memory Giga byte in smartphone P3
Years	10	10	10	10
Mean	2.54	0.13	1.43	-0.31
Std. Deviation	2.80	0.41	1.39	-1.09
Skewness	-1.52	-1.38	-0.13	0.84
Kurtosis	3.05	1.65	-0.88	0.51
	log RAM Giga byte in smartphone P4	log Battery milliAmpere hour in smartphone P5	log Display resolution total pixels in smartphone P6	
Years	10	10	10	
Mean	0.30	7.64	13.12	
Std. Deviation	0.41	7.77	13.33	
Skewness	-0.16	-6.94	-0.50	
Kurtosis	-0.65	64.64	-0.55	

Note: P=parasitic technology; H= Host technology. Numbers x in table are in natural logarithmic and have to be transformed with ex to obtain absolute value

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Conclusion

The competition between technologies is a dominant concept in economic literature to explain the diffusion and evolution of innovations in industrial dynamics. However, the interaction between technologies is often not one of competition, as there are many cases where technologies have different multi-mode interactions over time and space. Scientists should open the debate regarding nature and types of interaction between host (or master) technology and its subsystems of parasitic/symbiotic technologies that may explain and generalize vital aspects of the evolution of technology in markets and technical change in society.

The book here proposes that the interaction between technologies in complex systems is similar to the biological interaction of host-parasite systems that can explain evolutionary trajectories of interactive technologies over time and space. Empirical evidence presented in this book, based on the theory of technological parasitism, can clarify and generalize, whenever possible, some characteristics of the evolution of technology and generate theoretical and practical predictions for management of technology.

The results of scientific analyses reveal some general properties:

1. technological host (or master) systems with many parasitic technologies generate a rapid stepwise evolution of technological host-parasite systems not seen in technologies with fewer associated parasitic technologies and a low level of technological interaction.

2. the long-run behavior and evolution of any technology is *not* independent of the other associated technologies.

The book documented here makes a unique contribution, for the first time to our knowledge, by showing how technologies co-evolve by interacting in complex systems of host (or master)-parasitic technologies. In fact, studying inter-related or more symbiotic technologies as complex systems can help explain general aspects of technological and economic change in society. The theory here suggests that it may be possible to influence (improve) the long-term evolution of technology by increasing the fundamental interactions between parasitic and host (or master) technologies. Moreover, this conceptual scheme of technological parasitism can predict which technologies are likeliest to evolve rapidly. In particular, findings reveal that host (or master) technologies with many inter-related parasitic (component) technologies advance rapidly, whereas master technologies with fewer parasitic (component) technologies improve slowly. To put it differently, the findings here suggest that host technologies with more parasites tend to evolve faster. However, the inverse causal relation can be also actually valid: i.e., a technology that advances faster (driven by market forces) attracts more parasitic technologies as it opens up more market opportunities for new product and process development. This source of technological evolution, based on Schmookler's "demand pull" hypothesis, states that market size and market growth of products may exert a positive influence on the propensity to innovate inter-related products and/or processes (e.g., parasite technologies), though technological opportunities may vary widely across sectors and also over the history of individual technologies (Sahal, 1981). In short, environment factors and market signals can drive the selection criteria of host technologies among new potential parasitic technologies. Hence, the long-run evolution of host (or master) technology can attract new parasitic and/or symbiotic technologies that generate a coevolution of overall complex system of host technology in a context of dependency networks between technologies.

The results presented in this book support innovation strategy of firms on critical decisions of when to invest in R&D of new technologies, abandon the old or pursue an intermediate level of R&D investment between old and new technology for fostering technological advances that sustain and safeguard competitive advantage in markets. In this context of strategic management, Bryan *et al.* (2007, p. 41) argue that: "co-evolution can lead to reduced product development costs and increased responsiveness to market changes".

Hence, the analogy of the book here provides an appropriate theoretical framework to explain one of the characteristics of the evolution of technology in turbulent markets. However, the concept of technological evolution departs from biological evolution in fundamental ways. In general, technological innovations and their evolution pathways are due to entrepreneurs and/or firms that seek optimality, typically under economic criteria, such as minimization of cost, maximization of profit, etc. to achieve a competitive advantage with the prospect of a temporary monopoly power in markets. As a matter of fact, humans act as ecosystem engineers able to change the socioeconomic environment and support technical progress (cf., Solé *et al.*, 2013). In contrast to technology, living organisms are the result of tinkering that is undirected mutation plus a widespread reuse and combination of available elements to build new structures (Jacob, 1977).

The idea of a "technological parasitism" presented in the book here seems to be adequate in some cases but less in others because of the diversity of technologies and their interaction in complex systems and markets (cf., studies by Coccia M. over 2016-2020). Technology analysis here focuses on number of technological components considered like parasitic technologies of complex systems of product and/or process innovations. The suggested approach here is relatively simple when one considers the complexity of the evolution of technology, yet it is powerful in its capability to reproduce the evolutionary patterns similar to those observed in real datasets about the evolution of four example technologies (aircraft, tractor, locomotive and bicycle technology). Future development of this research, for a comprehensive analysis, has also to consider other factors and the modularity degrees of technological system for assessing their role for the evolution of technology.

In general, the analogy here keeps its validity in explaining and predicting several characteristics of the coevolution of technology in society (cf., Grodal *et al.*, 2015; Kauffman & Macready, 1995, p. 27ff). In particular, the theory of technological parasitism suggests some findings, properties and predictions that are a reasonable starting point for understanding the universal features of the coevolution of technologies that leads to technological and economic change in society. However, the conceptual scheme here, of course, cannot predict any given paths and characteristics of the evolution of technologies with precision. In fact, we know that other things are often not equal over time and space in the domain of technology.

Overall, then, the proposed theory here—technological parasitism based on the ecology-like interaction between technologies and innovations—may lay the foundation for development of more sophisticated concepts and theoretical frameworks in economics and management of technology. In particular, these findings here can encourage further theoretical exploration in the *terra incognita* of the interaction among technologies during economic change to reveal new properties of the nature and evolution of technology in turbulent markets. Future efforts in this research field will be directed to provide further empirical evidence, also considering dependency-network framework, to better evaluate this new theory, to develop other properties for explaining technological evolution directed to support innovation strategy for competitive advantage of firms focused, more and more, on new technologies that evolve rapidly in markets. To conclude, identifying generalizable theory of the evolution of technology at the intersection of engineering, economics, sociology, psychology, anthropology, and perhaps human biology is a non-trivial exercise. Wright (1997, p.1562) properly claims that: "In the world of technological change, bounded rationality is the rule."

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