Journal of Economics Bibliography
www.kspjournals.org
Volume 6 June 2019 Issue 2

Theories of the evolution of technology based on processes of competitive substitution and multi-mode interaction between technologies

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Abstract. Evolution of technology is a stepwise advancement of a complex system of artifact, driven by interaction with sub-systems and other systems, considering technical choices, technical requirements and science advances, which generate new and/or improved products or processes for use or consumption to satisfy increasing needs and/or to solve complex problems of people in society. This study explains evolution of technology with two different approaches: theories based on processes of competitive substitution of a new technology for the old one and theories considering a multi-mode interaction between technologies, such as the theory of technological parasitism. 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.
Keywords. Evolution of technology, Technological evolution, Technological change, Technological progress, Technological advances, Technological parasitism.
JEL. F34, F43, F63, C01.

1. 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: "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.

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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).

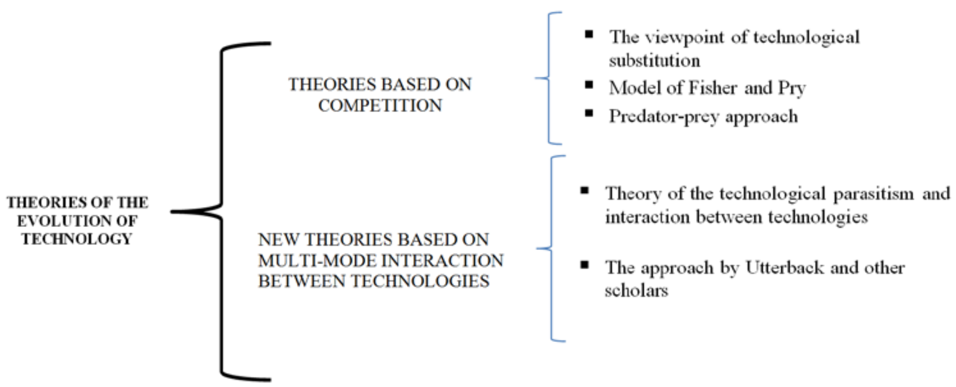

Figure 1. *Theories of the evolution of technology*

2. 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).

3. 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, $\forall i = 1, \dots, n$ and $j = 1, \dots, m$

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).

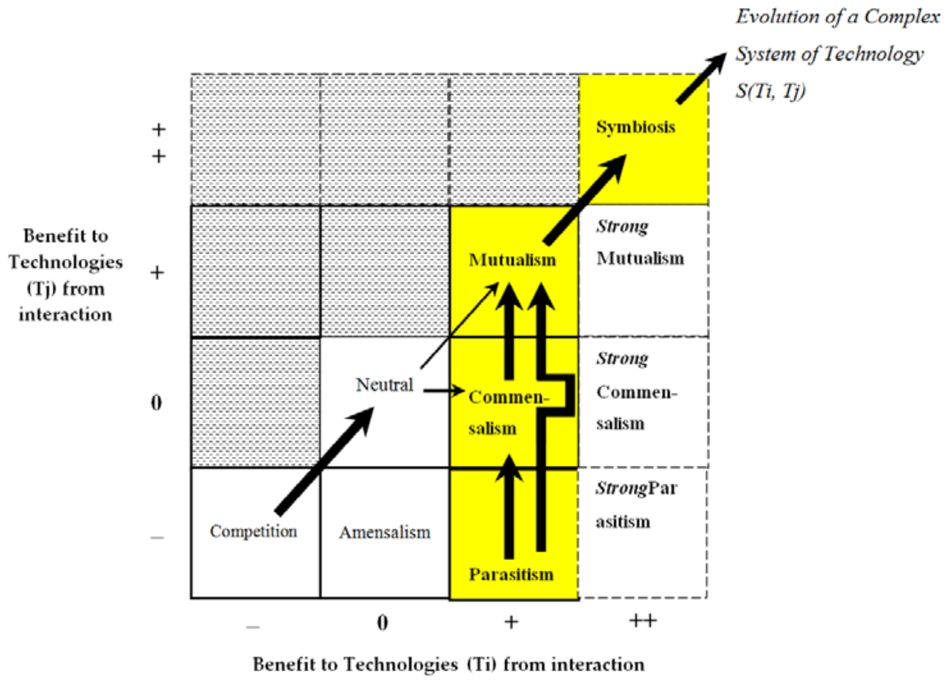

Figure 2. *Types of relationships between technologies and evolutionary pathways in a complex system. Note. The notions of positive, negative and neutral benefit to technologies Ti and Tj in S from mutual interaction are represented with following symbols of logic: +, –, 0 (zero); ++ is a strong positive 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.

4. 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."

Notes

[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.

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