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ENDOGENOUS INNOVATION: THE CREATIVE RESPONSE

FORTHCOMING IN ECONOMICS OF INNOVATION AND NEW TECHNOLOGY

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ABSTRACT. The limits of both evolutionary approaches, based upon biological metaphors, and the new growth theory based on the early economics of knowledge, are becoming apparent. Considerable progress can be made by implementing an evolutionary complexity approach that builds upon the legacy of Schumpeter (1947) with the notions of: i) reactive decision making; ii) multiple feedback; iii) innovation as the outcome of an emergent system process rather than individual action; iv); organized complexity and knowledge connectivity; iv) endogenous variety; vi) non ergodic path dependent dynamics. Building upon these bases, the paper articulates an endogenous theory of innovation centered upon the analysis of the systemic conditions that make the creative reaction and hence the introduction of innovations possible.

JEL classification: O31, C23, C25, L20.
Keywords: Innovation, Evolutionary Complexity, Path dependence.

1. INTRODUCTION

Economics of innovation has made considerable progress in the last decades. It is now recognized as specialized field of research and it is taught in most universities. The discovery of the residual and its crucial role in the increase of total factor productivity and hence in economic growth has given it a central place in economics (Solow, 1957). The understanding of the determinants of innovation, i.e. the cause of more than 50% of US economic growth in the years 1909-1949, became indispensable for economics to survive as a science able to explain economic activities. Moving from the study of the consequences of technological change on the working of the economic system, economics of innovation has made possible to better understand the processes by means of which innovation is being introduced in the economy. We know much better how and where innovation takes place.

Yet, we know very little why is innovation is introduced and even less when. The understanding of the determinants of innovation is still unclear. The ambition to understand innovation as an endogenous product of the working of economic activity has not yet been fulfilled. The promise of evolutionary economics and new growth theory to go beyond the limits of standard economics, where technological change falls like manna from heaven, did not yield the expected results (Antonelli, 2008a and 2009).

The retrieval and the implementation of the notion of creative response introduced by Schumpeter in his essay published in 1947 provide crucial clues to understanding innovation as the endogenous result of reactions – as opposed to a planned conducts of firms, caught in out-of-equilibrium conditions by the mismatch between the expectations that are necessary for the rolling activities of firms and the actual conditions of the ever changing factor and product markets, conditional upon the endogenous availability of knowledge externalities. The notion of creative response provides crucial clues to provide economics of innovation with a new analytical platform that integrates many different analytical traditions including the tools of the economics of complexity and enables to understand innovation as an endogenous process (Antonelli 2008a, 2009; 2011 and 2015a).

The retrieval of the legacy of Schumpeter (1947)[1] enables to elaborate a satisfactory explanation of the endogenous determinants of innovation introduction elaborating a comprehensive framework based on the notion

[1] See also Schumpeter (1947a).

of evolutionary complexity able to understanding why and when innovation are being introduced. This enables to go beyond the ambiguities and dead-ends of both the approaches building upon biological metaphors and the so-called new growth theory. Within the frame of economic complexity, innovation can be usefully viewed as an emergent property that is shaped and explained by the interactions among heterogeneous agents, embedded in the organized complexity of the economic system (Anderson, Arrow, Pines, 1988; Arthur, Durlauf, Lane, 1997; Lane et al., 2009; Antonelli, 2009; Arthur, 2009; 2010; 2015a; Fransman, 2010).

The rest of the paper is organized as it follows. Section 2 discusses the limits and the achievements of the two competing attempts to grasp innovation as an endogenous process: the new growth theory and the evolutionary approach. Section 3 shows how the notion of creative response introduced by Schumpeter (1947) enables to articulate a comprehensive platform that, including other important contributions, seems able to understand innovation as an endogenous process. Section 4 integrates into the Schumpeterian platform the tools of the economics of complexity to analyze innovation as a path dependent emergent property of an economic system characterized by high levels of organized complexity. The conclusions summarize the main results of the analysis.

2. BUILDING UPON THE SHOULDERS OF GIANTS

The new growth theory and the evolutionary approach are the two competing frameworks available in the current literature to study the economic determinants of innovation. They have provided the basic ingredients for an endogenous theory of innovation. The identification of the central relationship between the early economics of knowledge and the economic of growth is the main contribution of the new growth theory. The central role of the variety of innovations being introduced at each point in time is the main contribution of evolutionary approaches. The limits of both approaches, however, have become more and more evident.

The new growth theory impinges upon the results of the preliminary steps of the economics of knowledge to elaborate an endogenous account of economic growth. It builds upon the results of the enquiry about the economic properties of knowledge as an economic good. Technological knowledge is characterized by limited appropriability that has the twin effect to reduce the revenue that 'inventors' can earn from its generation, but -spilling through the system- also to reduce the costs of its generation for anybody else in the system. The non-excludable component of new technological knowledge generated at each point in time contributes directly the increase of total factor productivity at the system level: knowledge plays a central role as the engine of growth (Romer, 1990, 1994, 2015).

The elegant and articulated frame of the new growth theory justified its success and stirred a variety of applications and empirical tests that gradually questioned its foundations. It became clearer and clearer that the new growth theory was unable to cope with the strong and shared evidence about the huge variance of total factor productivity levels and rates of increase across agents, industries, regions, countries and, most importantly, historic times (Craft, 2010).

The recent advances of new economics of knowledge, especially at the microeconomic level, questioned some of its basic assumptions. First, it became apparent that the new growth theory rested upon quite an implicit postulate about a positive sum game between the effects of the excludable and non-excludable components of technological knowledge. The new growth theory, as a matter of fact, does not provide a clear analysis of the reasons why the losses, that 'inventors' suffer from the lack of appropriation of the non-excludable part of the knowledge they contributed to fund, should be lower than the benefits in terms of increased total factor productivity. Actually, at the microeconomic level, it is difficult to understand why a firm should experience an increase of total factor productivity stemming from expenses that have been made without any benefit in terms of revenue. Moreover, the microeconomics of knowledge suggests that even with a positive-sum-game the new growth theory does not provide any clue to understand how and why opportunistic behavior should not prevail. Even when the Romer' postulate of a positive-sum-game applies, in fact, each firms misses the appropriate incentives to invest resources in the generation of knowledge. The argument is stronger with a non-positive sum game, either zero or negative: firms have no incentives to invest resources in the generation of new knowledge. According to the recent advances of the microeconomics of knowledge, the new growth theory is unable to avoid the implications of Arrovian analysis of the negative effects of knowledge non-appropriability[2].

A second bundle of problems about the limits of the assumptions of the new growth theory that spillovers engender pure and instantaneous knowledge externalities -that can be absorbed and used at no costs- became progressively clear. The recent advances of the new economics of knowledge have explored the effects of knowledge cumulability, complementarity and non-exhaustibility and made clear the role of the stock of knowledge –both internal and external to each firm- in the recombinant generation of new technological knowledge. Technological knowledge is at the same time an input and an output characterized by high levels of tacitness that make the access to and the use of external knowledge difficult.

Agents can benefit from knowledge externalities only after appropriation lags and substantial efforts to screen, identify, absorb and recombine external knowledge as an input into the generation of new knowledge. Knowledge externalities are diachronic and pecuniary: i) Knowledge appropriability is transient rather than partial[3]. Technological knowledge

[2] See the Appendix.

[3] Following Arrow (1962), Romer's (1990 and 1994) appropriability of knowledge is considered as partial. Knowledge is split in two parts: the appropriable and the non-

can be appropriated by 'inventors' for a limited, but qualified stretch of time. It becomes a public good only after some time. The flows of knowledge generated at each point in time add to the stock of public knowledge only through time. As such knowledge externalities are diachronic as opposed to synchronic; ii) the absorption and eventual use of selected knowledge items extracted from the stock of public knowledge requires efforts and resources. External knowledge is not free. It has a cost that is lower than the cost of first generation. As such, knowledge externalities are pecuniary, as opposed to pure.

Thirdly, the evidence confirms that innovation takes place in highly idiosyncratic conditions with huge variance across agents, industries, regions and historic times. This evidence contrasts the assumptions of new growth theory that innovation is spontaneous, unlimited, ubiquitous and evenly distributed in time and space.

Finally, the limits of the implicit assumption that technological knowledge and technological innovation coincide seem more and more evident. The availability of knowledge externalities and more generally the idiosyncratic characteristics of knowledge are not sufficient to understand why firms do innovate. Knowledge externalities in other words are indeed a necessary condition for innovation to take place, but not a sufficient one. Firms are reluctant to introduce innovations and they can actually innovate only when a number of complementary conditions apply. Knowledge externalities are part of the set of conditions upon which innovation is contingent but they are not the single and exclusive factor.

As a consequence externalities are not only diachronic and pecuniary, but also stochastic, localized in time and space, rather than synchronic, pure or technical, ubiquitous in time and space and automatic. Structured interactions are necessary to use knowledge spillovers as inputs in the

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appropriable. This paper articulates the view that knowledge appropriability is transient, rather than partial. All knowledge is at first appropriated, but eventually leaks out and becomes public.

recombinant generation of new technological knowledge. Highly localized and specific circumstances make available external knowledge that can be accessed and used at cost that are below equilibrium levels. Knowledge externalities, moreover, are *a necessary but not sufficient condition* for the actual introduction of innovations and the consequent increase of total factor productivity (Antonelli and David, 2015).

Evolutionary approaches that build upon the path breaking contributions of Nelson and Winter (1982) have renewed the Schumpeterian centrality of innovation in economic theory and shown that economic system are characterized by perennial change both in technology and structure. To elaborate their framework, Nelson and Winter rely upon Darwinistic metaphors according to which agents try and change their routines only as a reaction to adversity[4]. In the rest of their 1982 book, however, Nelson and Winter, suggest that firms change their routines and introduce innovations without a specific cause. Firms learn and occasionally change their routines: it is not clear why firms would feel the need to change. Their changes are sorted out in the selection environment: some survive and are adopted. Many fail. Occasionally firms have the chance to introduce innovations i.e. new and superior technologies: as a matter of fact innovation is random and exogenous[5]. Innovation is, in fact, the ex-post result of the selection process.

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[4] Careful reading of Nelson and Winter (1982) seems to suggest that firms would change their routines and introduce innovations only as a reaction to adversity. See Nelson and Winter (1982): "we assume that if firms are sufficiently profitable they do no "searching" at all. They simply attempt to preserve their existing routines, and are driven to consider alternatives only under the pressure of adversity." (p.211). In so doing Nelson and Winter rule out the hypothesis that firms with profits above the average introduce innovations.

[5] See Nelson and Winter (1982): "In the orthodox formulation, the decision rules are assumed to be profit-maximizing over a sharply defined opportunity set that is taken as a datum, the firms in the industry and the industry as a whole are assumed to be at equilibrium size, and innovation (if treated at all) is absorbed into the traditional framework rather than mechanically. In evolutionary theory, decision rules are viewed as a legacy from firm's past and hence appropriate, at best, to the range of circumstances in which the firm customarily finds itself, and are viewed as unresponsive, or inappropriate to novel situations or situations encountered irregurarly. Firms are regarded as expanding or contracting in response to disequilibria, with no presumption that the industry is "near" equilibrium. Innovation is treated as stochastic and as variable across firms." (Nelson and Winter, 1982:165-166).

Once again the assumptions on which Nelson and Winter elaborate their Darwinistic approach imply that innovation should take place evenly across agents through time and space. There is no way to justify in their approach the huge variance of the actual innovation process. Substantial evidence shows that some agents innovate more than others, some regions innovate more than others, some industries are more innovative than others: innovations cluster in time and space.

As a matter of fact Nelson and Winter rely on an implicit postulate according to which *homo oeconomicus* is characterized by the spontaneous propensity to innovate. Yet their postulate about the spontaneous drive to change routine and introduce, occasionally, better technologies that are ex-post sorted out in the eventual selection process does not find the necessary support in the economics of decision-making. Agents are reluctant to make all the efforts that are necessary to innovate for two basic reasons: i) the innovation process is characterized by radical uncertainty. Its outcome and timing cannot be predicted, ii) because of limited appropriability and tradability, the economic exploitation of innovations is itself characterized by radical uncertainty. Agents need a specific motivation to try and innovate that goes beyond the need to cope with adversity and include the "Schumpeterian" hypothesis that profits above the average feed the innovation process (Schumpeter, 1942). Yet the large literature, that builds upon the contributions by Nelson and Winter (1973, 1982), consistently does not provide a clue to understand why firms innovate.

Second, according to Nelson and Winter, changes breed changes along standard Markov chains that, like trajectories, do not allow any possible changes, along time, in the speed and direction of the innovation process. As a consequence this type of innovation process is strongly deterministic and past dependent. History matters only at the beginning of the process. The occurrence of contingent events along the process bears no weight on its development since all possible outcomes have been defined at the outset.

The empirical evidence about the strong, diachronic and synchronic, variance of innovative activity, measured with any possible indicator, from innovation counts to patents, including total factor productivity rates of increase, across agents, industries, regions, countries and historic time, questions, not only the new growth theory but also and primarily, the evolutionary accounts as it raises the key question: why such a variance if all agents are equally eager to innovate? (Craft, 2010).

The innovation process in evolutionary approaches that use biological analogies is not endogenous as it stems from random events. In the Darwinistic approach, in fact, the generation of variety takes place randomly without any specific causality about the rate and the direction of the introduction of innovations[6]. Only the Darwinistic selection among the many innovative attempts can be grounded on solid economic foundations. Only innovations that actually fit into the specific economic conditions will be sorted out and diffused. The others will fails[7].

The search for an endogenous causation of innovation is not finished with standard evolutionary approaches. It is still necessary to understand the reasons why firms try and innovate. Along the same lines it remains unclear why the rates of introduction of innovation differ across economic space and most importantly historic times.

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[6] It seems quite surprising that little effort has been made to grafting the Lamarckian hypothesis that the phenotype can change the genotype to the economics of innovation. The Lamarckian approach provides an evolutionary framework into which the causality and intentionality of the introduction of innovations might be better elaborated.

[7] As a matter of fact the approach elaborated by Nelson and Winter (1982) is not able to go beyond the results of Alchian (1950:214) who writes: "Plants "grow" to the sunny side of buildings not because they "want to" in awareness of the fact that optimum or better conditions prevail there but rather because the leaves that happen to have more sunlight grow faster and their feeding system became stronger. Similarly, animals with configurations and habits more appropriate for survival under prevailing conditions have an higher probability to survive.".

3. THE SCHUMPETERIAN PLATFORM.

The 1947 essay by Joseph Schumpeter provides the opportunity to elaborate an analytical platform able to integrate different and yet complementary approaches elaborated in the literature so as to grasp innovation as the endogenous product of economic activity. Antonelli (2008a, 2011 and 2015a) analyzes in detail the 1947 essay by Schumpeter and highlight its key contributions:

i) Schumpeter (1947) makes clear that firms are reluctant to engage in innovation activities: when there is no mismatch between expected and actual product and factor market conditions firms are not considering the possibility to innovate. They are well aware of the radical uncertainty that characterizes the knowledge generation process and the actual outcome of the full range of innovation activities. They try and innovate –only- when the actual conditions of product and factor markets do not meet their expectations. This takes place both when profits and performance at large are below and above the average.

ii) the distinction between creative and adaptive response made by Schumpeter (1947) stresses the role of the co-occurrence of (knowledge) externalities in determining whether the reaction of firms can be actually creative or simply adaptive [8]. The mismatches without knowledge externalities – as much as knowledge externalities without mismatches - are not sufficient to engender the creative reaction that leads to the introduction of innovations.

[8] Note that we follow the Schumpeterian use of the notion of adaptive reaction as a form of passive attitude when no changes to the existing technology are possible. In fact the adaptive response is not defied as passive, but simply included in established practice. The possibility of technological change is not considered. In complexity theory, adaptive responses are an active choice that includes possible introduction of changes to the system by agents who try and adapt to its new characteristics. Following the Schumpeterian lexicon this would be a creative reaction (Miller and Page, 2007).

iii) the creative reaction engenders new mismatches and new knowledge externalities. Firms' creative reaction and the consequent introduction of innovations, cause out-of-equilibrium conditions for other firms which may be able to react creatively and engender new out-of-equilibrium conditions for yet other firms. These latter, in turn, may be able to react creatively, provided that the structural characteristics of the system –now fully endogenous - are able to continue to provide a flow of knowledge externalities that enable creative reaction (Antonelli, 2008a, 2011; Antonelli, Scellato, 2013).

The 1947 contribution can be regarded as the synthesis of the different contributions elaborated by Schumpeter that enables to build a comprehensive platform that allows the integration in a single framework of the following analytical blocks: a) reactive decision-making; b) the Neo-Schumpeterian approach; c) classical legacies; d) the new economics knowledge; e) the selective diffusion of innovations. Let us consider them in turn.

Reactive decision-making. The Schumpeterian focus on response rather than on planned conduct of firms and agents enables to take advantage of the behavioral analysis of decision-making. In an evolutionary complexity that builds on the notion of innovation as a creative response, the attributes of economic agents in terms of rationality acquire substantial relevance. The analysis of the limits to Olympian rationality and the notions of bounded and procedural rationality matter to understanding and implementing the Schumpeterian dynamics based on decision making procedures and the reaction and interactions among agents in the system (Simon, 1947).[9]

Herbert Simon notes that procedural rationality is the result of sequential reactions that take place when expectations and related decisions do not

[9] It seems appropriate to note that Schumpeter's 'Creative response in economic history' and Simon's *Administrative Behvior* were both published in 1947.

match the actual conditions of product and factor markets. At each point in time, agents try to articulate expectations upon which to base their choices. When these expectations do not match actual market conditions, agents are forced to react. Bounded rationality and the burden of sunk costs enable them to procedural rationality that is contingent on their specific conditions and on past decisions.

The prospect theory of Kahneman and Tversky (1979) and the regret theory elaborated by Loomes and Sugden (1982) apply very well to make clear how difficult it is to change the current way of doing business. Firms can overcome their regret to abandon the current routines only when unexpected circumstances expose them either to major opportunities or to major problems. The decision to try and innovate is taken only when the reluctance to change is overcome by unforeseen prospects for high profits or major losses that are engendered by emerging mismatches between expected and actual product and factor market conditions. This approach contrasts the theorizing of Darwinistic ascent according to which the innovative behavior of firms is spontaneous and automatic: firms would try and innovate without any specific inducement mechanisms. Here, instead, it is clear that the attempt to try and innovate is considered as a possible strategy only when firms are exposed to unexpected events.

Unexpected events affect the performances of firms. The reaction of firms takes place when unexpected events expose firms to performances that are far away from equilibrium, both lower and larger than the average. When firms experience equilibrium performances there are no reasons to try and react. Firms try and react when their performances are negative and expose them to failure. In this case the reaction is necessary in order to survive. The failure mechanism is put in place. Firms try and react, however, also when their performances are well above equilibrium levels. Fast rates of growth of the demand and high levels of profitability make possible to fund innovative activities (Bandura and Cervone, 1986; Rizzello and Turvani, 2002)[10].

The context in which firms react has a strong bearing on the characteristics and effects of their reaction. The outcome of their reactions is contingent on the external conditions. At each point in time, agents try to do their best within the strict limits of their bounded rationality; since they do not have access to all the relevant information and are not able to process all the information they are able to access, they cannot foresee the future. Each contingent decision at time t affects the range of possible choices at time t+1 and constrains the kinds of reactions they are able to articulate. The external context, in turn, exerts strong effects on the actual outcome of the specific and constrained reaction (Simon, 1969, 1979, 1982). Decision-making is intrinsically context dependent.[11]

Social interactions affect not only the behavior of agents in the formation of their preferences as consumers and their strategies as players in product and factor markets, but shape their capability to generate new technological knowledge by providing access to external knowledge. The frame within which such interactions take place plays a central role (Antonelli and Scellato, 2013).

The integration of the behavioral analyses about decision making make it possible to regard the creative response as an entrepreneurial action that characterizes and applies both to incumbent firms and agents. The

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10 Antonelli and Scellato (2011) tested the hypothesis of a U shaped relationship between profitability and innovation that has its minimum in the proximity of average levels of profitability.

11 Albin (1998) provides a clear definition of the notion of context dependent decision making: "A robust alternative to the rational choice program must also be more explicitly context dependent…But one promising path to discovering a knowable orderliness in human behavior that is context dependent and computationally bounded is to ask whether and when the social environment favors some behaviors over others and why. Evolutionary models in which the distribution of strategies in a population change in response to their success and in which mutation and innovation lead to new behaviors are a logical way to attach these issues." (Albin, 1998:71).

contradiction between the exclusive role of the entrepreneur as an outsider that innovates and enters the market place elaborated by Schumpeter (1934) and the corporation praised by Schumpeter (1942) as the engine for innovation can be reconciled with the appreciation of the entrepreneurial function that can be performed both by incumbents and outsiders, when the appropriate conditions are given (Audretsch, 2007).

The distinction introduced by Milton Friedman (1953) between subjective and objective rationality, and his claim that only the latter is relevant in economics since the market will always be able to select out firms that make the wrong choices so as to restore equilibrium conditions, no longer holds. The equilibrium conditions after the introduction of innovation are no longer the same as before. The distribution of agents unable to foresee the future and to make valid long-terms plans has important consequences for economics, at least when agents are put in the condition of being able to implement a successful creative reaction. Friedman's argument that markets are able to sort out agents that fail to make rational choices with no consequences for general equilibrium conditions is no longer valid. The introduction of innovation changes the fundamentals of the system; suboptimal choices have long-lasting consequences.

Market rivalry in the neoschumpeterian approach. The core of Schumpeter's 1947 contribution identifies the causes of the mismatches – which, combined with entrepreneurial resources and crucial knowledge externalities, qualify the systemic conditions as determinants of the stochastic and contingent possibility of creative responses and introduction of innovations – in the unexpected changes that occur both factor and product markets. The neoschumpeterian literature, blossomed in the US and influenced primarily by Schumpeter (1942), concentrated much attention on product markets. It emphasized the role of the corporation engaged in oligopolistic rivalry in product markets as the main, actually exclusive, factor of the mismatches (Scherer, 1982). This literature elaborated the so-called 'Schumpeterian hypotheses[12]' according to which: i) large firms are more likely to engage in research and development (R&D) activities and introduce innovations, than small firms, because of larger opportunity to appropriate the benefits of innovations, and economies of scale in conducting R&D activities (Fisher and Temin, 1973); ii) firms engaged in oligopolistic markets are more likely to introduce innovations than firms active in markets characterized by either perfect competition or monopoly (Dasgupta and Stiglitz, 1980). Large empirical evidence tested the Schumpeterian hypotheses with mixed results. Audretsch (1995 and 2006) provides strong evidence about the central role of small firms and entrepreneurship in the introduction of radical innovations showing that corporations failed in the key technologies –biotechnologies and informatics- that characterized technological change in the late decades of the XX century[13]. Aghion, Bloom, Blundell, Howitt (2005) confirmed the inverted-U relationship between market form, number of firms and innovative efforts. The importance of oligopolistic rivalry in stirring innovative efforts is not questioned, only its assumed exclusivity seems a limit[14].

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[12] See Kamien and Schwartz: "We attribute these hypotheses to Schumpeter because that is how they are commonly referred to in the literature on the subject" (Kamien and Schwartz, 1982: 22)

[13] The empirical evidence of Antonelli and Colombelli (2015b) shows that the relationship between size and innovation holds only with respect to the size of the stock of knowledge. Firms with a large stock of internal knowledge are more likely to introduce innovations than firms with a small stock of knowledge. This relationship is not confirmed when size is measured with other indicators such as sales and employment. The Schumpeterian Hypothesis holds because of the recombinant character of the knowledge generation process.

[14] Aghion, Akcigit, and Howitt, (2015) following the neoschumpeterian literature that impinges upon the legacy of Schumpeter (1942) does not take into account the hypothesis that firms may be induced to innovate by their negative performances. In the failure induced approach, instead, firms introduce innovation not only to gain monopoly rents, but also as a creative reaction to their falling profitability (Antonelli, 1989). The evidence provided by Antonelli and Scellato (2011) shows that there is a U relationship between profitability and innovation. Firms introduce innovations both when their profitability is negative and when their profitability is very high. Both stem from out-of-equilibrium conditions. In the former case the failure-inducement mechanism takes place. The introduction of innovations is determined by the effort to cope with adverse market conditions. In the latter case the large profitability reduce the liquidity constraints and provides firms with the opportunity to cope with the high levels of uncertainty of the innovation process.

The inclusion of the classical legacies. The 1947 contribution of Schumpeter enables to go beyond the neo-schumpeterian framework and broaden the analytical context accommodating among the causes of the mismatches, not only the oligopolistic rivalry in product markets or in the exogenous supply of entrepreneurs, but also the changes that take place in factor markets and product markets. This allows to grafting the classical contributions in the economics of technological change. Marx and Smith shared the same strong assumption that technological change is endogenous, but regarded it as taking place in response to changes in factor demand and aggregate demand, respectively. A large literature has been built on this legacy elaborating the induced technological change approach and the demand pull hypothesis. Both can be integrated successfully into the creative response framework and considerably enrich the scope of analysis.

Along these lines, analysis of the direction of technological change within the induced technological change approaches elaborated by John Hicks (1932) and Vernon Ruttan (1997) based on early Marxian intuition, can contribute to evolutionary complexity. Inclusion of the induced technological change approach, based on Marx's legacy, helps to integrate analysis of the effects of changes in the factor markets not only on the rate of introduction of innovations but also on its direction.

The notion of technological congruence is useful in this context. Technological congruence is an emergent system property defined by the matching between the relative size of outputs' elasticity with the relative abundance and cost of inputs in local factor markets. With given total costs, output is larger, the larger is the output elasticity of the cheapest input. It is consequently clear that all changes in factor markets are likely to induce creative responses: i) that consist of the introduction of new technologies, ii) that are biased i.e. are characterized by changes in the composition of the output elasticity of inputs that reflect the new conditions in factor markets, and iii) help increasing or restoring the levels of technological congruence with positive effects on total factor productivity (Antonelli, 2015c). The hypothesis that both the rate and the direction of technological change are induced by changes in factor markets that push firms to introduce directed technological change, is perfectly consistent with the Schumpeterian platform where firms innovate while trying to react to unexpected changes to the economic conditions upon which their tentative equilibrium solutions had been built (Antonelli, 2008a)[15].

Similarly, the contributions to the demand pull approach based on the intuition of Adam Smith and later elaborated by Allyn Young (1928) and Nicholas Kaldor (1981), on the central relationship between the extent of the market, the degree of division of labor, and hence of specialization, can be successfully accommodated as major sources of mismatches. This dynamics is especially effective when user-producer knowledge interactions enhanced by increased levels of competent demand provide opportunities for learning and eventually generating new technological knowledge and introducing innovations (Schmookler, 1966). In the Schumpeterian synthesis, changes in the aggregate levels of demand matter as much changes to the individual demand curve of oligopolistic corporations for altering the expected equilibrium conditions[16]. Recent attempts in evolutionary economics to better consider the active role of demand in shaping both structural and technological change, contribute to this line of analysis (Saviotti, Pyka, 2013).

The new economics of knowledge. The new growth theory has shown the central role of technological knowledge to understanding technological change and growth. The Schumpeterian platform enables the integration of

[15] Antonelli and Quatraro (2010) provide strong empirical evidence on the causal relationship between changes in factor prices, the introduction of directed technological changes and the increase of total factor productivity. Antonelli (2015b) articulates a model of Schumpeterian growth based on the endogenous accumulation of capital and the related reduction of its relative user cost that induces the search for higher levels of technological congruence based on the introduction of capital intensive technological change.

[16] Antonelli and Gehringer (2015a and 2015b), test the competent demand pull hypothesis according to which demand actually pulls technological change and total factor productivity growth only when it is associated with effective knowledge interactions that parallel market transactions along vertical value chains between competent users and producers.

recent advances in the economics of knowledge. The new economic of knowledge, in fact, has much enriched the analysis of the economic properties of knowledge and investigated not only knowledge appropriability, but also knowledge cumulability, non-exhaustibility and complementarity.

After much emphasis on the aggregate technology production function where knowledge enters as an input into the generation of any other good, the attention concentrated on the generation process of knowledge, viewed as an intentional and dedicated activity characterized by the recombination of existing knowledge items. Once more the Schumpeterian legacy provides basic guidance: the generation of new knowledge and consequently the introduction of innovations is the result of the recombination of existing knowledge items. As Schumpeter puts it: ”To produce means to combine materials and forces within our reach…differently” (Schumpeter, 1911/1934:65). According to Brian Arthur who elaborates the Schumpeterian legacy: “ new technologies were not ‘inventions’ that came from nowhere. All the examples I was looking at were created-constructed, put together, assembled-from previously existing technologies. Technologies in other words consisted of other technologies, they arose as combinations of other technologies” (Arthur, 2009:2).

The stock of public knowledge enters as an indispensable input into the generation of new knowledge. At each point in time the new knowledge generated adds to the stock of knowledge that keeps increasing. The generation of additional knowledge may benefit of the increasing size of the stock of quasi-public knowledge, provided that the costs of external knowledge keep declining[17]. The generation of knowledge acquires the typical traits of a non-ergodic process where the present is influenced, at

[17] The increase of the stock of quasi-external knowledge and the introduction of innovations may undermine the quality of the knowledge governance mechanisms engendering congestion effects and more generally changing the structure of interactions and transactions that enable the access to the stock of knowledge.

each point in time, by the past. This approach has important implications: i) the characteristics of the stock of existing knowledge shape the direction and the rate of the generation of new knowledge; ii) the larger is the stock of knowledge and the better its composition in terms of coherence, complementarity and rarity of its components, the lower is the cost of knowledge as an input into the recombinant knowledge generation, the lower is the cost of knowledge as an input and hence, for a given budget, the lower is the cost of knowledge as an output[18] and the larger is the knowledge output and the likelihood that the creative reaction takes place with the eventual introduction of innovations and the increase of total factor productivity[19].

The stock of public knowledge is an essential input into the generation of new knowledge: no new knowledge can be generated by an individual agent without access to and use of knowledge generated by third parties. Its accumulation and access conditions are determined by the organization and the composition of learning activities that take place within each

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18 The empirical evidence of Antonelli and Colombelli (2015b) shows that the amount and the structure of external knowledge and the internal stocks of knowledge that firms can access and use in the generation of new technological knowledge help firms to reduce the costs of knowledge. The empirical section is based upon a panel of European public companies for the period 1995 – 2006, for which information about patents have been gathered. The econometric analysis of the costs of knowledge explores the role of R&D expenditures, the stock of knowledge internal and external to each firm on the unit costs of patents. In order to articulate the different facets of the external knowledge that is made accessible by proximity with firms co-localized in the same region (NUTS2), they take into account include other variables proxying for regional variety, complementarity and similarity. The results confirm the hypothesis that the size and the composition of the stock of external knowledge play a key role in reducing the actual cost of the generation of new technological knowledge at the firm level.

19 Antonelli and Gehringer (2016) articulate the hypothesis that the use of external knowledge is necessary to complement the recombinant generation of new knowledge. The empirical evidence of 20 OECD countries in the years 1975-2010 confirms that when the access to the external knowledge occurs at costs below the social value of knowledge, firms benefit from pecuniary knowledge externalities and are actually able to introduce productivity enhancing innovations that the growth of total factor productivity is negatively associated with the costs of knowledge. Total factor productivity thus increases faster where and when the costs of knowledge are lower.

system, and by the quality of the market transactions and availability of qualified and fertile knowledge interactions.

Not only the size of the stock of public knowledge, but also its composition matters. The understanding of the heterogeneity of knowledge enables important progress with the exploration of a new dimension: the role of the composition, next to the size, of the stock of external knowledge. The coherence, relatedness and rarity of the components of the knowledge stock play an important positive role in the generation of innovations[20]. The stock of knowledge of different economic systems exhibits high levels of longitudinal and cros-sectional variance in terms of organized complexity[21].

The analysis of the co-occurences of patents in the different technological classes enables to appreciate the composition of the stock of knowledge in terms of coherence and complementarity (Nesta and Saviotti, 2005 and 2006)[22].

In the new economic of knowledge the generation of new knowledge is viewed more and more as the collective and systemic result of the

[20] See Antonelli, Crespi, Mongeau Oaspina and Scellato (2016) for an empirical analysis of the role of knowledge Jacobs externalities in the knowledge generation function.

[21] The composition of the stock of knowledge in terms of variety, rarity, relatedeness changes across systems and most importantly through time. The quality of the composition can improve as well as decline as the application of the methodology first elaborated by Hidalgo and Hausmann (2009) to studying the composition of the stock of knowledge enables to measure.

[22] Antonelli, Krafft, Quatraro, (2010) show how the analysis of the co-occurrence of technological classes within two or more patent applications, allows the identification and measurement of the levels of coherence and complementary of the stock of knowledge. Their empirical investigation confirms that the recombination process has been more effective in countries characterized by higher levels of coherence and specialization of their knowledge stock. Countries better able to master the recombinant generation of new technological knowledge have experienced higher rates of increase of national multifactor productivity growth.

recombinant integration of different kinds of knowledge as inputs[23]. External knowledge cannot be any longer regarded as a supplementary factor that can augment output but rather as complementary, indispensable inputs that are strictly necessary to generate new technological knowledge and introduce technological innovations[24]. The generation of knowledge is the result of both the efforts and actions of individual agents and of the intrinsic characteristics of the system, in terms of organized complexity and knowledge connectivity, into which agents are embedded (Antonelli and Link, 2015; Antonelli and David, 2016)[25].

The joint appreciation of the effects of knowledge cumulability, complementarity and non-exhaustibility together with the new appreciation of the transient character of knowledge appropriability enables to grasp the dynamics and the role of diachronic knowledge externalities. At each point in time the flows of knowledge generated add to the stock of public knowledge, but only with a time lag. Knowledge producers, in fact, can retain the command of their 'inventions' although for a limited stretch of time. At the firm level knowledge non-appropriability limits its exclusive, internal, cumulability: proprietary knowledge gradually, but inevitably, spills and becomes a public good

[23] Antonelli, Crespi, Mongeau Ospina, Scellato (2015) introduce the notion of Jacobs knowledge externalities to study the effects of the composition of the stock of knowledge of European regions and test their relevance in the knowledge generation function.

[24] Antonelli and Colombelli (2015a) test the hypothesis that external and internal knowledge are strictly complementary inputs in the recombinant knowledge generation process. Neither input can fall below minimum levels without putting at risk the production of new technological knowledge.

[25] As a matter of fact the notion of non-appropriability has been first introduced by Schumpeter. Innovators can command the benefits of their innovations only for a limited stretch of time. Eventually, and inevitably, however, competitors react. Knowledge has the same property of profit that is intrinsically transient: it "has the most lamentable similarity with the drying up of a spring" (Schumpeter, 1934: p.209). In Schumpeter innovators do enjoy the appropriation of the rents stemming from the introduction of innovations, albeit for a limited stretch of time. Eventually, in fact, the exclusive command of the new technology leaks out, imitation takes place together with entry. Market prices fall together with profits. In Schumpeter there are not appropriable and non-appropriable components of innovations. All innovations are first appropriable and become later public goods. The sequence between the first appropriation and the eventual leakage is intrinsically Schumpeterian.

(Griliches, 1986 and 1992). Knowledge cumulability displays instead, its powerful effects at the system level.

The laws of accumulation of the stock of public knowledge play an important role in this context. The integration of the flows of new knowledge into the stock of public knowledge may be more or less effective both with respect to its size and its composition. Knowledge flows can remain dispersed and fragmented into the system, or do add on in a systematic, coherent and effective way. The accumulation is more effective the higher are the levels of knowledge connectivity. And, as a consequence, the higher is the knowledge connectivity and the better is the size and composition of the stock of knowledge and hence the higher are the levels of diachronic and pecuniary knowledge externalities. The knowledge connectivity of the system plays a second important role as it engenders different levels of absorption costs of the stock of public knowledge. Once more the larger are the levels of knowledge connectivity, the lower the costs of accessing and using the stock of public knowledge and the larger the pecuniary knowledge externalities.

The recombinant generation of technological knowledge benefits from the access and use of the stock of public knowledge as an input. External knowledge however is not free. Knowledge interactions are strictly necessary because of the strong and irreducible tacit and sticky content of all kinds of existing knowledge. Knowledge differs from information exactly because of its tacit content. In turn, the tacit content of knowledge makes knowledge interactions strictly necessary to access existing knowledge external to each agent. As a consequence, the access to and the acquisition of external knowledge are not free and may take place only in specific circumstances. Relevant activities are necessary in order to screen, identify, access and finally use external knowledge that is spilling in the system because of transient appropriability. Because of the strong tacit content of technological knowledge both transactions and interactions are necessary in order to absorb external knowledge [26]. Knowledge externalities are pecuniary rather than technical (Antonelli, 2008b; Aghion and Jaravel, 2015).

The appreciation of the key role of the size and composition of the stock of knowledge and the consequent levels of knowledge externalities as endogenous elements of the system dynamics enables to acknowledge, within the Schumpeterian platform, the amount of knowledge available within the system, and the structure of the interactions among the components in which each knowledge item is stored, as the result of past creative reactions[27]. The quality of the knowledge governance systems in place plays a crucial role in shaping their distribution in time and space. As a consequence the distribution in space and time of knowledge externalities is far from ubiquitous and homogeneous. Knowledge externalities are highly localized in their specific context of transactions and interactions and are exposed to the interaction of a variety of factors. The levels of knowledge externalities are strongly affected by the access, absorption and use cost of external knowledge. The quality of the knowledge governance mechanisms in place in each system and at each point in time are crucial to assess the actual levels of access and absorption cost. The stock of quasi-public knowledge may increase over time, but its composition and the quality of knowledge governance mechanisms may decline. Its decay may be engendered by the very same increase of the size of the stock of quasi-public knowledge: congestion may reduce the actual

[26] To explore the endogeneity of knowledge externalities David Lane introduced the key notions of: i) generative relations, e.g.: "the generative potential of their relationships with other agents. We then show how semantic uncertainty may emerge in the context of generative relationships – and how this uncertainty may give rise to new attributions of identity that may then be instantiated in new artifacts or new kinds of agent roles and relationships." (Lane and Maxfield, 2005:48); and ii) scaffolding structures "to show how market systems emerge through the construction of scaffolding structures in agent space. Through these structures, the agents who operate within the market system jointly confront their ontological uncertainty. Scaffolding structures provide a framework for controlling the kinds of new entities – both agents and artifacts – that enter the market system, and for aligning the attributions of agents in the market system about one another and the artifacts they make, exchange, install, maintain and use. Through scaffolding structures, agents can consolidate a zone of agent-artifact space, making it sufficiently stable to support both markets and the generation of new artifacts to be traded within those markets." (Lane and Maxfield, 2005:48).

[27] See the Appendix.

knowledge connectivity of the system. Consequently, knowledge externalities are stochastic rather than deterministic: they are, themselves, in fact, an emergent property of the system that may take place with varying levels of strength, including both their increase and decline. (Antonelli and David, 2016).

The Schumpeterian platform based upon the 1947 essay makes it possible to implement a dynamic understanding of the origin of and changes in the systems of innovations as the endogenous result of the interaction among the creative response of the agents and the –changing- characteristics of the system that define the endogenous availability of knowledge externalities and ultimately the cost of external knowledge. Systems of innovation keep changing size, density, borders, specialization, and ultimately connectivity levels (Nelson, 1993; Malerba, 2005; Martin and Boschma, 2010).

Their punctuated distribution affects the Schumpeterian dynamics. At one extreme we can identify situations where the poor quality of the knowledge governance mechanisms weakens the accumulation of the stock of knowledge and the access conditions so as to impede creative reactions: the system copes with mismatches simply by means of technical change with the eventual reproduction of a Marshallian equilibrium. At the other extreme we find the possibility of persistent innovation in economic systems, qualified by high quality knowledge governance mechanisms that support the accumulation of large stocks of coherent knowledge, hence the flows of pecuniary knowledge externalities that in turn favor the re-generation of strong knowledge externalities that support, along an extended period of time, a self-sustained innovative process based on the continual introduction of innovations that increase the generation of new knowledge externalities and the widespread occurrence of creative reactions in the system. Between the two extremes there are systems that may be able to support creative reactions for a limited time: following a first round of innovations the system can no longer feed a sustained process and the Marshallian equilibrium takes over again[28].

The selective diffusion of innovations. The Schumpeterian platform can integrate the substantial advances made by standard evolutionary economics in the analysis of selective diffusion processes. This literature has provided a strong and sophisticated analytical framework to understand the selective diffusion of some innovations with respect to others (Foster and Metcalfe, 2012).

The Schumpeterian platform can benefit from biological analyses of the selection of the species that have been –randomly- generated. It provides in fact useful hints to understand the characteristics of the processes and the underlying factors that allow some of the many innovations that have been randomly and accidentally introduced to eventually diffuse through the economic system, while others are not adopted. The intuition that at each point in time many alternative innovations compete and only a few succeed and will be eventually adopted and diffused is an important contribution of standard evolutionary approaches that can be successfully retained in the broad Schumpeterian platform (Nelson and Winter, 1973, 1982).

[28] Limited knowledge appropriability and the related spillover of proprietary knowledge are at the heart of both the Marshallian and the Schumpeterian dynamics. In the former they engender imitation externalities bounded to less efficient firms. In the Schumpeterian dynamics, instead, they can be used by all firms, including the most advanced ones. For this reason we shall call them respectively, imitation externalities and knowledge externalities.The Marshallian process and the Schumpeterian dynamics can be considered sequential steps that share a common understanding of the endogenous change that is intrinsic to economic systems. While in Marshall initial variance is given and exogenous and long term equilibrium stops the generation of externalities, in Schumpeter the self-reinforcing creation of knowledge externalities may keep the system in a self-sustained process of growth. The Schumpeterian dynamics can be regarded as a special case of the Marshallian dynamics that takes place when externalities –available to all firms including most performing ones- enable the introduction of innovations that account for the reproduction of superior performances and variety (Antonelli and Ferraris, 2016).

By the same token, the Schumpeterian platform can integrate the replicator analysis which provides important insights into the effects on economic growth of the variety of technologies at each point in time (Metcalfe, 2007; Metcalfe, Boden, 1992). In so doing, it provides a new analytical framework to study the consequences of innovation within the limits of the assumption that qualified circumstances impede to the agents belonging to the failing species any creative reaction that would increase endogeneously variety. Like other approaches based upon biological metaphors, the replicator analysis is not able to incorporate the endogenous emergence of innovations.

In this context, the notion of dominant design can be regarded as a major analytical tool that helps substantiating the notion of emergence. At each point in time firms try and introduce many different innovations. Only a fraction of them fits in the -new- product and factor markets conditions. Their selection is partly influenced by their potential complementarities that are reinforced and valorized by the introduction of incremental innovations. This process of selection and convergence leads to the eventual identification of a dominant design (Utterback 1994, Anderson and Tushman 1990).

In sum, it seems that the insight of Schumpeter (1947) enables to elaborate a comprehensive and integrated Schumpeterian platform that goes beyond both the evolutionary approaches of biological ascent and the new growth theory, which, as a matter of fact, although with different assumptions, share the basic assumption that the diversity of agents and alternative technologies, including innovations, are spontaneously reproduced by the system as the result of automatic processes.

The Schumpeterian platform provides the basic tools to account for endogenous innovation implementing the notions of rugged landscapes introduced by Paul Krugman (1994 and 1995) and of ecosystem framed by Martin Fransman (2010).

4. TOWARDS AN EVOLUTIONARY COMPLEXITY OF ENDOGENOUS INNOVATION

The Schumpeterian platform provides the foundations of an evolutionary complexity approach that enables to understand: i) the systemic determinants of innovation as an endogenous process that is based upon reactive decision-making highly sensitive to the institutional characteristics of the system in terms of the structured organization of the micro-level interactions among heterogeneous agents that make possible the generation and use of knowledge at costs that are below equilibrium levels, ii) the consequences of the sequential bifurcations that are determined by the aggregate consequences of the micro-level interactions of heterogeneous agents that are credited with the capability to introduce technological and structural changes that alter the organized complexity of the system; iii) the role of thresholds and non-linearity in the relations between the key components of the system dynamics stressing the effects of ‘small events’ that are able to change the levels of organized complexity of the system, the consequent availability of pecuniary knowledge externalities and the non-ergodic dynamics of the system[29] (Lane and Maxfield, 1997; Lane et al. 2009; Bonifati, 2010) (Arthur, Durlauf, Lane, 1997; Miller and Page, 2007).

The Schumpeterian legacy accommodates the basic tools of complexity economics: feedback, emergence, organized complexity and knowledge connectivity, endogenous variety, path dependence. Let us consider them, in turn.

[29] Agents based simulation (ABS) is a powerful methodology that is able to mimic the dynamics of complex systems characterized by thresholds and non-linearity that determine the outcome of the microlevel interactions among heterogeneous agents framed into scaffolding structures. Antonelli and Ferrari (2011) apply an agent based simulation model to explore the characteristics of the organized complexity of an economic system as the determinant of endogenous technological and structural change.

Feedback. According to the Merrian-Webster dictionary feedback is: "the return to the input of a part of the output of a machine, system, or process". In economics the notion of externalities accommodates effectively the basic feedback mechanism. Externalities, in fact, account for the changes of individual action and performance engendered by the effects at the system level of prior action. The introduction of innovations as the result of a creative response to a mismatch between expected and actual market conditions, conditional to the availability of effective knowledge externalities provides the case of augmented and multiple feedback. While standard feedbacks consist usually in one-sided effects, the innovation process is a vector of multiple feedbacks that can be both positive and negative. The innovation process is likely to stir a three pronged system of feedbacks: i) economic feedback concerning product and factor markets; ii) knowledge feedback concerning the composition of the stock of quasi-public knowledge; iii) knowledge governance feedback concerning the mechanisms that rule the conditions of access and use of the stock of quasi-public knowledge. The direction and intensity of each may differ from the others. The successful introduction of innovations may have positive effects both in terms of increased levels of total factor productivity and increased quality of the knowledge stock and knowledge governance as well as positive economic effects coupled by negative ones if and when it undermines the quality of the stock of knowledge in terms of composition and/or of the knowledge governance mechanisms, engendering an increase –rather than a decrease- in the costs of accessing and using the stock of quasi-public knowledge (North, 2010).

Emergence. The application of the notion of emergent system property to the economics of innovation provides a fertile context into which the Schumpeterian notion of innovation as a creative reaction, contingent upon the characteristics of the system that arises in special circumstances, when a variety of specific conditions apply and the interactions between the agents and the characteristics of the system engender multiple feedbacks, can be generalized and implemented. Innovation is the endogenous result of the combination of mismatches with the micro-level interactions among heterogeneous agents that, for given characteristics of the organized complexity of the system, may yield the creation of positive pecuniary knowledge externalities (Antonelli, 2008a; 2009; 2011).

The notion of emergent system property elaborated by complexity theory is most useful to accommodate and yet implement the Schumpeterian notion of innovation as a creative reaction: "an emergent system property takes place when the elements in a system react to the outcome those agents together create" (Arthur, 2014). Consequently, emergence is both a product and process; it has both static and dynamic aspects that may be both positive and negative [30].

Analysis of the crucial role of the interplay between individual decision making based on the notion of reaction, and the sorting role of the characteristics of the context of action of each individual agent, makes clear that innovation is an emergent property of the system rather than the result of individual action. The role of the economic environment in assessing the real possibility that the reaction of individual agents may be creative as opposed to adaptive, stresses the systemic character of the innovation process. The characteristics of the system are central to assessing the rate and direction of the innovative process. From this viewpoint, the notion of innovation as an emergent property of the economic system into which the agents are embedded, reduces the weight of the individual entrepreneur, stresses the collective role of the innovation process and highlights the weight of the system.

The mismatches can lead to the creative reactions and hence to actual introduction of innovations only if the system is endowed with appropriate levels of organized complexity that make knowledge externalities available and hence make the generation of new technological knowledge

[30] To quote Brian Arthur Brian Arthur in his presentation "Complexity Economics and Innovation Complexity Economics: A Different Framework for Economic Thought" delivered at the 15th Schumpeter Society Conference "Foundations of Economic Change – Behaviour, Interaction and Aggregate Outcomes" held in Jena, 27-30 July 2014. See Arthur (2015).

not only possible but cheaper than in equilibrium conditions. Without appropriate levels of organized complexity, knowledge externalities are not sufficient to enable the generation of new technological knowledge at costs that are below equilibrium and agents are bound to adaptive reactions. Region A in Figure 2 shows how the bifurcation takes place.

Emergent properties can be contrasted with so-called resultant properties, understood as the properties of wholes that are possessed by the individual elements of which those wholes are composed. Whereas the existence of emergent properties requires that certain elements stand in specific relations to each other, thereby forming a particular structure or whole, resultant properties are possessed by the individual elements irrespective of how they are related to one another; these resultant properties obtain even when those elements are taken in isolation or when the elements occur as an unstructured aggregation or 'heap' (Harper and Lewis, 2012).

The distinction between system and resultant properties is most important for the economics of innovation. As long as innovation is the ultimate cause of the increase of total factor productivity levels it is, in fact, quite difficult if not impossible to regard it as the outcome of the resultant property of individual action. The understanding of total factor productivity relies upon the answer to the key question of why the individual agent would have not been able to maximize the use of inputs that cause innovation – so that their marginal productivity would match their costs-remains un-explained. Taking advantage of the notion of emergent system property it is impossible to accept the hypothesis that innovation is the result of individual action irrespective of its localized context. The identification of innovation as an emergent system property allows to regarding the structure of the system in terms of interactions and connections, the quality and size of the stock of quasi-public knowledge and the consequent access costs as the necessary complementary factors that –together with individual action- explain the endogenous causation of innovation and hence of total factor productivity increase.

At each point in time the introduction of innovations and the consequent creative destruction engenders new mismatches between plans and actual market conditions. The introduction of innovations is the primary source of the unexpected changes in product and factor markets that stirs the reaction of firms. Firms try to cope with the unexpected product and factor market conditions. The reaction of each individual firm will be creative and consist in the introduction of further technological changes if and when the system is –*again*- able to support individual entrepreneurial action with the accumulation of the stock of knowledge and the consequent provision of appropriate amounts of knowledge externalities.

At each point in time the –*changing*- levels of the stock of knowledge, both in terms of size and composition, and of the quality of knowledge governance mechanisms and consequently of the actual levels of pecuniary knowledge externalities are crucial and far from deterministic. Their levels in fact are not given as they depend upon the changing levels of organized complexity of the system. The generation of additional knowledge and the introduction of innovations at time t1 may undermine the quality of both the knowledge governance mechanisms and the stock of knowledge in term of composition at time t2 and hence lead to increase –rather than the reduce- the costs of accessing, absorbing and using the stock of quasi-public knowledge as an input in the generation of additional knowledge.

The characteristics of the system in which firms are localized and specifically its levels of organized complexity and knowledge connectivity, are not given, as they keep changing and are not exogenous –as it is assumed in NK models-, but intrinsically endogenous.[31] The dynamics of the system feeds continuously on the interplay between out-of-equilibrium conditions, firms' reactions, accumulation of large and coherent stock of knowledge, effective external knowledge search, low

[31] NK models assume the characteristics of the knowledge landscape to be exogenous (Levinthal, 1997; Sorenson, Rivkin, Fleming, 2006).

cost generation of new technological knowledge, the –eventual-introduction of productivity-enhancing technological innovations, price reductions and eventual new out-of-equilibrium conditions. This dynamics is characterized by structural and technological changes that -at each point in time- re-shape the levels of knowledge connectivity as well as the size and the composition of the knowledge stock that firms can access and the amount of knowledge externalities actually available to firms. Such changes can have both positive and negative effects on the cost of access to the stock of quasi-public knowledge. Endogenous knowledge externalities are at the heart of the innovation system as much as endogenous innovation[32].

Organized complexity. The composition of the system into which reaction can be either adaptive or creative is crucial and endogenous. The organized complexity of a system differs according to its composition in terms of the characteristics of its components and their relations. A wide range of mesoeconomic characteristics, such as the distribution of clusters, the architecture of interactions and transactions within districts and networks, the levels of skilled workers mobility, the types of institutional set-up, the openness to international trade, the architecture of value chains and the role of the key sectors and technologies from which knowledge flows, as synthetized by the sectoral architecture play a role in assessing the changing size and composition of the stock of knowledge.

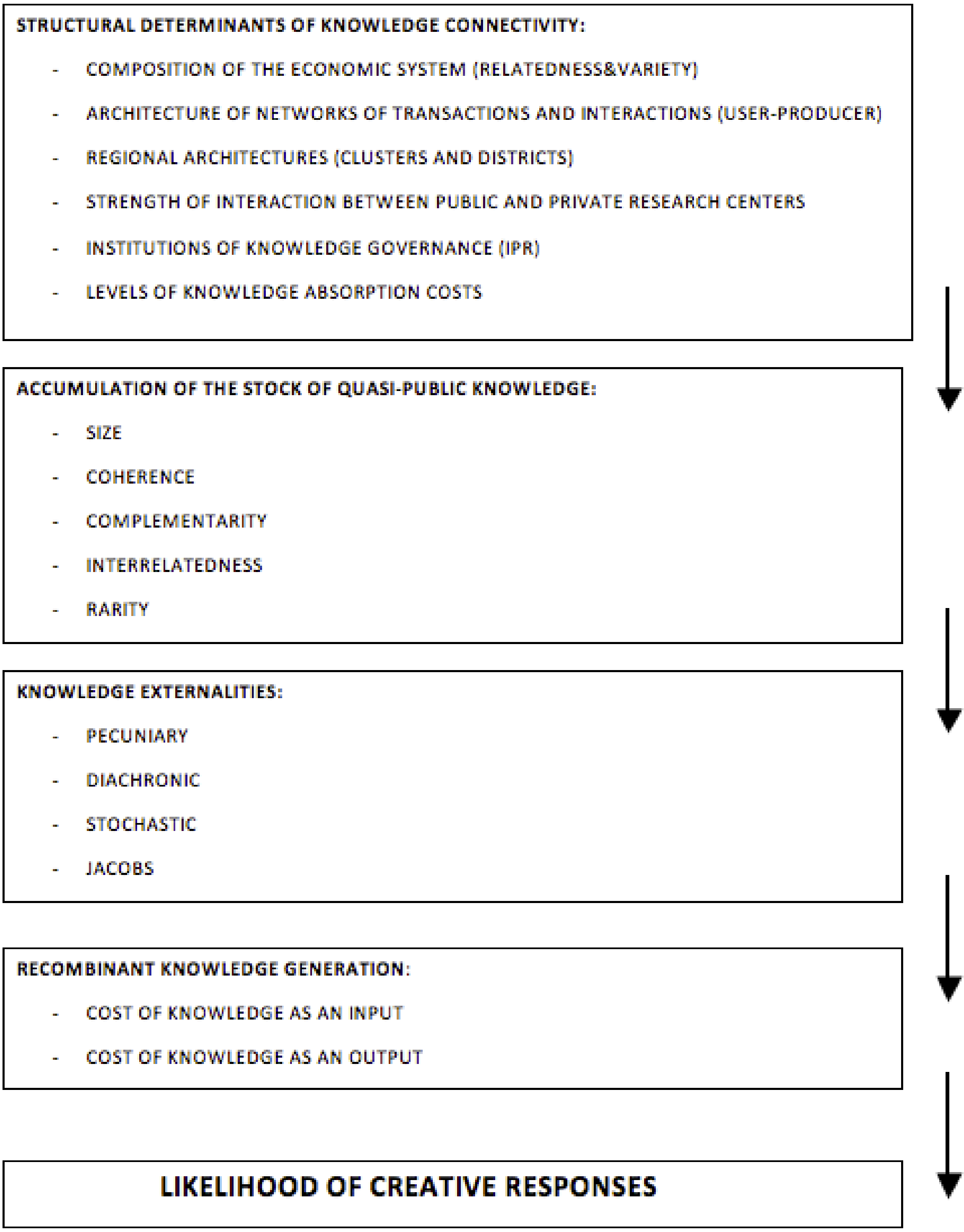
The new understanding of the heterogeneity of knowledge adds a new layer to the composition of the system: next to firms, regions and industries, the types of knowledge that characterize the stocks of both internal and external knowledge play an important role. Because of the intrinsic heterogeneity of knowledge, the stocks of knowledge differ in terms of specialization, diversification, complementarity, coherence, interrelatedness and rarity, interoperability and interdependence. The mix

[32] Antonelli and Ferraris (2015) elaborate an agent based model to analyse the dynamics of endogenous knowledge externalities.

of knowledge items that characterizes the stock of knowledge can be more or less effective in supporting the availability of knowledge externalities and hence the likelihood of creative reactions. Moreover the changing composition of the stock of quasi-public knowledge may have both positive and negative effects on the generation of new knowledge

Figure 1 exhibits the details of the working of the organized complexity.

FIGURE 1. THE WORKING OF ORGANIZED COMPLEXITY



Not all systems enjoy at all times and for ever the advantages of organized complexity and knowledge connectivity. Systems endowed with high levels of organized complexity and hence knowledge connectivity are better able than others to sustain the accumulation of a large and coherent stock of knowledge and hence support the generation of new knowledge externalities and hence the introduction of innovations. This capability is not given once for ever as it keeps changing in both directions: progress and decline (Page, 2011).

The quote of the famous candle's light metaphor by Thomas Jefferson is most useful to grasp how the institutional and structural organization of a system plays the key role of dissemination mechanism of the knowledge flows that enables the creative reaction and hence the introduction of innovations[33]. The organized complexity of the system plays the same role of the Jeffersonian architectural design of the distribution of mirrors that is able to maximize the amount of light produced by each candle.

The architecture of the interactions and transactions among learning agents in terms of networks and percolation structures has a central role to explain the accumulation of the stock of knowledge, both in terms of size and composition, generation of knowledge externalities, the consequent generation of technological knowledge and the eventual introduction of innovations. The rates of introduction of innovations and consequently the rates of increase of total factor productivity are likely to be larger, the better is the organized complexity and the consequent knowledge connectivity of the system.

[33] Thomas Jefferson's famous sentence: "He who receives an idea from me, receives instruction himself without lessening mine; as he who lights his taper [(candle)] at mine, receives light without darkening me. That ideas should freely spread from one to another over the globe, for the moral and mutual instruction of man, and improvement of his condition, seems to have been peculiarly and benevolently designed by nature, when she made them, like fire, expansible over all space, without lessening their density in any point, and like the air in which we breathe, move, and have our physical being, incapable of confinement or exclusive appropriation." Note that the distinction between non-rivalry in user value and non-rivalry in exchange value is most relevant in this context.

The quality of organized complexity plays a key role as the sorting device of the dynamics of the system. When the quality of organized complexity is high, and the knowledge connectivity is strong enough to favor the accumulation of the stock of knowledge, system enters a loop of self-sustained creative reactions, technological and structural changes, generation of both new knowledge externalities and new mismatches that fed further changes. The dynamics of the system can stop when the generation of new knowledge, the introduction of technological and structural changes have negative –rather than positive- effects on the quality of both the composition of the stock of quasi-public knowledge and the organized complexity of the system.

At the other extreme, there is equilibrium: one of the many possible outcomes of the Schumpeterian dynamics. It takes place when the levels of organized complexity are not appropriate to favor the accumulation of a large and well-structured stock of knowledge that generate the sufficient amount and quality of knowledge externalities that are necessary to make the reaction of firms creative. With low levels of organized complexity and poor knowledge connectivity, the reaction of firms is adaptive and leads to equilibrium conditions. Innovations are not introduced, no new mismatches and no new knowledge externalities are being generated: no forces are any longer at play to modify the decisions of agents. The Marshallian selection of variety takes place until the dynamics of the system expires. Equilibrium is a possibility and it is actually a frequent outcome that takes place when no innovative feedbacks are at work and externalities are -no longer- available.

The levels of organized complexity of a system are endogenous to the system itself as they depend upon the structure and architecture of knowledge interactions and transactions that take place within the system.

They are far from automatic as they are the result of processes that are dynamic, endogenous, non-ergodic and far from deterministic. The introduction of innovations has multiple effects: i) to create mismatches between expectation and the actual conditions of product and factor markets; ii) to reshape the organized complexity of the system changing the levels of knowledge connectivity determined by the structure of knowledge interactions and transactions iii) to change the size and composition of the stock of public knowledge upon which the provision of knowledge externalities depend; and iv) to shape the generation of additional technological knowledge. The creative reaction affects the levels of knowledge connectivity – with effects that may be both positive and negative- and hence the amount of knowledge externalities without which the introduction of innovations is impossible.

At each point in time each firm discovers that, because of the creative destruction following the introduction of innovations, the actual conditions of: i) product and factor markets, ii) the organized complexity of the system and the levels of knowledge connectivity, iii) the size and composition of the stock of knowledge, and iv) the actual levels of knowledge externalities are no longer the expected ones. Again, each firm considers the possibility to cope with the unexpected mismatches either by adaptive response that consists in movements within the existing technology and the existing structure of the economy or creative responses that consist in technological and structural changes. Here the structural consequences of the introduction of innovations on the organized complexity of the system become crucial. Because of the introduction of innovations at time t, the structural conditions of the system at time t+1 may be now different. Previous creative responses may have affected the conditions that are necessary for the generation of new additional technological knowledge. The introduction of innovations may have changed the structure of interactions and transactions, and hence the levels of knowledge connectivity and consequently the size and composition of the stock of knowledge and the actual amount of knowledge externalities available in the system, either increasing or decreasing their levels.

The dynamics of creative reactions can be self-feeding and persistent, so that the introduction of innovations at time t is the cause of the introduction of further innovations at time t+1, only when two conditions are fulfilled. This result, in fact, takes place only in specific circumstances, if and when the introduction of innovations, besides the effect of engendering mismatches in product and factor markets, has the complementary effect of increasing the levels of knowledge connectivity and consequently the stock of knowledge and the amount of knowledge externalities without reducing them below the threshold levels that are necessary to support the reaction and make it creative. In these special conditions creative reactions cause creative destructions that support the further introduction of innovations. In this case the consequences of the introduction of innovations are the causes of the introduction of further innovations.

When, instead, the introduction of innovations does not only engenders mismatches in product and factor markets but has also negative effects on the organized complexity of the system that are at the origin of the deterioration and reduction of the levels of knowledge connectivity and the size and composition of the stock of knowledge, hence of the availability and the levels of knowledge externalities, the chances that the creative reaction may take place again are reduced.

The generation of additional technological knowledge and the introduction of innovations may have negative consequences on the quality of the stock of quasi-public knowledge and on the levels of organized complexity of the system and hence on the amount of knowledge externalities increasing the levels of search, absorption, decodification costs and in general of all the range of activities that are necessary to access and use external knowledge as an input into the recombinant generation of new knowledge.

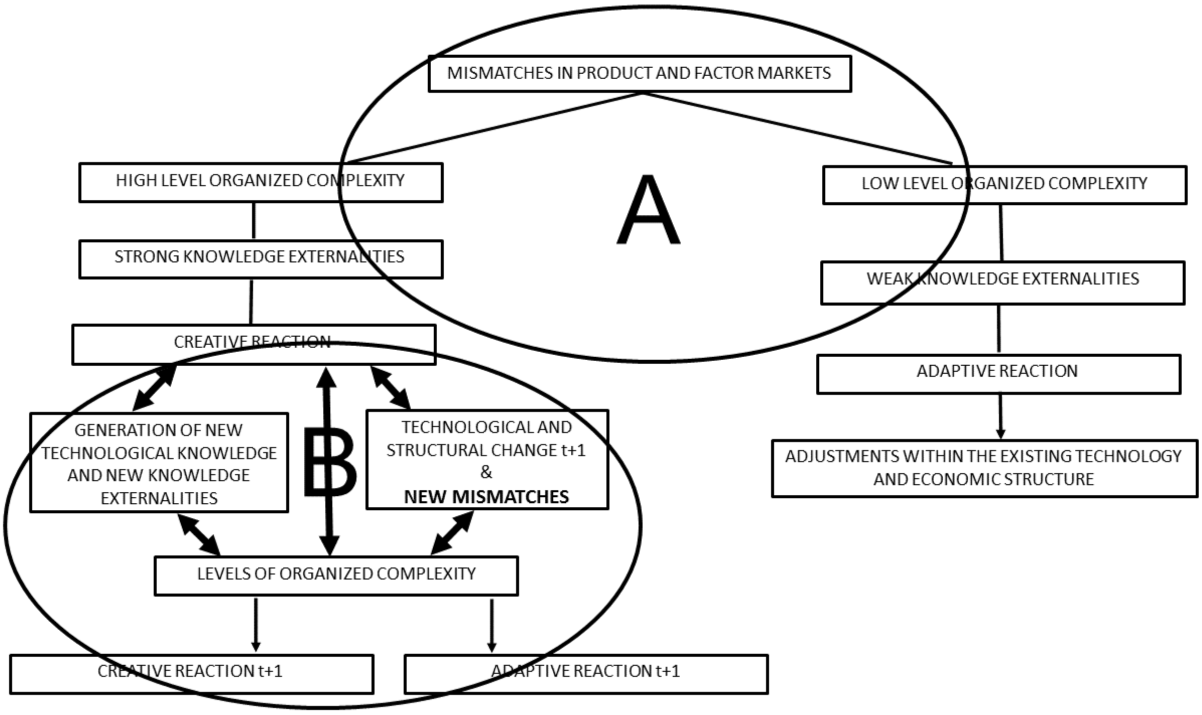
The generation of additional technological knowledge and the introduction of innovations may have structural consequences that affect the levels of knowledge connectivity of the system and hence the size and composition of the stock of knowledge affecting the viability and sustainability of the mechanisms of knowledge governance and the institutional set that had been effective until then. The generation of additional technological knowledge and the introduction of innovations may have reduced the levels of knowledge connectivity, the coherence, variety and rarity of the stock of knowledge and the scope of activity of the key sectors, created diseconomies of agglomeration and excess density. The basic mechanisms of knowledge governance may be no longer appropriate to coordinate the division of creative labor and the dissemination of knowledge [34].

With lower levels of knowledge connectivity and a reduction of the rates of accumulation of the stock of quasi-public knowledge, the decline of knowledge externalities, the reaction of each firm may become adaptive. The system is no longer able to support the continual introduction of innovations and the dynamics converge to equilibrium levels. Firms adjust quantities to prices and prices to quantities without any further changes in product and factor markets.

Region B of Figure 2 exhibits the working of the second bifurcation. If the changes in technological knowledge and in the organized complexity of the system increase its knowledge connectivity so as to favor the generation of new knowledge externalities, the innovation process keeps momentum. If instead the technological and structural changes reduce the levels of knowledge connectivity of the system and undermine the size and composition of the stock of knowledge and hence the knowledge externalities available within the system, the chances that a creative reaction takes place decline and the innovation process stops.

[34] Antonelli Patrucco and Quatraro (2011) test the hypothesis of non-linear –inverted U-relationship between density and knowledge externalities and show that -beyond a threshold- excess agglomeration of innovative activity has negative effects on knowledge governance mechanisms with the consequent reduction in the quality and availability of pecuniary knowledge externalities.

Fig. 2. ENDOGENOUS INNOVATION AND ORGANIZED COMPLEXITY AS EMERGING SYSTEM PROPERTIES



In the Schumpeterian dynamics the levels of organized complexity, however, are themselves endogenous and can improve or deteriorate according to the structural and technological changes that are introduced along the process. The levels of organized complexity and knowledge connectivity are themselves a system emergent property.

The understanding of the fortuitous, punctuated and stochastic character of the organized complexity that engenders endogenous knowledge externalities enables to account for the great diachronic and synchronic variance of the rates of introduction of innovations and the rates of increase of total factor productivity (Mokyr, 1990; Craft, 2010).

Endogenous variety. In the Schumpeterian dynamics of endogenous innovation the variety of agents plays a central role and is itself endogenous. Agents are heterogeneous because of their location in the different spaces that constitute the system and the consequent participation to the differentiated activities that take place within it. Agents react in different ways to the mismatches between planned and actual market conditions according to the amount of knowledge externalities that are available in their proximity. The variety of agents and the heterogeneity of the system are the endogenous products of the reactive dynamics, built into the Schumpeterian dynamics. The appreciation of the endogeneity of variety has the immediate consequence to call attention on the characteristics of the dynamics of the heterogeneity within the system and its endogenous organization.

Path dependence. The grafting of tools of complexity analysis and the retrieval of a correct appreciation of the Schumpeterian legacy, makes it possible to understanding the historical and endogenous character of economic change achieving a much stronger foundation and broader scope of application for the economics of innovation. The process of economic change, including the generation of technological change, the introduction of innovations and the transformation of the structure of economic systems, can be better understood as a path dependent non-ergodic endogenous dynamics where history matters, and yet the changing conditions into which the dynamics displays its process affect its changing speed, direction and very survival (Blume, Durlauf, 2006).

The generation of technological knowledge is itself a non-ergodic process characterized by diachronic knowledge externalities. The generation of new knowledge in fact consists in the recombination of existing knowledge items. The stock of existing knowledge is an indispensable input into the generation of knowledge as an output. The flows of new proprietary knowledge generated at each point in time add on –with due lags engendered by the limited duration of appropriation of inventors- to the public stock of knowledge. The changing composition and size of the stock of public knowledge yields changes in the flows of diachronic knowledge externalities that enable the reduction of the costs of knowledge as an input and hence of knowledge as an output.

The loop of endogenous accumulation of the stock of knowledge, generation of technological knowledge and innovations is a possible dynamic process that is far from deterministic. The process is indeed non-ergodic as the events that take place in the past bear effects on the choices of firms and the types of reaction that they can practice, but it is heavily affected by the events that occur along the process[35]. A system can support and assist the creative reaction of agents for a given length of time until when the continuous introduction of additional innovations engenders the increasing size, composition and accessibility of the stock of knowledge and hence the generation of positive externalities. The characteristics of the system are not defined for ever at the outset of non-ergodic dynamics but are exposed to contingent events along the process, including the endogenous introduction of innovations (David, 2005).

Path dependence is intrinsic to evolutionary complexity because the interplay between the innovative efforts of the agents surprised by out-of-equilibrium conditions, the characteristics and the effects in terms of limited reversibility of their decisions taken at time t-1, and the characteristics of the system affects not only the type of reaction - adaptive or creative - and the outcome of the innovative efforts but also the structure of the system and its capability to provide access to knowledge externalities. Structural and technological changes are intertwined in a dynamic process that is intrinsically historical, and as such, affected by the effects of contingent events that are determined by the stochastic evolution of events[36].

The context in which firms try to react to mismatches between expectations and the actual conditions of product and factor markets, is

[35] Audretsch, Lehmann and Hinger (2015) elaborate the interesting notion of "spillover entrepreneurship" to stress the crucial role of entrepreneurship, as an intentional activity, that is necessary to accessing and using knowledge spillovers. Knowledge spillovers are far from spontaneous and automatic and cannot be accessed by passive users.

[36] See for the empirical evidence on the role of contingent events on the persistence of innovative activity Antonelli, Crespi and Scellato (2012, 2013, 2015).

shaped at each point in time by the decisions taken in the past. The reaction is contingent on the conditions determined by the choices made in the past. As such, its effects are non-ergodic and are path dependent as opposed to past dependent because the new choices may correct the old ones and direct the process towards unexpected outcomes.

The creative response and the consequent introduction of innovation are a consequence of the characteristics of the system but also a cause of a second type of feedbacks and endogenous processes. The introduction of innovations is likely to affect the very conditions that make further creative response possible. In other words, it is clear that knowledge externalities are indeed external to each firm but absolutely endogenous to the system. The introduction of a specific innovation, in a specific context and at a specific time, can reinforce the provision of knowledge externalities as much as it may deteriorate it. Once again, the process dynamics is typically historical, i.e. non-ergodic but path dependent as opposed to past dependent.

In this context, longitudinal correlation among the sequence of events that take place along time, can exhibit non-transitive properties such that, while the correlation between event A at time t_1 and event B at time $t_{2,}$ and the correlation between event B at time t_2 and event C at time t_3, happen to be strong, the correlation between event A and C may be very weak (David, 2005, 2007).

Appreciation of the path dependent character of these dynamic processes questions the use of standard Markov chains. Standard Markov chains are dynamic stochastic processes characterized by the presence of discrete values of the states, and more importantly, by the fact that the conditional probability of a state at time t depends exclusively on the state at time t-1. This implies that the process has no memory and only the last state influences the subsequent state. If the process is path dependent, instead, Multiple Probability Transition Matrices (MPTM) apply. MPTM rely on the computation of different probability transition matrices in relevant sub-periods that are identified by significant contingent events that are expected to affect the transition probabilities between the innovative and non-innovative status of the agents. Comparison of the parameters of the MTPM in different sub-periods allows better identification of the path dependent character of the innovation process. In particular, observation of significantly different parameters for the MTPM in different sub-periods might be an indication that the extent of the hysteresis is affected by contingent events, and hence, the innovation process can be qualified as path-dependent (Antonelli, Crespi, Scellato, 2015).

The Schumpeterian platform shares the intrinsic characteristics of a high order emergence. The notion of third order emergence nicely accommodates this dynamics. According to Martin and Sunley (2012: 341) “third order emergence is an ‘emergent phenomena and systems characterized by ‘memory’ where an amplification of high-order influences on parts is combined with a selective sampling of these influences which reintroduces the parts into different realizations of the system over time, imparting both continuity with and divergence from prior states of the system.” The dynamics of diachronic knowledge externalities that stem from the accumulation of the stocks of public knowledge is at the center of the non-ergodic characters that shape endogenous innovation.

In fact, we see that at each point in time key characteristics of the system - determined by the past and yet exposed to contingent changes- qualify the reaction of agents caught in out-of-equilibrium conditions, whether creative allowing them to introduce innovations through access to knowledge externalities at time t, or adaptive because they have no access to knowledge externalities. The occurrence of the systemic characteristics that qualify the levels of knowledge connectivity and make knowledge externalities available, combined with the entrepreneurial attributes of the managers of incumbent corporations and the entry of new firms make the mismatch between expected and actual conditions in both product and factor markets, endogenous. The accumulation of the stock of knowledge and the consequent flows of knowledge externalities are at the same time the result of individual action and its cause.

5. CONCLUSIONS

The claim that evolutionary economics drawing upon biological metaphors can explain why innovation is endogenous and does not fall like manna from heaven has yet to be justified. Variety and innovation is automatically reproduced within the system without any intentionality and any causality. Biological evolutionary economics is exposed to the same basic criticism of new growth theory where innovation is determined by exogenous forces: respectively unlimited and automatic knowledge spillover and a spontaneous and automatic drive to introduce innovations.

Understanding innovation as an endogenous and economic process can no longer rely upon the assumption that the variety within a system be perennially renewed by random recombinations of the basic traits of its agents. At the same time the assumptions of a spontaneous and unlimited generation of knowledge spillovers, upon which the new growth theory impinges upon, appear less and less reliable. The new analysis of the generation of technological knowledge confirms that knowledge externalities are far from being automatic and ubiquitous. Quite on the opposite, knowledge externalities are available only in the specific circumstances highly localized in space and time of organized complexity that make external knowledge not only available, but also accessible at costs that are below the equilibrium levels of reproduction.

The 1947 essay by Joseph Schumpeter is a quasi-forgotten landmark that makes it possible to implement a robust analytical platform for a broader and more inclusive economics of endogenous innovation that accommodates five new radical elements: i) innovation is the result of an unplanned response to unexpected occurrences; ii) changes in factor markets, together with all changes in product markets as much as in the levels of aggregate demand, play a role in causing the mismatches that push firms to try to innovate; iii) the chances that the creative response to the mismatches takes place are strictly contingent on the characteristics of the system and the availability of knowledge externalities; iv) the introduction of new technologies alters the fundamentals characteristics of the organized complexity of the system with respect the levels of knowledge connectivity and hence the amount of knowledge externalities that are available at each point in time; v) both the generation of technological and structural change are endogenous as they are emergent and path dependent system properties.

Innovation takes place and total factor productivity actually increases only when two conditions jointly apply: i) the endogenous structure of the system attains levels of organized complexity and knowledge connectivity that enables to support the accumulation of a stock of accessible quasi-public knowledge and hence to generate new technological knowledge at costs that are below equilibrium levels, and ii) firms caught in out-of-equilibrium conditions are actually able and ready to take advantage of knowledge externalities and actually introduce innovations. The first key bifurcation takes place when the levels of organized complexity and the consequent levels of knowledge externalities are sufficient to support the reaction of firms and enable to make it creative instead of adaptive (Antonelli, 2008, 2011, 2013).

At each point in time, because the introduction of innovations does not only affect product and factor markets but also the organized complexity of the system and the working of knowledge connectivity in terms of accumulation of the stocks of knowledge and the consequent generation of knowledge externalities with both positive and negative effects, a second basic bifurcation takes place in the process. The structural effects of innovations shape the alternative between a dynamics of self-sustained introduction of innovations and the convergence of the system to equilibrium. If and when the effects are not negative, a new wave of creative reactions can take place so as to allow the introduction of further innovations that reproduce variety within the system and to push forward the technological frontier that supports the continual expansion of the economic system and the rates of economic growth.

If and when, because of congestion, the levels of knowledge connectivity decline together with the rate of knowledge accumulation, and the effects on the availability, the levels of knowledge externalities are negative and the quality of the systems of innovations declines, firms will be no longer able to elaborate a creative reaction. They will try and cope with the mismatches between the expected and the actual conditions of product and factor markets by means of adaptive reactions. Equilibrium is one of the many possible outcomes.

The Schumpeterian platform enables to appreciate the systemic and yet punctuated determinants of innovation as an endogenous process based upon individual reactions that are highly sensitive to the institutional characteristics of the system in terms of the structural organization of the micro-level interactions that make possible the accumulation, generation and use of knowledge in society. In this context, the procedural rationality of agents plays a central role. Agents try to innovate only as a reaction to unexpected changes. Schumpeterian firms make relevant mistakes, are caught in out-of-equilibrium by unforeseeable events and only then consider as a possible solution the introduction of an innovation. Reaction is a typical form of procedural rationality: firms consider opportunities and perspectives only after the occurrence of a sequence of unexpected events. Their success is contingent on the characteristics of the system that become apparent ex-post.

The Schumpeterian creative response empowers and specifies the notion of stratified and multiple feedback. The grafting of the tools of complexity economics, and specifically the notions of emergence, path dependence, endogenous variety and organized complexity, and knowledge connectivity into the Schumpeterian platform, provides a comprehensive and robust evolutionary complexity framework in which to study innovation as a system property –as opposed to a resultant property- that is an endogenous, dynamic, non ergodic and stochastic process with intrinsic systemic characteristics. Its path dependent dynamics is shaped by the changing levels of organized complexity of the system in terms of composition, organization, architecture and institutional context within which agents interact and participate in the collective endeavor of accumulation, generation and use of technological knowledge. Economics of innovation can finally rely on an analytical framework able to explain its endogenous determinants.

6. Appendix

As it is well known the new growth theory builds upon the intuition of Zvi Griliches about the role of knowledge externalities on the levels of total factor productivity (Griliches, 1979, 1984, 1992). Griliches introduced the "technology production function" where internal knowledge (IK) –the stock of knowledge that each firm can appropriate- enters with its output elasticity (c), next to the standard inputs of capital (C) with its output elasticity (a), labor (L) with its output elasticity (b). The output of each firm is influenced by the stock of quasi-public knowledge that spills in the atmosphere (EK) and accounts for total factor productivity (A):

(1) $Y = A\,(C^{a}\,L^{b}\,IK^{c})$

(2) $A = (EK)$

Griliches did not pretend to elaborate a theory of growth: he provided the methodology to assess the role of knowledge externalities. As Griliches (1995:63) notes: "This formulation was applied to R&D expenditures by Griliches (1979) and rediscovered by Romer (1990)".

Romer did attempt to extract, from the notion of spillovers, a theory of economic growth. With respect to Griliches's specification, Romer takes into account total knowledge (K=IK+EK) and splits its output elasticity (γ) into two components: the appropriable ($\gamma 1$) and the non-appropriable ($\gamma 2$). Total factor productivity is accounted by the non-appropriable component ($K^{\gamma 2}$). Increasing returns do take place at the system level but not at the firm level. Firms fund research and development activities according to the marginal productivity of the appropriable component ($\gamma 1$).

The crucial hypothesis specified by Romer reads as it follows:

(3) $Y_i = A\ (C^a\ L^b\ K^{\gamma})$
where $(a+b+(\gamma 1 + \gamma 2) > 1$

At the system level there are increasing returns that stem from the characteristics of knowledge. At the firm level, however, because of the limited appropriability of knowledge, firms have not access to increasing returns, but enjoy the positive effects of the access to knowledge spillover on total factor productivity:

(4) $Y_i = A\ (C^a\ L^b\ K^{\gamma 1})$
where $a+b+\gamma 1 = 1$
(5) $A_i = f\ (K^{\gamma 2})$

The specification by Romer is problematic from two viewpoints: i) it is not clear what are the idiosyncratic characteristics that discriminate between the appropriable and the non-appropriable components of knowledge; as a consequence ii) it is not clear what is the ratio between the first and the second. This ambiguity has major effects with respect to the coherence between the firm level of action and the aggregate behavior. The analysis of the derived demand of knowledge (Antonelli, 2017) is most useful:

(6) $dY/dK = (\gamma\ Y/K\ p_Y)$

Firms have no incentives to invest more that the levels of the value of the marginal product of the knowledge that they can appropriate ($\gamma 1\ \ Y/K\ p_Y$)

and has no incentive to generate the equilibrium amount of knowledge defined by the value of its total marginal product (γ Y/K p_Y). The Arrovian market failure takes place together with the undersupply of knowledge.

In our approach, the distinction between the appropriable and the non-appropriable components does not take place instantaneously and synchronically. The distinction takes place through time, diachronically. Actually there is not a static distinction that would stem from intrinsic properties of knowledge. The distinction is dynamic: all knowledge is proprietary and can be appropriated for a short period of time as well as all knowledge eventually spills and adds to the stock of public knowledge, with a time lag.

The notion of diachronic knowledge externalities enables to overcome the limits of the standard specification of the new growth theory. In this approach firms can fully appropriate the economic benefits stemming from the generation of new technological knowledge and the eventual introduction of innovations, but only for a limited stretch of time. After the closure of the time window of appropriation, the flows of new technological knowledge add on to the stock of public knowledge. Hence the total knowledge generated by each firm (K) splits into the two components:

(7) K = IK + EK

The flow of knowledge produced each year by each firm (K) splits and adds either to the stock of internal knowledge (IK) that can be appropriated or to the stock of quasi-public knowledge EK. The stock of quasi-public knowledge is the summation, after a short time window (n), in the time interval (N-n) of the flow of knowledge generated at each point in time (K). The stock of proprietary knowledge (IK) is the summation - just for a short time window of appropriation (n)- of the knowledge (K) generated by each firm.

(8) $EK = g\left(\sum_{i=1}^{N-n} K_i\right)$

$$(9)\ IK = \sum_{i=N-n+1}^{N} K_i$$

The generation of technological knowledge is, in fact, itself the result of a dedicated economic activity that can be analyzed by means of the knowledge generation function. The generation of knowledge, however, is characterized by high levels of risks. Only firms in out-of-equilibrium conditions are able to take such high levels of risks. The knowledge generation function is activated primarily if not exclusively by firms that experience a mismatch between the expected and the actual conditions of product and factor markets with performances that are either below or above equilibrium levels. Firms facing exit and bankrupt are forced to try and generate new technological knowledge in order to survive. Firms that enjoy extra-profits can afford the risks associated with the generation of new knowledge because of low levels of opportunity costs stemming from the relative abundance of liquidity and resources. Firms that are in the proximity of equilibrium conditions with performances close to the average are reluctant to engage in the generation of new technological knowledge and in the eventual introduction of innovations.

The notion of diachronic knowledge externalities enables to implement the knowledge generation function, next to the technology production function, as an indispensable component of the following system of equations:

$$(10)\ K = (EK^{\square}\ IK^{b}\ R\&D^{c})$$

$$(11)\ C_K = z\ EK + v\ IK + rR\&D$$

$$(12)\ z = h\ (\ EK, KCON\ )$$

$$(13)\ Y = A\ (C^{\square}\ L^{\square}\ IK^{c})$$

$$(14)\ C_Y = wL + rC + uIK$$

K is produced by means of the recombination of the knowledge items that are available in the stock of quasi-public knowledge (EK) and in the stock of proprietary knowledge (IK) that each firm can command for a limited period of time, and of R&D activities. The use of both IK and EK takes place at a cost: respectively the v measures the unit cost of the resources that are necessary to retrieve and use the stock of internal knowledge, z measures the unit cost of the resources that are necessary to select, draw, access and use the relevant and complementary units of knowledge that are available in the stock of quasi-public knowledge. R&D activities have a unit cost r.

As equation (12) makes clear, the cost of external knowledge (z) changes with the size and the quality of the stock of quasi-public knowledge (EK) and the levels of knowledge connectivity of the system (KCON). The laws of accumulation of the stock of quasi-public knowledge and of the changing quality of the knowledge connectivity of the system play a central role in the dynamics of the system. The actual accumulation of the stock of quasi-public knowledge is far from deterministic. The new knowledge items can remain dispersed and fragmented in the system, or contribute the accumulation of a well structured, coherent and inclusive stock of quasi-public knowledge that can be used and accessed effectively. The new flows of quasi-public knowledge may have both positive and negative effects on the actual cost of accessing and using the stock. The organized complexity of the system and its levels of knowledge connectivity can improve over time as well as decline.

The laws of accumulation of the stock of quasi-public knowledge (EK) and the costs of accessing and using it as an input into the generation of new knowledge define the levels of the costs of external knowledge (z) have powerful effects directly on the knowledge generation function (10) and indirectly on the technology production function (13). The levels of the costs of accessing and using the stock of quasi-public knowledge (z) in fact have two effects:

i) in the knowledge generation function (10) where the stock of public knowledge EK enters as an indispensable input, next to internal knowledge (IK): it is clear that the lower are the costs of external knowledge (z) and the lower are the unit costs of knowledge as an output (u).

ii) in the technology production function (13) knowledge produced (K) upstream, enters as an input, next to capital (C) and labor (L). Hence with a given budget, the lower is the cost of external knowledge (u) and the larger is the amount of knowledge (K) that contributes as an indispensable complementary input to the production of the output Y, and the lower are the unit costs of output Y.

The difference between the actual, historic levels of the cost of external knowledge, respectively as an input (z) in the knowledge generation function and the cost of knowledge as an input (u) in the technology production function and the equilibrium levels -based on the assumption that knowledge is a standard good so that its cost equals its marginal productivity- accounts for the levels of total factor productivity as measured by the ratio of the actual, historic levels of Y to the expected levels of output when the price of inputs is in equilibrium (Antonelli, 2013).

The stock of quasi-public knowledge affects the working of the system with two distinct mechanisms: i) a direct role exerted by the effects of knowledge externalities in the generation of new knowledge and ii) consequently an indirect role in the downstream technology production.

Firms are able to try and take advantage of the low cost of knowledge made possible by the high quality and size of the stock of quasi-public knowledge only when are exposed to mismatches between expected and actual factor and product market conditions. The sheer availability of knowledge externalities is not sufficient for firms to try and innovate, as much as mismatches, without appropriate levels of knowledge externalities, are not sufficient to account for the successful introduction of innovations.

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