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THE GENERATION OF KNOWLEDGE AS AN EMERGENT SYSTEM PROPERTY: AN INTRODUCTION

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The understanding of the generation of knowledge as the result of an intentional and dedicated economic activity has been the result of quite a long process. The starting point can be identified in the creation of the departments of research and development (R&D) that characterized the corporation and in the appreciation of the crucial role of the learning processes that enable the accumulation of 'localized' competence (Chandler, 1962). The process leads to the eventual understanding of the generation of knowledge as a recombinant activity and the gradual grasping of the knowledge generation process as the emergent property of the system required quite an articulated sequence of steps. Its final outcome is the identification of knowledge as the result of an intentional and dedicated collective activity shaped not only by the interaction between the individual efforts of 'inventors' but also and mainly by the characteristics of the system in which each agent is embedded.

The new economics of knowledge has progressively shifted analysis from the properties of knowledge as an economic good to the characteristics of the knowledge generation process as a dedicated economic activity aimed at its generation. According to the latest advances in the economics of knowledge, new technological knowledge is generated by means of the recombination of the existing technological knowledge. The recombinant knowledge generation process is heavily influenced by the mutual interdependence between the characteristics of individual action and of the context into which it takes place.

The knowledge generation function was first introduced in the literature, somewhat accidentally, by Zvi Griliches (1979), implemented by Pakes and Griliches (1984), articulated by Adam Jaffe (1986) and fully elaborated by Weitzman (1996 and 1998), Fleming and Sorenson (2001) and Arthur (2011) who characterize the generation of new technological knowledge as the output of the recombination of existing knowledge. The notion of the knowledge generation function specifically studies the process and inputs that make the generation of knowledge as an output possible. The knowledge generation function differs from the technology production function, one of the pillars of the applied economics of innovation, where knowledge, along with capital and labor, is considered explicitly as an input in the standard production function for all the other goods.

Griliches (1979 and 1988) explores the relationship between R&D activities and the knowledge output as a byproduct of his attention to the structure of lags of R&D activities that is necessary to compute the stock of R&D capital properly. In a note he mentions the "*complication*" that knowledge is itself a dependent variable in a 'knowledge production function' where past and current R&D efforts are the independent variables. Pakes and Griliches (1984) implement the 'accidental' discovery of Griliches (1979) with an explicit analysis of the knowledge generation process where next to the stock of R&D capital, external knowledge plays a role in the generation of new technological knowledge. Jaffe (1986) is considered to be the first to perform an explicit empirical analysis of the knowledge generation function: the number of patents is treated as the output of a Cobb-Douglas production function where internal R&D expenditures together with the spillovers of related knowledge generated by other firms are the independent variables.

Weitzman (1996) opened up a new path in this literature by framing knowledge generation as a recombinant process where existing knowledge items enter as inputs shedding new light on the role of knowledge indivisibility and cumulability. The generation of knowledge is a recombination process that relies on the current efforts of research and the learning of each agent as well as on the stock of existing knowledge both internal and external to each agent.

As Brian Arthur puts it: "I realized that 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).

Antonelli (1999) suggests that technological knowledge is the output of a bundle of dedicated activities such as learning, R&D, search and technological transactions and interactions with the scientific community that enable firms to acquire the four knowledge inputs i.e. internal and external, tacit and codified knowledge required to generate new technological knowledge. Along these lines, Patrucco (2008 and 2009) uses explicitly a Cobb-Douglas specification of the knowledge generation function to stress at the same time the complementarity between external and internal knowledge and their substitutability that, however, can only take place within well-defined ranges. Fleming and Sorenson (2001) and Fleming (2001) show how the generation of technological knowledge follows a branching process where the previous modules feed the new ones. Silva (2014) is able to model the "Jefferson's candle light effect" with the notion of a knowledge multiplier defined by the extent to which external knowledge enhances the innovative capacity of each firm. The larger the knowledge multiplier, then the stronger the cumulative positive effects of external knowledge on the generation of new knowledge.

The new focus on the recombinant character of the knowledge generation process has unveiled and stressed characteristics of technological knowledge that, although they had been identified in the first phase, received lesser attention, namely indivisibility and hence complementarity and cumulativity. Due to indivisibility, the generation of new technological knowledge impinges on the stock of knowledge, both internal and external to each agent. Due to complementarity the current research and learning efforts of each agent impinge upon the current efforts of other agents. Hence, it can only be generated if and when existing technological knowledge can be used as an intermediary input for the generation of new knowledge. Its non-exhaustibility makes these repeated uses not only possible, but increasingly more effective along with an increase in the stock of knowledge.

The specification of the knowledge generation function as a combinatorial process can be regarded as the first step in a long research process enriched by the major acquisitions of the empirical analysis. Since the early steps of the theoretical analysis, in fact, a growing empirical literature has enriched the understanding of the characteristics of the knowledge generation function, assessing the role of different measures and proxies for both knowledge inputs and knowledge outputs and providing important contributions to understanding the complementarity of the external flows and stocks with the flows and stocks of knowledge internal to each firm and the heterogeneity of knowledge as a composite bundle of differentiated items.

The first steps show that the differences in the levels of innovation activity across countries and regions are explained by the differences in the level of inputs such as R&D manpower and spending invested in the generation of innovations (Furman et al., 2002; Fritsch, 2002 and O´Huallachain and Leslie, 2007). Crépon, Duguet and Mairesse (CDM) (1998) make big progress by providing the first econometric analysis of the knowledge generation function combined with the technology production function in a single framework.

The discovery of the role of the composition of the knowledge base and of the stocks and flows of external knowledge is the result of an array of empirical studies that stress the limits of the elementary relationship between R&D expenses and output in terms of patents. Arora and Gambardella, (1990) show that, in biotechnology, external knowledge is an indispensable input for the generation of new technological knowledge. Cassiman and Veugelers confirm its complementarity and highlight the limited possibility of substituting it with internal R&D activities (Veugelers and Cassiman, 1999, and Cassiman and Veugelers, 2006). Loof and Johanson (2014) and Johanson and Loof (2015) stress the complementarity between internal and external knowledge showing that internal research activities are indispensable for accessing and using external knowledge as much as the access to external knowledge is indispensable for performing effective R&D activities intramuros. Strumsky, Lobo, Van der Leeuw, (2012) and Youn, Bettencourt, Strumsky, Lobo (2014) provide rich evidence, based on U.S. patent records dating from 1790 to 2010, that confirms the central role of knowledge cumulativity. Antonelli and Colombelli (2015) show that the knowledge generation function displays the typical traits of a O-ring technology where internal and external knowledge are strictly complementary. Agents that have access to knowledge externalities cannot generate new technological knowledge without research and learning efforts as much as agents that invest large resources in research and learning cannot generate new technological knowledge if they have no access to external knowledge. Internal and external knowledge are Kremer complementary and neither one can fall to zero levels (Kremer, 1993).

The identification of the central role of the stocks and flows of external knowledge enables to understand that the successful introduction of technological innovations is the result of matching the characteristics of the system in which firms are embedded and their strategies. Most importantly, it becomes increasingly clear that systematic and structured interactions between users and possessors are needed to use tacit and sticky knowledge again as an input for the generation of new knowledge. Knowledge tacitness and limited appropriability require sophisticated mechanisms of knowledge interactions among agents. These can parallel market transactions of goods so as to engender transactions-cum-knowledge interactions, take place by means of dedicated organizations or by means of the mobility of skilled personnel. Knowledge interactions take place both among firms and between the business sector and the public research system so that the necessary specialization can occur and favor exchanges between research units. The notion of generative interactions plays a central role in this approach (Antonelli and Scellato, 2013). The amount of external knowledge and viability of workable interactions influence the capability of firms to generate new technological knowledge (Howells, Andrew, Mali, 2003).

When access conditions to the local pools of knowledge make the actual generation of new technological knowledge possible and feed the introduction of innovations, actual gales of technological change may emerge. The easier the access to the local pools of knowledge, then the larger the amount of knowledge that firms can generate (Feldman, 2003).

The analysis of the recombinant generation of technological knowledge confirms its intrinsic collective nature (Allen, 1983). The generation of knowledge by each individual requires a complex web of institutional and organizational devices that make the participation of a variety of agents with different incentive mechanisms possible. Knowledge is both a collective good and the result of a collective activity. It is a collective good because the interactions between users and 'inventors' are indispensable for it. The generation of knowledge cannot be separated from its use (Cowan and Jonard, 2003; Cowan, Jonard and Zimmermann, 2007).

Knowledge is the result of a collective process due to its indivisibility, and specifically due to its diachronic cumulability and synchronic complementarity, the recombinant generation of knowledge requires the active participation of a variety of agents who possess the complementary fragments of the pool of knowledge required for its implementation (Allen, 1983; Kogut, 2000; Antonelli, 2000). As Montobbio and Sterzi (2011) show, the generation of knowledge is higher where and when the institutional set-up makes inventing together possible.

The generation of technological knowledge is a collective process shaped by the interdependence between the action of individual agents and the structural characteristics of the system. As such, it can be regarded as the emergent property of the system in which firms, and learning agents at large, are embedded. It occurs when and if the structure of the system in which firms are localized provide access to external knowledge enabling the creative reaction of firms that leads to the introduction of innovations. The quality of the system in terms of access conditions to common knowledge is crucial not only to supporting the creative reaction of firms and hence the rate of introduction of innovations, but also to assessing the direction of technological change in terms of its composition between product and process innovations. The appreciation of knowledge as an emerging property of the system in which agents are embedded can be regarded as the end result of this long process of empirical investigations and theoretical implementations (Antonelli, 2011)

A corollary of the analysis is that not only the amount of innovations being introduced but also their typology is influenced by the characteristics of the system in which firms are embedded, providing further support to the view that innovation shares the intrinsic features of an emergent system property**.** This analysis also highlights how and why the types of external knowledge at time *t* may influence the direction of technological change in an economic system, shaping the generation of new technological knowledge and consequently the types of technological spillover at time *t+1* by feeding a self-reinforcing process.

The new understanding of the central role of the existing stock of knowledge, both internal and external to each firm, for the generation of new knowledge, and of the intrinsic heterogeneity of knowledge -now regarded as a bundle of knowledge pieces with great differences and idiosyncratic characteristics- calls attention on the matching problems between the types of knowledge internal to each firm and the types of external knowledge(s) that are available. A poor matching between internal and external knowledge(s) reduces the chances of generating successfully new technological knowledge. These new elements enable to re-discover a key characteristic of knowledge generation: radical uncertainty and serendipity (Stephan, 1999).

It is difficult to fully define ex-ante the output of the knowledge generation process. The actual amount of new knowledge, its timing, and its content cannot be easily predicted at the onset of the knowledge generation process. Firms engage in the knowledge generation process in order to introduce technological and organizational innovations with well-defined product and market characteristics. Yet the generation process is shaped by intrinsic serendipity. The achievement of the desired results may be delayed, even substantially. The knowledge generation process, instead, may yield un-expected results. The bundle of types of external knowledge that can be actually accessed and used as necessary inputs into knowledge generation and their matching with the internal stock of knowledge(s) is an important cause of the stochastic and unpredictable character of the recombinant knowledge generation activity, and its outcomes, in terms of rates and direction (Fleming, 2001). The firm has to cope with the problems raised to its innovation strategy by both the lack of the expected knowledge inputs and the exploitation of the non-expected ones (Loasby, 1976).

The radical uncertainty and unpredictability of the knowledge generation process adds to the limits of knowledge as an economic good as a major element of the Arrovian postulate about the undersupply of knowledge. Firms are reluctant to generate the appropriate quantities of knowledge, not only because of its limited appropriability and tradability, but also because of the unbearable levels of risks that characterize both its generation and exploitation. Because of the radical uncertainty of the knowledge generation process financial institutions are even more reluctant to provide financial resources to fund the generation of new technological knowledge. Bankers especially suffer an intrinsic asymmetry. They are exposed to the high levels of risks of failure that would undermine the possibility of would-be-inventors to pay back the credits, while they cannot participate to the profits that the successful generation of knowledge and the eventual introduction of innovations might yield. Substantial credit rationing limits the access to financial resources for potential 'inventors'. Firms can fund the generation of new technological knowledge only by means of internal funds or by means to the equity markets (Stiglitz and Weiss, 1981). Both engender asymmetries in favor of large incumbents with high levels of profitability that can better cope with the financial constraints stemming from the radical uncertainty of the generation of new technological knowledge (Dasgupta and Stiglitz, 1980).

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