From knowledge spillovers to knowledge interactions: Towards a systemic approach to innovation

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From knowledge spillovers to knowledge interactions: Toward a systemic approach to the understanding of knowledge generation and distribution[1]

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Abstract. The paper aims to providing an integrated theoretical framework for questioning the traditional understanding of the conditions under which geographical space favours knowledge creation and local dynamics of innovation and growth. The paper shows the analytical elements of the methodological shift in the economics of knowledge from an ex ante perspective that values static allocation problems, towards an ex post perspective that appreciates the actual conditions that support the production and diffusion of knowledge, one that values feedbacks, complementarities and interactions. The essential argument here is that systemic interactions and networking among innovators are necessary conditions for the success of knowledge creation, and that intentional action is required in order to benefit from knowledge flows. Within this perspective, knowledge is understood as a collective good where the coordination of the division of knowledge and of innovative activities has most relevant governance implications: interactions and networking plays a most important role here. Since, in fact, technological knowledge is fragmented into several portions of internal and external, tacit and codified competencies, which are commanded by different organisations, coordination between those organisations is most important to recombine the different and yet interdependent portions of knowledge, to integrate these and augment the internal competencies of firms. Knowledge interactions emerge as strategic processes in the production of new knowledge, and should be a central issue in a research agenda that value the systemic character of the innovation process.

Keywords: Collective knowledge; Knowledge governance; Interactions; Networking; Spillovers.

JEL Classifications; O31; O33

1. Introduction

Traditional economic approaches view technological knowledge as either a pure public or pure private good and are focused on *ex ante* allocation problems, which derive from well-know market failures in achieving both private efficiency in the generation of knowledge and social welfare in

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the diffusion of knowledge. These market failures are summarized in the most typical knowledge trade-off: when private incentives are strong enough to ensure the firm's appropriation of the returns from investments in knowledge and innovation, social diffusion of knowledge and the related social welfare are harmed. V*ice versa,* when knowledge regimes encourage the socialization of innovation benefits, private incentives to innovate are low, and therefore underproduced, underutilized and unevenly distributed. Such approaches lead to the identification of specific and top-down institutions governing knowledge production and distribution. Public provision of knowledge, on the one hand, and *intra muros* R&D and innovation on the other have been seen as the most appropriate governance structures to overcome the problems of underinvestment in knowledge, together with intellectual property rights and the patenting systems. The latter, however, when too strong and rigid, enforce private incentives to innovate but can harm social diffusion, in turn pointing out another element of the classical knowledge trade-off (Patrucco, 2008).

Either technological knowledge is considered a pure public or a pure private good, in traditional perspectives knowledge is the result of linear and deductive processes that neglect important complementarities between public and private portions of knowledge, related feedbacks and the systemic and complex nature of the dynamics of knowledge generation and distribution.

Recent achievements in the economics of innovation and knowledge questioned such standard views. Here, Schumpeterian perspectives on innovation that value interdependencies, technological complementarities and knowledge interactions, can successfully integrate and augment both the Arrovian approach to public knowledge and the market-for-knowledge approach. This integration can yield major benefits to the understanding of the characteristics, processes and governance of knowledge.

First, such an integrated approach considers knowledge as the result of emergent and bottom-up processes, which are localized in the geographical and technological space. Second, such processes are characterized by systemic feedbacks and complementarities between different actors, both public and private, involved in the creation and distribution of knowledge. Such processes, and more precisely the effective role of interactions and the absorption of external knowledge by proactive firms, shape the attributes of knowledge itself. Technological knowledge is now understood as a collective good, the systemic outcome of cumulative and recombinatorial dynamics between public and private, internal and external knowledge, and in which interactions and learning among actors plays a key role. Third, the institutional, technological and geographical characteristics of innovation systems, in terms of variety and complementarity of actors, and connections among these, become new object for the implementation of appropriate knowledge governance mechanisms. In this perspective, the new economics of knowledge clearly shifts the focus from an *ex ante* towards an *ex post* perspective on the generation, circulation and governance of technological knowledge.

The aim of this paper is to show the analytical elements of such a methodological shift from an ex ante perspective that values allocation problems, towards an ex post perspective that appreciates the actual conditions that support the generation and distribution of knowledge, together with the valorisation of feedbacks, complementarities and interactions. Technological knowledge and innovation systems are the emergent and collective outcomes of bottom-up processes that valorise the structural and dynamic characteristics of economic systems. Within this perspective, the dynamics of collective knowledge can be understood as a matter of knowledge coordination with most relevant governance implications, and within which knowledge interactions play a most important role. Since knowledge is fragmented into several portions of internal and external, tacit and codified competencies, which are owned by different organisations, coordination between those organisations is most important to circulate, access and recombine the different and yet interdependent portions of knowledge. Knowledge interactions, defined in terms of the number and quality of connections and processes of interaction between the different knowledge owners, trigger the exchange and integration of complementary capabilities and therefore are seen as a specific mode of coordination of the division of knowledge. The paper is organized as follows. Section 2 identifies the elements of the economics of technological knowledge and points to the idea of knowledge interactions as crucial mechanisms in the generation and distribution of knowledge in a collective approach. Section 3 enriches the framework with the integration of the problem of the coordination of the division of knowledge. It articulates the characteristics of the different forms of governance of knowledge and puts the complex system of interconnections among a variety of organisations that own fragmented, imperfect and yet complementary kinds of knowledge at the centre of the issue of knowledge coordination. Conclusions summarize and identify implications for innovation policy and knowledge governance.

2. The basic elements of collective knowledge and the role of interactions

2.1. Shifting approaches to the economics of knowledge: knowledge as a public, private and collective good

Traditional economics of technological knowledge builds upon the recognition of important market failures in the generation and diffusion of knowledge. Considering either the classical Arrovian microeconomics of technological knowledge (Arrow, 1962a,b and 1969) or the application of the transaction costs approach developed by Ronald Coase (Coase, 1937 and 1960) and Oliver Williamson (1975, 1985 and 1996) to the economics of knowledge with the development of the notion of markets for knowledge (Arora, Fosfuri and Gambardella, 2001), pure markets generate allocation failures that undermine either private or public efficiency in the creation and distribution of technological knowledge. Clearly, standard economics of knowledge focuses on the *ex ante* perspective and allocation inefficiencies are the results of a well-known set of characteristics qualifying knowledge as an economic good.

According to Kenneth Arrow, knowledge is non-appropriable, non-excludable, non tradable and non-divisible. Moreover, knowledge is the outcome of a deductive and linear process that utilizes scientific discoveries and developments in pure research and applies these into the specific activities of the firm. Such characteristics lead to market failures in the generation of knowledge that are due to the trade-off between the social benefits of a public diffusion of knowledge and the gains stemming from the private appropriation of inventive efforts. Imitation, free riding and opportunism could undermine the latter when the diffusion of knowledge is public.

On the other hand, the elaboration upon the Coasian approach to the analysis of the costs of using the market puts emphasis on the fact that high levels of transaction costs in the market exchange are also due to the need of controlling the behaviours of eventual free riders and opportunists, when technological knowledge has the characteristics of the Arrovian public good. If we apply the transaction costs approach to the economics of technological knowledge, the failure of market allocation in supporting efficient knowledge production and diffusion can explain vertical integration strategies in the firm and in-house creation of new knowledge, which now can be seen as the main processes underlining the generation and accumulation of technological knowledge (Williamson, 1975, 1985 and 1996; Langlois, 1992). Specific markets for knowledge (Arora, Fosfuri and Gambardella, 2001; Guilhon, 2001), based on intellectual property rights and the development of appropriation strategies centred upon patents, are implemented in order to try and overcome the limits of both public provision of knowledge and vertical integration of R&D (Langlois, 2003).

In the Arrovian case, technological knowledge is understood as a public good. Public provision and diffusion of knowledge, especially via the academic system and public infrastructures, is seen as the only viable governance mechanism overcoming the knowledge trade-off, while intellectual property rights can increase appropriability but reduce the scope for social diffusion. Strong cumulability between different waves and stocks of knowledge is one of the most important effects that such public character bears on the generation of new technological knowledge. In the markets-for-knowledge perspective, instead, *intra muros* innovative activity, enforced by IPRs, can lead to private efficiency in the generation of technological knowledge, which can be thought of as a pure private good characterized by full appropriablity, excludability, divisibility and tradability but very low (external) cumulative effects. Cumulability of knowledge is possible within the boundaries of the firm, but is more and more difficult with portions of knowledge that have been produced outside the firm. IPRs regimes and the patenting system arguably play a most important role in enforcing the governance of such characteristics and in stimulating in-house knowledge production processes.

Such standard approaches has been challenged by the integration of the achievements in different fields of economic analysis, such as industrial economics, economics of organization, economics of learning, regional economics and the economics of science and university, into the broader field of the economics of innovation (Antonelli, 1995; Feldman, 1994; Geuna, 1999; Loasby, 1999; Malerba, 2002). The characteristics, processes and governance of technological knowledge can be put into a new light and understood from a different perspective, which critically and originally implements the traditional economics of technological knowledge.

In this new approach, knowledge is an emergent, bottom-up and systemic phenomenon. Knowledge is fed by strong feedbacks and non-linearity between the public and the private sectors, and between internal (to the firm) knowledge and knowledge sourced externally, which can in turn bear important increasing returns in the production of new knowledge. Learning takes place within and outside the firm. Interactions and exchange between firms' tacit knowledge and external general knowledge play a major role in contributing the eventual process of knowledge creation and distribution. Therefore, technological knowledge is characterized by important complementarities and recombinatorial effects between scientific, general knowledge resembling the Arrovian public good, and private, tacit and appropriable knowledge. Moreover and consequently, technological knowledge is understood as a collective good that can be easily and yet imperfectly cumulable and tradable.

Let us detail the specific elements and processes qualifying collective knowledge.

The intrinsic indivisibility of technological knowledge, well-understood by the seminal work of Kenneth Arrow, can be specified into more precise notions: 1) cumulability, when indivisibility applies to the vertical complementarity between the accumulated stock of previous knowledge and the new flows of knowledge; 2) complexity, when indivisibility refers to the horizontal variety of portions of knowledge that are necessary and indispensable to generate a new portion of knowledge; 3) fungibility, that is complement to complexity and refers to the variety of uses and applications of a single bit of knowledge, which can be replicated with low (incremental and variable) costs (Antonelli, 2003 and 2005).

Building upon the Nelson and Winter (1982) approach to tacit knowledge, which challenged the traditional notion of knowledge as a pure public good, knowledge is now characterized also by high levels of appropriability. Knowledge is regarded as a quasi-private good, based upon tacit learning and it is embodied and localized in specific routines, human capital and artefacts. Therefore it is very idiosyncratic and characterized by high levels of intrinsic (but not complete) appropriability and excludability. Moreover, knowledge is sticky, as a consequence of near-appropriability and the localized and embodied character.

The notions of near-decomposability and modularity elaborated by Herbert Simon enrich the Nelson and Winter's approach. The bundle of technological knowledge can be decomposed in modules, each of which is organized around links of complementarity to other modules. Ties of complementarity can be stronger or weaker according to the technological, industrial and institutional characteristics of the economic space in which each module is developed. Since technological knowledge is embodied in very specific human, organizational and technological structures, it can be appropriated, decomposed, replicated and recomposed more easily and at a faster pace only within modules that are located in proximate economic spaces (Brusoni and Prencipe, 2001; Langlois, 2002; Simon, 1981).

Furthermore, knowledge can be tacit, codified and articulable. According to the prevailing characteristics of knowledge in terms of tacitness, codification and articulability, an array of different interaction modes and contexts can be more or less appropriate in favouring access, diffusion and the transformation of pre-existing modules of knowledge into new ones (Ancori, Bureth and Cohendet, 2000). When the industrial and technological features of knowledge and the set of norms and rules which determinate the development and introduction of a new given portion of knowledge are not expressed and formalized in specific 'book of instructions', namely a codebook, knowledge is tacit. In this case the pertinent knowledge base is not public and relying on a pure scientific base, but is much more the result of the implicit accumulation of experience, routines and learning by doing. Because such knowledge base is mainly personal, even when it is shared within a community, vis-à-vis interactions, master-apprentice-like relations and learning on the task are the typical modes of access and accumulation of that knowledge (Polanyi, 1958 and 1966).

At the opposite, when technological knowledge relies upon scientific knowledge, a specific codebook defining the characteristics of a given module of knowledge and the relevant development procedures exists. The members of the scientific and technological community systematically and explicitly refer to that codebook when accessing and integrating that knowledge. In this case, knowledge is codified and public to a great extent. Acquisition and distribution occur mostly by means of 'blueprints'.

In between tacit and codified knowledge, articulable knowledge presupposes some degree of codification when considering the base of knowledge measures depending upon. Nevertheless, the codebook that establishes the definitions of such knowledge and the procedures for its access and implementation into a new portion of knowledge or a new innovation is not manifest even to the members of the community which finally employs and develops knowledge itself. Even though an explicit book of definitions and instructions exists, it is not explicitly consulted and the contents of the codebook have been so fully internalised and appropriated within the community that they operate as implicit sources of technical knowledge and procedural rules. Articulation being social interaction, the degree to which articulable knowledge is public or private, and hence the extent to which it is shared within the community, depend on the costs of access, transmission and absorption of the relevant technical specifications and implementation procedures (Cowan, David and Foray, 2000).

The specification into articulability, tacitness and codification is most important in the understanding of collective knowledge in that it focuses on the communication codes, protocols and more generally on the system of interactions lying behind a given knowledge base. In turn, the context and processes of interactions are shaped by the extent to which actors are proximate, not only from a geographical and technological viewpoint. The notion of proximity can be enriched and it can now be defined in terms of a number of dimensions: geographical, technological, social, cognitive and organizational.

2.2. From knowledge spillovers to knowledge interactions

The understanding of the elements of the economics of knowledge interactions benefit and is qualified when considering three strands in the literature on innovation.

First, different kinds of externalities are said to contribute local accumulation of technological knowledge, which have been identified in an extensive body of empirical literature following the seminal contribution of Glaeser, Kallal, Scheinkman and Shleifer (1992). The MAR (Marshall-Arrow-Romer) externalities tradition argues that geographical concentration and specialization in a single industry, coupled with local specialization strategies, foster technical externalities to be generated, transmitted and accumulated by local firms. The emergence and growth of a local body of technological knowledge is the result of intra-industry and geographically well-defined flows of technical know-how. Secondly, the so-called Jacobs externalities tradition (Jacobs, 1969) alternatively gives prominence both to inter-industrial knowledge transfer among geographically proximate but technologically different industries, and to local economic differentiation in contrast with specialization. Moreover, Jacobs stresses the role of cities and metropolitan areas as especially conducive for the effective exploitation of inter-industrial technical externalities and hence for the growth of local clusters of technological knowledge. Integrating the two approaches, Porter (1990) insisted on geographical specialization as a factor stimulating the effective diffusion of technological externalities, hence the MAR externalities argument. However, the role of internal competition and hence of economic differentiation is seen as crucial in the growth of local technological clusters, that is the Jacobs externalities argument. Technological knowledge is now localized because of the local competitive interactions between firms in the same technical space. In this context, Porter emphasizes the role of large firms as key actors in the local clustering of technological knowledge and innovation dynamics.

Much empirical evidence gathered in the geography of innovation elaborated on the idea that agglomeration and therefore geographical proximity *per se* facilitate the transmission of knowledge and that localized externalities are a major driver of technological progress and economic growth (Jaffe, Trajtenberg and Henderson, 1993; Jaffe and Trajtenberg, 1999; Audretsch and Feldman, 1996; Dumais, Ellison and Glaeser, 2002).

This strand of literature clearly builds upon the Arrovian analysis of knowledge subsequently developed in the methodology by Griliches (1979 and 1992) and Jaffe (1986) with the well-known idea of a technology production function[2]. In these studies knowledge is seen as a public good, and knowledge externalities are a direct consequence of well-known characteristics of technological knowledge: non-divisibility, non-appropriability, non-rivalry in use, non-excludability. Knowledge externalities augment and supplement as a further input the production of other goods by means of capital and labour (Antonelli, 2014).

Within well-defined geographical and technological spaces, knowledge and ideas are inputs that spill free across firms. The accumulation of labour, capital and R&D is the unique requirement for knowledge spillovers to take place and to exert positive and unconditional effects on output and productivity growth. Firms co-located in the geographical and technological space are able to take advantage from knowledge spillovers without occurring in any learning or transaction costs.

[2] New growth theory models (Romer, 1986 and 1990) were also implemented along the line of analysis with generic and specific knowledge being as a matter of fact supplementary to each other. Also in new growth theory, learning occurs without costs and without the need of purposive and intentional effort to benefit from knowledge externalities.

However, such empirical evidence is far from being uncontroversial, both with regard to whether agglomeration favours knowledge externalities and with regard to the conditions under which geographical proximity facilitates the distribution of knowledge and the exploitation of external knowledge by co-localized firms (Breschi and Lissoni, 2001; Thompson and Fox Kean, 2005; Boschma and Weterings, 2005). More specifically, recent contributions qualified the relation between proximity, externalities and innovation, questioning the idea that this relation is always positive, independently of the presence of specific conditions. Agglomeration can yield both positive and negative consequences in terms of knowledge externalities. Most importantly and contrary to the received treatment of knowledge spillovers, the exploitation of externalities by co-located firms is not the necessary and automatic consequence of geographical proximity and "industrial atmosphere". On the contrary, firms willing to benefit from knowledge externalities need to commit resources for undertaking intentional activities of learning, interaction and cooperation that bear specific costs (Boschma and Iammarino, 2009; Antonelli, Patrucco and Quatraro, 2010; D'Este, Guy and Iammarino, 2012). A deeper understanding of the dynamics underlying the working of knowledge externalities is needed in order to identify the characteristics and sources of regional innovation systems. Such contributions make the point that the production and accumulation of technological knowledge is the result of peculiar, constrained and yet complex interdependences between technical and geographical factors such as labour mobility, feedbacks through formal and informal networks, technology agreements, University-industry linkages, and sub-contracting.

Therefore, the second and key element the economics of collective knowledge is building upon is the appreciation of the importance of external knowledge and the related learning efforts firms need to put in place in order to benefit from knowledge sourced externally. External knowledge can be considered as an essential and non-disposable input as much as internal learning and R&D activities. Such inputs cannot be considered as substitute, or merely supplementary to each other as in the Griliches' technology production function but they must be considered as strictly complementary for knowledge to be generated. Increasing returns in the production of knowledge can take place only when both internal and external knowledge are available and integrated into the firm's production process. Both internal and external knowledge are equally necessary and indispensable for the generation of new knowledge (Weitzman, 1996 and 1998; Patrucco, 2008; Antonelli, 2014).

Agglomeration per se is not sufficient anymore to give rise to knowledge transfer and to engender the benefits associated to knowledge externalities. The specificity of conditions characterizing particular places and times have a powerful effect on the production and circulation of technological knowledge, and therefore diverse geographical spaces affect in different ways the dynamics of technological knowledge over time (Gertler, 1995).

The benefits stemming from knowledge externalities can be geographically bounded provided that co-location makes available an array of conducive circumstances for firms to share their knowledge, circulate their routines, establish innovation partnerships and integrate knowledge acquired from external sources with their own knowledge base. In this context, the role of interactions and of the embeddedness of the firm within geographical networks has been stressed. In other words, it has been highlighted that it is not mere co-location that favours knowledge to spill over and benefits proximate firms. It is instead the involvement of firms within selective and complex networks that makes localized learning possible and knowledge externalities available for co-located firms (Patrucco, 2005; Malmberg and Maskell, 2006; Giuliani, 2007) because of different kind of proximity that vary from geographical to institutional (Graf, 2011), from social (Breschi and Lissoni, 2009) to cognitive (Noteboom et alii, 2007).

The major achievement of this field of analysis is the recognition that only firms able to establish interconnections with a variety of knowledge producers can take advantage from the complementarity between their internal knowledge base and external resources. Elaborating further upon the research path opened by Cohen and Levinthal (1989 and 1990), different contributions confirm that firms purposefully establish interactions within networks precisely to access knowledge inputs sourced externally (e.g., Zahra and George, 2002; Roper, Du and Love, 2008; Love and Roper, 2009). Such literature shows that a net of knowledge transactions has progressively paralleled the generation of innovation and knowledge by means of vertically integrated R&D activities because a single firm is not able to invest the sufficient amount of resources to develop new knowledge through a fully internal process. The use of external knowledge inputs may yield clear advantages in overcoming the technological and financial limitations of in-house innovation, and may enlarge technological opportunities through the search of the external environment. At the same time, some internal technological competencies are necessary to explore for the more appropriate external knowledge available, as well as to enable an efficient absorption and use of the knowledge sourced externally.

The diffusion of external knowledge is now a key determinant in the generation of new knowledge and innovation. Technological knowledge and the eventual introduction of innovation are now understood as the results of a cumulative process of distribution and recombination of different, pre-existing bits of knowledge embodied in a variety of actors.

An array of problematic consequences arises from such collective character of knowledge and highlights the key role assumed by interactions in the process of knowledge creation and distribution. Knowledge interactions are therefore the third essential element that needs to be appreciated to understand the economics of collective knowledge.

Access to existing external knowledge is the necessary condition improving the effectiveness and rate of knowledge generation, enabling the acquisition and accumulation of knowledge already stored but dispersed in a number of different but yet complementary users. However, since knowledge is industry- and region-specific and ultimately individual, it is also very idiosyncratic and costly to be used elsewhere, i.e. in other regions, other industries and also other firms and individuals. A growing body of both empirical and theoretical literature shows that the gains from knowledge externalities by both users and imitators are not free. Knowledge does not spill over spontaneously. Its identification, access and exploitation by third parties require some dedicated resources and an array of costs is typically relevant: imitation costs (Mansfield, Schwartz and Wagner, 1981), absorption costs (Cohen and Levinthal, 1989; Griffith, Redding and Van Reenen, 2003), networking costs (Agrawal, Cockburn and McHale, 2006; Beugelsdijk, 2007), cognitive costs (Nooteboom et alii, 2007), relational costs (Glaeser and Scheinkman, 2000), congestion costs (Boschma, 2005; Frenken, Van Oort, Verburg, 2007). The acquisition of external knowledge requires therefore qualified interactions with other agents. The exploitation of knowledge externalities implies the commitment of resources that are necessary to searching, screening, understanding, absorbing, purchasing and acquiring knowledge generated by other firms. The capability of agents to access external knowledge depends on the network of relations and common codes of interactions.

These features bear important implications for the tradability, and more generally the diffusion of knowledge, especially when considering the contribution of the transaction costs approach. The notion of markets for knowledge is most important here (Arora, Fosfuri and Gambardella, 2001; Guilhon, 2001). In fact, technological knowledge is quasi-tradable and it can be exchanged in both embodied forms (for instance, via labour mobility, and technologies and products flows) and disembodied forms, through the markets for knowledge implemented upon knowledge-intensive business services (KIBS), patents and licenses. The more embodied is knowledge and the more it is only nearly-tradable, that is circulated within co-localized modules and between actors complementary from a technological viewpoint (Timmermans and Boschma, 2014). The more disembodied and general is knowledge and the more efficient are market institutions, the lower are transaction costs and the more effective are intellectual property rights in enforcing both appropriability and tradability. Here, knowledge transactions based on contracts effectively complements knowledge interactions.

Consequently, conditions for the access and exploitation of knowledge sourced externally are harmed by 1) communication costs, that is, the costs agents must face to access, i.e. to search, store and decode the relevant bits of idiosyncratic knowledge owned by different and complementary actors; and 2) the trade-off between internal knowledge production costs and external knowledge access costs. Internal knowledge production costs can be defined as the costs necessary to put in place internal learning and R&D efforts, while access costs can be specified into interaction costs and transaction costs, and defined as the costs necessary to implement connections and learning between the firm and the system in which it is embedded, in order to access external portions of knowledge.

In other words, knowledge interactions arises as a fruitful research field in the economics of innovation in that actors must face specific costs to access and internalise portions of external knowledge, which can be very different from those already accumulated and used internally, but which are strictly complementary to internal R&D and learning, and indispensable for the working of the entire process of knowledge generation. Knowledge interactions emerge as a key element in the systemic approach to innovation together with the complementarity of external knowledge, and in contrast to traditional views on innovation and knowledge (Table 1).

Table 1. Contrasted views on external knowledge and learning

Essential features ***Economic approaches***	External knowledge	Interactions and learning
Knowledge as a public good	- Supplementary - Knowledge externalities augment capital and labour	- Automatic effects of technological and geographical proximity - No learning, interaction or transactions costs to benefit from external knowledge - Free activities
Knowledge as a collective good	- Complementary to internal R&D and learning - Non disposable for the working of knowledge generation	- Purposive and intentional efforts to benefit from external knowledge - Costly activities

Communication opportunities and recombinatorial learning are at the base of the integration and recombination of existing complementary kinds of knowledge, most of which are external to the firm. They benefit from agglomeration economies, technological complementarities, social and institutional proximity. The number and quality of connections characterizing innovation systems and their capacity to carry complementary flows of knowledge play a major role in internalising knowledge spillovers within the system, exploiting external knowledge and knowledge interdependencies, in turn building the conditions under which collective learning can take place and knowledge can be both generated and distributed efficiently.

The processes by means of which each element, internal and external, scientific and tacit, of technological knowledge is generated and distributed affect such characteristics and reveal a variety of interaction mechanisms that are specific to each type of knowledge (Antonelli, 1999): 1) recombination matters to access external general knowledge and to integrate it into the specific productive activity of the firm. Here, intellectual property right regimes and university-industry linkages exert a key role; 2) socialization enhances the diffusion of external tacit knowledge by means of labour mobility and informal interactions between workers as well as between scientists. Such informal interactions are supported by the social characteristics, defined in terms of trust and the reciprocity of knowledge exchange, of the environment in which actors play; 3) learning allows internal tacit knowledge to be accumulated, embodied in and transmitted through firms' routines, organizational structures and human capital. The dynamics of investments in human capital and machines play a most important role here; 4) finally, R&D activity in firms, universities and public laboratories, supports the generation of internal and external general knowledge that can be appropriated by means of IPRs and knowledge transactions. Firm's and university's patenting and licensing activities favour the tradability of such private general knowledge in the markets for knowledge.

Each of these processes is necessary for the dynamics of collective knowledge to fully take place. Technological knowledge is now viewed as a process of interpolating relationships among 1) firm-based learning and accumulation of internal tacit knowledge, 2) intra-muros R&D activities which favour codified knowledge to be gathered, 3) access to external tacit know-how and competence, 4) accumulation and recombination of existing external codified knowledge.

Within this perspective, the analysis of the interaction between internal knowledge production costs, and external transaction and interaction costs that are necessary to access external modules of knowledge, can be the base for the understanding of the problem of coordination of the division of knowledge within the approach to collective technological knowledge (Patrucco, 2009). The trade-off between internal knowledge production costs and external access costs moreover can contribute the understanding of the bundle of coordination within innovation systems and paves the way for the analysis of knowledge interactions as a mechanisms for the governance of collective technological knowledge.

In this perspective, innovation systems emerge as the complex result of the different processes of access, recombination and integration of complementary portions of knowledge showing different characteristics.

3. The division of knowledge, interactions and the governance of innovation

Economics of innovation has been recently expanding as a fertile domain to apply the analysis of the changes occurring in the structure of interactions between organizations, their characteristics and their effects, as developed by complexity theory (Lane and Maxfield, 2005; Antonelli, 2005; Frenken, 2006).

Integrating insights from complexity theory, economics of innovation and knowledge enriched with the analysis of the role of interactions and networks the understanding of learning as an intentional, mindful and purposive behavior put in place by myopic firms, that is one of the cores of the economics of innovation. Actors intentionally interact and learn in order to acquire and coordinate knowledge and competences sourced externally. These are complementary to those internally developed by each actor, since no single actor is able to command all the competences necessary to innovate in isolation. Firms are able to innovate when they can access and absorb competencies sourced externally, learned through interactions and recombined with the internal knowledge of the firm (Cohen and Levinthal, 1989 and 1990). Only when firms select and manage effectively external linkages, firms can exploit complementarities between internal knowledge and the capabilities provided by external organizations such as other firms, universities and R&D centers (Patrucco, 2008).

The grafting of complexity theory into the body of economics of innovation (Antonelli, 2011) recently put into a new light Marshallian insights about the coordination of the division of knowledge (Richardson, 1972; Loasby, 2002). Along the lines paved by Friedrich von Hayek (1945) and Herbert Simon (1962), technological knowledge can be defined as a complex system of interconnections among a variety of organisations that own fragmented, imperfect and yet complementary kinds of knowledge. These basically involve technical know-how, organisational skills and competencies in understanding consumers', users', suppliers' and markets' behaviours, each of which in turn relies on a different combination of tacit capabilities and scientific knowledge sourced both internally and externally. Moreover, the way in which interconnections among the different actors of the system are implemented is main issue at stake in order to both exploit interdependencies (i.e., knowledge at the system level is not the mere addition of knowledge at the different micro levels) and make such exploitation efficient (i.e., reducing the cost of the interactions needed to increase knowledge at the system level).

This points to the question of how economic agents and their organizations acquire and coordinate innovative capabilities and new knowledge. Following the seminal contribution of Keith Pavitt (1998), a rich stream of studies has highlighted that the division of labour has major implications for the organization of innovation (Brusoni and Prencipe 2001; Jacobides, 2006; Brusoni, Prencipe and Pavitt, 2011),

Innovation systems clearly provide evidence for such division of labour between different producers of knowledge that perform different and yet complementary innovative activities, and stress the need of coordination and governing mechanisms. Here, for instance, larger firms often base their activity on formally trained competencies and focus their technological activity on R&D-intensive processes, subcontracting the production of components and intermediary inputs to small firms that are characterised by tacit know-how and that are often specialised in very specific manufacturing processes. At the same time, large firms can cooperate and even contract pure research to the academic system. In such a situation, very often consultants provide knowledge-intensive services in order to integrate, for instance, R&D-intensive competencies into the daily routines of small producers or the outcome of pure research into the activity of large firms. When the different portions of knowledge belonging to small and large firms, to consultants and to universities need to be integrated into each other in order to generate the eventual innovation we finally observe, coordination matters.

The analysis of the organization of knowledge generation and diffusion in innovation systems is at the centre of an intense and rich debate between scholars arguing how complex environments are better coordinated and managed. Three main organizational solutions have been characterized as appropriate for accessing and coordinating external knowledge in complex environments such as innovation systems: a) vertically integrated firms guided by managerial authority and command; b) horizontal networks based both on modular organizations that relies upon market transactions and outsourcing and on spontaneous interactions such as in the case of districts; c) directed and hierarchical networks between collaborative and complementary partners and centred upon key firms. Table 1 summarizes these differences both in terms of the coordination features of the different organizational solutions, and in terms of the implications for the innovation process.

Table 2. Characteristics, costs and benefits of the different knowledge governance mechanisms

GOVERNANCE FORM **FEATURES**	**THE INTEGRATED FIRM**	**THE HORIZONTAL NETWORK**	**THE HIERARCHICAL NETWORK**
Empirical evidence	Fordist firm	- Industrial districts - Technological clusters - Modular networks - Markets for knowledge based on arms' length transactions and spot contracts	- Open technological alliances - Coalitions for innovation - Technology platforms - Innovation platforms
Coordination	Managerial control	- Spontaneous interactions (districts) - Market transactions (modularized networks)	Directed
Inclusion	Limited	Open and diffused	Selective variety
Design costs	High	- Low because of spontaneous coordination (districts) - High because of contracts and IPRs definition (markets for knowledge) - High because of standard interface setting (modular networks)	High
Networking costs	Low	High due to redundant connections	Limited because of platform leader gatekeeping
Knowledge	Perfect	Fragmented (both in district and modular networks)	Fragmented

Product design strategy	Top-down and ex-ante	- Bottom-up and ex-post (district-like networks) - Top-down and ex-ante (modularized networks)	Co-design
Economies of specialization	Limited	High because of the division of labor	High because of competences variety
Learning economies	Bounded to firm competencies	- Collective learning (district) - Competencies sourced externally through transactions (modularized networks)	Search for complementarity and collective learning
Circulation of knowledge	Limited to the firm boundaries	- Open and diffused (district) - Conditional to IPRs (modularized network)	Selective
Innovation process	Internal R&D	- Knowledge externalities (district) - Private R&D (modularized network)	Collective (integration of internal R&D and external sourcing)

3.1. From vertical integration of R&D to modular networks and markets for knowledge

While the vertically integrated R&D model dominated nearly the entire XX century, taking advantage from scale and scope economies in R&D (Chandler, 1977; Penrose, 1959), its progressive demise and vanishing-out opened up a range of decentralized forms of organizing innovative and productive capabilities, based either on outsourcing and market transactions, or on collaborations (Langlois, 2004).

The vertically integrated corporation and its R&D laboratories see their margins of autonomy and self-sufficiency shrink. In particular, large companies lose their prime position as the place par excellence for the production of innovation. In fact, in a complex environment, characterized by continuous changes in the features of the products and production technologies, by radical uncertainty and by ever more extreme scientific and technological specialization, the individual company has difficulty in managing, purely through the capacities produced internally, all the competencies needed for the process of the generation of new knowledge.

The picture briefly summarized above thus questions not only the model of the integrated corporation, but also the traditional schemes of the organization of innovation. This implies that the linear and closed model must be replaced and firms must structure themselves so as to be able to draw advantage from the external knowledge available integrating it effectively with the knowledge produced internally (Chesbrough, Vanhaverbeke and West, 2006).

As a consequence, consensus has grown in recent times amongst innovation scholars around the idea that, if firms are not able to develop independently a sufficient innovation capacity on their own, they can implement a variety of solutions that goes from one extreme (vertical integration), to another (the market), passing through a variety of hybrid strategies, forms of strategic alliances and inter-organizational relations aimed at minimizing the costs of external co-ordination and the maximization of the creative contribution of the individual companies. This has opened the way to the analysis of the various forms of decentralization, specialization and division of innovation and production that emerged following the crisis of the vertically integrated corporation.

The original view put forward by Herbert Simon (Simon, 1962 and 2002) has been the point of departure, especially in economics and management sciences, of the literature on modularity and market outsourcing. In recent years, this literature addresses the conditions under which modular and market-like organizational structures are preferred to integrated solutions (Sanchez and Mahoney, 1996; Arora, Gambardella and Rullani, 1998; Baldwin and Clark, 1997). When systems grow so extensively and the interconnections between the different elements and sub-systems become so numerous, their coordination under an integrated structure is almost unfeasible. Then modular organizations are preferred and they imply breaking up the system into almost independent sub-systems that interact each other on a weak base and through standardized interfaces. In Baldwin and Clark (1997) and Langlois (2002), for instance, these modular strategies and the organization of production and innovation as nearly decomposable systems are seen as appropriate solutions to manage complex and otherwise troublesome organizations and technologies.

As claimed by this literature (e.g., Chesbrough and Teece, 1996), firms can switch from integrated organization of innovation to modular strategies according to the characteristics of the technologies and the knowledge they build upon in order to introduce novelty. The more systemic, interconnected and articulated are the knowledge bases and technologies necessary to innovate, the more efficient is the adoption of modular organization; on the contrary, the smaller is the number of elements that need to interact to generate an innovation, the easier is the coordination through vertical integration of R&D.

3.2. Organizational innovations in the governance of knowledge: hierarchical networks and platforms

The main critiques moved to this approach have highlighted two key points. First, complex systems and technologies are precisely such because it is not possible to decompose these into discrete chunks as modular strategies would assume. One of the key aspects of complexity relies in fact in the non-decomposability of the different elements and sub-systems. Firms are interdependent in both their structures and strategies because of the feedbacks loops that stems from their interactions, and changes in the characteristics and conduct of one firm determine transformations in interconnected organizations (Stacey, 1995). Second, firms do not necessarily swing between pure modular or pure integrated solutions when they are facing the choice of how organize their innovative activity. Instead, the features of the two opposite solutions coexist and firms are able to rely upon a variety of inter-organizational arrangements that may bring about advantages of both modularity and integration (Brusoni and Prencipe, 2001). Moreover, and consequently, in complex systems increasing heterogeneity of technological capabilities and interconnections implies that innovative firms need to command a wider and wider set of knowledge in order to be able to effectively organize inter-firms relations and absorb technological skills from external sources (Brusoni, Prencipe and Pavitt, 2001).

In this regards, economics and management, as well as sociological literature progressively provides consensus that networks are a third way whose efficiency relies in the fact that they make learning and innovation possible by exploiting resource heterogeneity across embedded firms. Combining the flexibility of markets with the visible hand of organization, inter-firm ties reduce the costs of access to dispersed and diverse sources of knowledge, which is then considered the main driver of innovation and new knowledge generation (Powell, 1990; Kogut and Zander, 1992; Powell, Koput and Smith-Doerr, 1996; Uzzi, 1997; Burt, 2000; Kogut, 2000; Ahuja, 2000; Smith-Doerr and Powell, 2005).

Innovation studies in particular gathered consensus upon the idea that networks are loci of innovation because collaboration favors the access to a broad set of complementary technological competencies and becomes an opportunity to recombine existing resources held by individual firms into new knowledge. In particular, the structure of the network influences the chances firms have to innovate, and being embedded in well-developed and heterogeneous environments enhancing the likelihood firms have to learn from knowledge sourced externally (e.g., De Bresson and Amesse, 1991; Helper, MacDuffie and Sabel, 2000; Zahra and George, 2002; Love and Roper, 2009; Ozman, 2009).

The growth of clusters and districts (Breschi and Malerba, 2005) is for instance centered upon the implementation of horizontal networks where the provision of knowledge is the result of the increasing specialization and division of labor in the production of knowledge and where both formal and informal mechanisms allows trustworthy knowledge exchange and user-producer knowledge interactions. Well-defined geographical spaces provide the proper environment for the development of such networks where and when they concentrate not only specialized firms that interact within the supply chain or across different sectors, but also with knowledge-intensive business services, R&D labs and universities.

The qualitative structure of the network and the role played by specific actors received a primary importance in this literature and different structures have been identified together with their relative advantages. In particular, two opposite configurations have been particularly successful in the literature: networks characterized by structures with strong and redundant ties have been contrasted to structures with weak, non-redundant ties and "structural holes" (Burt, 1992; Coleman, 1990).

Following Granovetter's (1973) argument about the "strength of weak ties", Burt (1992 and 2000) in particular argues that networks with dense and strong ties are inefficient in accessing external knowledge both because they may yield a lack in the variety of resources needed to innovate, and because they also imply a redundant communication structure, with more connections than needed and higher communication costs. Hierarchical structures characterized by non-redundant ties are instead more appropriate to organize innovation because of the key role played by "structural holes". "Structural holes" are key actors occupying a brokerage position between nodes. They arbitrate and flow knowledge between firms and groups of firms that are not tied each other and for this reason occupy a powerful and central position in the structure, which hence assumes a clear hierarchical configuration.

Coleman (1990) and subsequently Uzzi (1997 and 1999) elaborated the opposite claim, arguing that redundant ties, and dense networks have a clear advantage when firms need to exchange and communicate complex knowledge. Redundant connections promote trust-based relations and lead easily to cooperative behaviors. This favors innovation as a collective action through repeated exchange of complementary information and knowledge among the different organization of the systems. This structure tends to be flatter and characterized by actors with overlapping competencies as well as power in the network.

Evidence on which structure is likely to be more appropriate as innovation strategy in more general terms is mixed, and recently features of both dense and sparse networks have been proved to be positively correlated to firm performances (Rowley, Behrens and Krackhardt, 2000; Reagan and McEvily, 2003).

On the one hand, the increasing division of labor brought about by complexity in both products and knowledge engenders an increase in the number of specific components and bodies knowledge that need to be recombined in the final product. Redundant connections are often necessary in order to complement different specialized skills and directly share the relevant knowledge among different firms in the systems. Direct collaboration, i.e. not mediated by a structural hole, between for instance two specialized suppliers, can be for instance necessary to co-define and co-implement a new component or a sub-system of a complex product. In this case the network has some features of the dense and flat structure described by Coleman and Uzzi.

On the other, however, increasing specialization requires the broadening of the knowledge base of system integrators as coordinating organizations in order both to understand innovations and knowledge sourced externally and to manage the network of outsourced components and sub-systems of technologies and knowledge. Networks can be characterized by structural holes, arbitrating through a hierarchy the interactions between organizations that are not directly connected. System integrators for instance can be defined as specific type of structural holes at the center of a recombinatorial flow of different bodies of technological knowledge in complex innovations (Sturgeon, 2002; Prencipe, Davies and Hobday, 2003). The competence of a system integrator in this case involves the ability to govern the networked process by which innovations are collectively produced and shared (Kogut, 2000). In this regard, networks where system integrators play as central brokers do not suffer the weaknesses of pure modular strategies, where the system is conceived as easily decoupled in interdependent chunks.

In particular, the idea of hierarchical networks is emerging in the literature on innovation and an array of this type of networks can be identified, stemming from technological alliances (Hagedoorn and Hesen, 2007), to coalitions for innovation (Gilson, Sabel and Scott, 2009), from network centred around system integrators (Prencipe, Davies and Hobday, 2003) to technology and innovation platforms (Gawer and Cusumano, 2002; Gawer, 2009; Consoli and Patrucco, 2008; Patrucco, 2012). These are networks in which the interactions do not emerge and evolve spontaneously (like in traditional clusters and districts), but in which key players (e.g., platform leaders and system integrators) exercise a guiding role on the behavior of the other actors, selecting the members of the platform itself and directing the behavior and the evolution of the system as a whole. Moreover, the active search for knowledge complementarity and exploitation of variety (contrasted to mere agglomeration) between different activities characterizes these organizational solutions, which appear therefore to be structured and designed with a view to precise and pre-determined innovation goals. Knowledge interactions in these types of networks are complemented by knowledge transactions (Antonelli and Patrucco, 2014) as means to coordinate the variety of knowledge-generating activities performed by the different members of the network and to effectively exploit knowledge complementarities.

Hierarchical networks like platforms produce an outcome – an innovation – that is the result of collective learning and alignment of investments. In platform organizations, a variety of agents participate to the production and supply of products and services; each unit exists independently according to own goals and capacity but, at the same time, responds to a collective goal through shared communication rules. Hierarchical networks stress therefore the role of the complex structure of relations necessary to exploit, create and transmit technological capabilities. In this regard, a central component for the rationale underpinning platforms is maximising the variety of contributions stemming from a variegated knowledge base while maintaining coherence through a minimum level of hierarchy deployed by key firms as platform leaders. In this regard, platforms are purposefully open to entry of new actors and, thereby, of new competences: the extent of contribution by each additional unit depends endogenously on the relative value of internal competences measured against the collective goal.

In this sense, hierarchical networks represent a new organizational innovation, increasingly significant also from an empirical viewpoint since they are more and more frequently applied to different industries. These types of networks are also new governance solutions for the coordination of knowledge generation and distribution, alternative to either vertical integration of R&D through large firms, or modular systems and markets for knowledge based on contracts and IPRs, or spontaneous clusters and districts based on geographical agglomeration. The systemic generation and distribution of technological knowledge is now the result of a complex set of collaborative strategies between firms' based learning and the absorption of external knowledge originated in both firms (e.g., suppliers, clients, rivals) and institutions (e.g., universities, R&D labs, TTOs). The presence of multiple, formal and informal, interactions, the active and intentional participation of firms in such networks and the guidance of platform leaders, gatekeepers and system integrators foster these.

4. Conclusions and policy implications

The approach to knowledge as a collective good appreciates complementarities among different kinds of knowledge and the need of special efforts at the micro and system level to put in place interactions, connections and viability conditions that make such complementary kinds of knowledge accessible. In this perspective, the generation of technological knowledge does not only impinge on firm-based R&D and learning by doing, but implies systemic interactions and external learning between firms (i.e., user-producer relations within the same sector, and inter-industrial relationships) and between these and non-manufacturing institutions (for instance, universities and knowledge intensive business services). The production of collective knowledge is thus characterized by interdependencies among different kinds of knowledge generated and accumulated in different specific contexts by a plurality of actors. The production of technological knowledge is therefore a systemic activity as a result of the interactions necessary to access and make complementary kinds of knowledge circulated. In turn, technological knowledge is the result of such interactions among actors characterized by industrial, technological, organizational and institutional specific features.

Second, and consequently, the conditions for interactions and learning mechanisms play a major role in the dynamics of technological knowledge. Firms able to establish interconnections with a variety of actors can take advantage from and internalise complementarities between internal and external knowledge. Learning refers to both technologies and techniques that are already in place within the firm and to bundles of external embodied and disembodied knowledge. New amounts of knowledge and new technologies can be more easily introduced in those fields in which the firm has already accumulated competencies and know-how.

Either when considering the case of private mechanisms for the creation and appropriation of knowledge or in the case of public provision through the academic and public research system, the related assumptions on the characteristics of technological knowledge, and consequently the related governance mechanisms, has been challenged by the collective approach to technological knowledge. In this approach knowledge is the result of interdependencies and feedbacks between different organisations that are both horizontally and vertically complementary. Different modes of coordination and governance arise from such interdependencies and feedbacks, and they cannot be defined but *ex post* as the result of the network of specific knowledge interactions implemented by the firms.

Technological knowledge is therefore collective because it is the result of shared and intentional processes of knowledge interactions. A variety of knowledge owners and knowledge producers (such as, large and small manufacturing firms, University, business services, R&D centres and business associations) need to be willingly involved in such a collective process. In this respect, technological knowledge is an emergent property of a complex network of interactions that characterise innovation systems. Knowledge interactions are a crucial element in such emergent dynamics in that they trigger the extent to which external knowledge can be circulated, accessed and eventually internalized at the system level.

This has major implications for innovation systems. Innovation systems as well are emergent phenomena according to the capacity of innovative actors to distribute, access and recombine complementary portions of knowledge within a given economic space. In this context, firms are facing an increase in the complexity of the interactions and connections necessary to effectively exploit knowledge externalities and integrate knowledge sourced externally. Innovation systems able to coordinate such a complex net of interconnections among various actors will also successfully internalise knowledge externalities at the system level. Innovation systems can be based upon different combinations of knowledge interactions and knowledge transactions according to the kind of knowledge they are using and producing. Knowledge transactions can prevail when knowledge can be more easily appropriated and traded, in both embodied and disembodied forms, through patents and contracts, and innovation systems take the form of modular networks and markets for knowledge. At the opposite, innovation systems are centred around knowledge interactions when collaborations goes beyond arms' length transactions and spot contracts but instead involved long term agreements, quasi-integration between users and producers, and processes of co-design, like in clusters and districts. In between, the implementation of organizational innovations developing articulated and hierarchical networks that combine both knowledge transactions and knowledge interactions is becoming an increasingly diffused mode of coordinating knowledge generation and distribution. In these types of networks, leading firms dynamically select the members of the systems with the dual aim of exploiting knowledge complementarities and preserving network cohesion and common goals.

This analysis is relevant from the viewpoint of both the strategic management of innovation and the innovation policy. At the strategic level, both the active selection of the members of the network and their structured coordination should become a major goal for the management of innovation systems in that they enable to overcome the limits of the spontaneous coordination of innovative efforts within networks. Moreover, firms willing to assume a leading role within innovation systems should be able to combine at the same time: i) the scope of knowledge complementarities, avoiding redundancies of technological capabilities; and ii) the response to common goals, avoiding excessive dispersion of resources.

From the innovation policy viewpoint, hierarchical networks such as platforms, open alliances and coalitions should be key elements of regional, national and transnational innovation systems. More specifically, the idea of building a European research and innovation area such as the one depicted in the agenda of Horizon 2020 emphasizes connections and relations as drivers for fostering innovative performances and growth at the European level. Innovation platforms, open alliances and coalitions should be considered as valued policy tools to implement such connections and developed a European innovation system, and should deserve appropriate diffusion.

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