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COMPLEXITY AND THE COORDINATION OF TECHNOLOGICAL KNOWLEDGE: THE CASE OF INNOVATION PLATFORMS*

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1. Introduction

The chapter integrates insights from complexity theory into the economics of technological knowledge in order to reflect systematically on the variety of forms and processes that underpin knowledge production, dissemination and coordination. In so doing the chapter brings together two complementary bodies of scholarly research: the analysis of multiple interactions occurring within network-type structures which is typical of the literature on complex dynamic systems; on the other hand the study of learning processes as intentional, mindful and purposive behaviors set in motion by myopic agents, which is at heart of the economics of innovation. For what concerns the formalization of structured interactions and the emergence of networks we draw from complexity theory and emphasise the intentional nature of those interactions aimed at sourcing external

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knowledge and competences, and integrating them in the extant repertoires. In this view actors possess limited resources and knowledge, and their ability to innovate is contingent to the implementation of selective interactions by means of research, development and learning processes.

Complexity theories emerge in economics as a response to the need of understanding systematically the dynamics of innovation and technological knowledge taking place in increasingly dispersed contexts (see Antonelli, 2011, this book). This approach facilitates the appreciation of both structural and dynamic properties of evolving economic systems; the changing forms of interaction across actors are crucial for the evolution of the system at the aggregate level as much as the changing characteristics of individual actors at micro level. The network of interactions between agents is central to accessing and creating new knowledge, and in particular exploiting complementarities with other organizations embedded in the network. Innovative firms are therefore able to select and manage efficiently external linkages while implementing learning processes enabled by both external linkages and strategic investments in technological communication with other organizations.

These complex nets of interactions and the transformation that their structures undergo call for the purposeful coordination in order to reap the potential of knowledge creation and dissemination that is typical of diverse environments. The chapter focuses on innovation platforms, that is, systemic infrastructures for the organization and coordination of distributed innovation processes. Their recent emergence responds to the rationale of maximizing variety in the ecology of knowledge types while maintaining coherence by means of some degree of hierarchy. In platform-type of structures key nodes are crucial in determining at once the relative contribution of peripheral units as well as the performance of the whole system. There is growing evidence on the significance of innovation platforms in different sectoral contexts where innovation and the successful exploitation of new technological knowledge require integrating a variety of complementary competences.

To analyze this phenomenon the chapter taps onto two complementary bodies of scholarly research: the analysis of multiple interactions occurring within collective structures, which is typical of the literature on complex dynamic systems, and the study of learning processes as purposive behaviors set in motion by myopic agents, which stands at heart of the economics of innovation. More to the point, our study builds on the appreciation of three distinctive dynamic structural properties of innovation platforms: hierarchical causation; coordinated variety; and selective openness. The juxtaposition of these three, it is argued, shapes the structure of non-redundant connections that make up innovation platforms. The chapter is structured as follows. Section 1 introduces the basic conceptual framework; section 2 overviews the literature on complexity and its connection with innovation and technological change with various articulations in relation to intertwined organizational and cognitive dynamics. Section 3 introduces the concept of Innovation platform and the underpinning component processes. The last Section concludes and summarizes.

2. Background

Let us begin with a concise appreciation of the fact that the nature of the innovation process has changed over the last two decades.[1] Three of such changes deserve closer attention. The first is that products, services and processes have progressively drawn on wider ranges of constituent parts and, a fortiori, of knowledge bases. This phenomenon is ascribed to search for both cost reductions and differentiation as well as to increased availability of specialized components. The second type of change is the growing tendency of products, services and processes to be used in symbiotic fashion. The resulting trajectory is one in which products that were originally conceived as meeting different needs co-exist in a systemic context of use. Yet one more important change concerns the type of knowledge that best enables and facilitates innovation in such a fast-changing scenario. It is clear that combined together the first two points entail for individual firms the challenge to enlarge the range of capabilities while at the same time preserving internal coherence.

Summing up, as the technological complexity embedded in products and services increases and the contexts of use grow diverse while remaining symbiotic, other things being equal, the reliance of a firm on its own resources does necessarily diminish. These phenomena are widely discussed in the scholarly debate, especially in two areas of research. The first is the theory of complex systems, whose convergence towards social sciences has begun more than a decade ago under the pressure of economists who sought to understand the

[1] Of course to scholars of innovation and technological change such a statement is almost tautological since for years they insisted that innovation is an essentially dynamic phenomenon.

dynamics of collective processes. These approaches adopt as unit of analysis the interactions across the components rather than the individual parts; such interactions, in turn, define the criteria of access to as well as the rules that govern cooperation within collective environments. In the evolution of complex systems the aggregate and the individual dimensions are intertwined (Arthur et al, 1997; Foster, 2005). The corollary is that the architecture of such systems is not a datum but rather a dynamic, emergent property stemming from the coordination of a myriad individual characteristics and behaviours.

The economics of innovation is the second body of work that is most directly relevant to the phenomena discussed before. In a nutshell this area of scholarly research aims at understanding how wealth is created from human knowledge. The starting point is that economic agents are boundedly rational, and deal with innate uncertainty by building on experience and learning to develop skills and decision rules (Nelson and Winter, 1982; Loasby, 1998; Antonelli, 2008; Simon, 1962). Strong emphasis is placed in this context on the sources of human knowledge, on the procedures by which this is applied to solve specific problems, and on the effects that the latter bears on the context of application. A crucial point, different from other approaches to economic agency, is that these interactions are explicitly embedded in a context, that is to say, a time and a place. Accordingly the relevant metric for these processes is historical – as opposed to spatial (see O´Driscoll and Rizzo 1985) – time: the gist of economic actions is the development of cognitive processes and of associated choices along an irreversible time arrow.

This frame entails a view of human agency that is of development and not of mere allocation, and elucidates on the trait d´union between the two approaches. To bring the argument home, a staple of the economics of innovation is that as individual actors possess limited resources and knowledge, they necessarily need to search, develop and establish interactions in evolving environments. Moreover like complex systems theory, the economics of technological change focuses on non-deterministic, multi-level relationships which are necessary but not sufficient condition to organize successfully for innovation.

From the foregoing discussion it is clear that in dynamic environments characterized by recurrent changes in product characteristics and production technologies, the internal capabilities of individual firms hardly suffice. It is also clear that strategies for the governance of knowledge are critical for survival (Pavitt, 2002; Antonelli, 2008). To this end firms deepen specialization and establish connections to access and contribute to collective knowledge. New knowledge is facilitated by complementarities, rather than substitutability, between internal and external knowledge: the greater the scale of networking the more intense the internal know-how needed to understand, command and recombine external capabilities (Patrucco, 2008). On the basis of prospective costs associated to changes in their knowledge base, firms position themselves along a strategic spectrum whose extremes are either vertical integration or the market.

Notwithstanding the widespread significance of vertical disintegration, some forms of production and provision cannot be served efficiently by market mechanisms and managed through vertical disintegration and total outsourcing only. Hybrid solutions, like networks, are more appropriate when the design of inter-organizational relationships seeks to minimize costs due to external coordination, and to maximize the creative contribution of individual firms (Langlois, 1992). In turn, complex dynamic systems feature simultaneous availability of the outlined options and cyclical adaptation of strategic designs (Ethiraj and Levinthal, 2004). Put another way, decision-making in such contexts is driven by 'dynamic' coordination, that is, by generative interactions that facilitate changes in production, technologies, networks of suppliers, and in the modules of relevant knowledge (Lane and Maxfield, 1997; Loasby, 2002; Potts, 2001).

The paper illustrates the case of innovation platforms an emerging form of knowledge governance which has captured the attention of scholars and policy-makers alike in recent years.

2.1. Complex systems and the dynamics of knowledge

The theory of complexity is progressively emerging in the evolutionary economics of innovation as a new paradigm able to explain the structural and dynamic properties of knowledge generation and diffusion as well as the related emergence of innovation. Complexity theory is intrinsically both systemic and dynamic, and may be most useful in the understanding of the characteristics and processes of knowledge creation, diffusion, exploitation as well as the emergence and transformation of architectures for the coordination of knowledge through time (Antonelli, 2008).

In broad terms, complex economic systems can be defined as a set of heterogeneous actors that interact in order to create new knowledge as well as to organise and change their activities through time. However, a closer look at the properties of complex systems highlights a variety of intertwining elements within complex systems. First, actors within complex systems are heterogeneous in terms of the competencies and knowledge they possess; second and consequently, actors have access only to portions knowledge that are feasible through the cognitive map underpinning their search heuristics. In this sense they use limited cognitive resources and create new knowledge through trial and error and continuous revision of their behaviours. Third, interaction between heterogeneous actors is central to the effect of both creating and enabling access to knowledge. Moreover, these interactions occur in a local space defined by shared economic, social, technological, cognitive and geographical settings. Because of this, the behaviours of actors will likely feature some degree of inflexibility and stickiness in adapting and reacting to changes in the environment. In particular, the structure of the environment bounds such adaptation and reaction and in turn the conduct of actors is limited by irreversibility (Arthur et al 1997; Rosser, 1999).

Recent advances in the evolutionary school provide major contributions to integrate and improve such understanding. Evolutionary economists built upon Nelson and Winter's (1982) analysis by developing the idea that the features of economic change are biased by the behavior of actors with idiosyncratic competencies, especially with regard to innovative capabilities and technological skills. Each firm is distinct and unique with respect to the technological knowledge and the ability to introduce innovation. Therefore there is very limited interchangeability and substitutability, high complementarity and strong specialization and differentiation in the space of technological competencies.

Along this line, the integration of the analysis of the characteristics of knowledge and of the process of knowledge creation is a major step forward in the understanding of the dynamic properties of complex economic systems. When looked at through the lenses of the complexity perspective the infrastructures aimed at the creation and use of technological knowledge are characterized by 1) intrinsic and radical uncertainty, i.e. the mismatch between firms expectations, planned strategies and actual results (for instance because of failures in facing changes in consumers' needs through new products), and 2) non-decomposability, i.e. complex systems are irreducible systems, where the behavior and performance of a single actor may affect the behavior and performance of the entire system. Albeit agents are myopic and characterized by irreversibility in their choices and behaviors, they are also creative and can react to unplanned and unexpected interdependencies typical of complex environment. Imagination and creativity are required in order to introduce changes in the environment as well as for the environment itself to evolve. In turn, the changes and the evolution of both the system and the behaviors of agents can be understood only in historical time: complex systems are intrinsically dynamic. In a dynamic perspective, therefore, in such systems the behaviors of individual agents and the evolution of the environment shape each other because of the interaction between individual creativity and structural irreversibility. The dynamics of complex systems depends upon the interaction both between micro and macro elements, and between individual actors themselves (Antonelli, 2007; Arthur, 2007; Foster, 1993 and 2005; Hanusch and Pyka, 2007; Lane and Maxfield, 2005; Loasby, 2002).

Complex economic systems are characterized by non-ergodicity, social interactions, phase transition and emergent properties. Non-ergodic path dependency applies when a little shock at one point in time, and not necessarily at the onset of the process, affects the long run dynamics of a system. Phase transitions consist in qualitative changes that can be determined by small changes in the parameters of the system. Emergent properties are properties of a system that apply at a specific level of aggregation of a system. In the theory of complexity, feedback and interactions play a key role in assessing the conduct of agents and specifically the chances of changing their behavior[2] (Durlauf, 2005).

Most importantly, complex dynamic systems are distinguished by processes of true transformation (rather than mere transition), where the changes in the system affect both the properties of the architecture of the system and the properties of its entities, namely firms and organizations. The dynamics of complex systems are based on evolutionary processes that are not driven by variety and selection (as traditionally in evolutionary thinking) but by differentiation of the activities of actors and the changes in the institutions the coordinate the division of labor among those actors. In other words, two kinds of

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[2] Complex systems are characterized by phase transition precisely because, in a non-decomposable system, a shock occurring to a single actor, for instance a firm unable to face the structural uncertainty of changing market conditions, has effects that dramatically impinge on the behavior of the interdependent actors. The innovation we eventually observe is exactly an emergent property of the creative reaction of the system of interactive firms to the shock and the changes in the performance of the system itself.

differentiation are at works here: 1) differentiation in the functional and technological specialization of firms; 2) differentiation in the architecture of the system. These transform the relationships between actors, in turn transforming the architecture of the system, i.e. the structure of interactions between actors. The two processes clearly co-evolve by means of the feedbacks between the behaviors of actors and the architecture of the system in which firms are embedded. Such a co-evolution qualifies the openness of the system and the coordinating architecture (Lane et al, 2009; Metcalfe, 2007).

The structural and dynamic characteristics of complex systems involve the integration of different and complementary elements and components, which in turn reflect different and complementary spaces of technological competencies. Individual actors put in place connections in order to access and generate new knowledge, and thus to react to cognitive and structural boundaries and the changes that have occurred in the environment. Learning takes place in myopic, i.e. characterized by limited and specific knowledge, but creative firms and this learning underpins the generation of new knowledge. The process of creation of new knowledge relies upon the complementarity between internal and external portions of knowledge (Patrucco, 2009). The larger the adoption of networking as a means to access and use external knowledge modules, the larger the complementary internal know-how required by the firm to be able to understand, command and recombine this modules of external knowledge. Increasing returns in the generation of new knowledge build upon the exploitation of complementarities between internal and external knowledge and the implementation of a collective pool of knowledge and competencies through interactions (Patrucco, 2008). In turn, creative firms benefiting from complementary modules of knowledge are able not only to introduce new knowledge but also to change the structure of their connections and the architecture of the network in which they are embedded, eventually modifying the processes and mechanisms of coordination.

In this respect, interactive learning from external sources provides new ideas able either to improve existing technologies or to be the basis for the development of brand new ones. Knowledge creation is not only a collective process, i.e. depending upon the contribution of different and complementary actors, but also a recombinant, cumulative and path-dependent one (Weitzman, 1996 and 1998). The creation of new knowledge is seen as building upon itself through the new recombination of existing ideas. Such recombination is clearly affected by both the structural characteristics of the network in which it takes place and the historical sequence of previous combinations of ideas.

Focusing on the organization of knowledge interactions, rather than merely on the structure of their net is a crucial analytical shift in order to grasp the causes and the consequences of the changing structure, composition and coordination of the system in which actors interplay (see Antonelli, 2011, this book). The network of interactions between agents is the central mechanism through which they can access and create new knowledge, exploiting complementarities. Changes in the organization and structure of such network, introduced by myopic but creative agents as a response to modification in their environment, induce changes in the institutions of coordination of complementary activities and competencies. The feedbacks between micro behaviors and the structural boundaries of the system in turn shape the evolution of the system itself (Arthur, 2009).

Economic complexity is an emerging phenomenon that is the outcome of a continuously transforming process of interaction between firms, each of which is characterized by different capabilities and placed in different technological domain. The notion of the coordination of knowledge is central in this context, in order to understand in which way complex systems evolve and the dynamics of knowledge creation and change take place. Knowledge coordination occurs through the generative structure of interactions between actors and the changes in such networks operated by bounded but creative actors (Lane and Maxfield, 1997).

The notion of coalitions for innovation has been recently outlined (Antonelli, 2010) precisely to shift attention to the role that the coordination of inter-organizational linkages has on the implementation of effective innovation as well as the generation of new productive and technological knowledge. When innovation and knowledge are collective features of the interactions between different actors, effective coalitions for innovation align the heterogeneous capabilities of the partners embedded in the network and achieve the mutual directedness of their strategic interactions in order to guarantee the cohesion and the coordination of the complex net of interactions that characterizes the innovation process, as well as to cope with the structural uncertainty of the innovation process through some degree of hierarchical authority and power centrality in the network.

Next sub-section is dedicated to frame the analysis of the different modes through which economic actors can organize and govern technological knowledge. This should pave the way for introducing and articulating the concept of "innovation platforms" in section 3.

2.2. Governing technological knowledge: integration, modularity and networking

The analysis of the organization of innovative activities and the management of knowledge generation and diffusion in complex systems has been at the centre of an intense and rich debate between scholars arguing how technological knowledge can be successfully coordinated and which is the more effective organizational form through which firms can acquire and manage their innovative and productive capabilities in particular. As it is well known, three type of organization received attention in the literature: the vertically integrated firm, the market-based and modular organization, and the hybrids such as networks and collaborative ventures.

The role of managerial authority, command and hierarchy has been central through almost the entire XX century and different authors argued that the vertically integrated firm is a superior solution either because of scale, scope and learning economies in R&D (Penrose, 1957, Chandler, 1977) or because, as David Teece (1984) argued, it is more efficient in managing radical (or "systemic", to use his words) innovation. According to the definition introduced by Teece (1984), a new product or technology that requires changes in different and connected elements of the system in which it will be placed, can be defined as a systemic innovation – in contrast to "autonomous" innovations that easily fit into the system already existing without calling for consequent, diffused and simultaneous changes elsewhere in the system. Following this work, in the literature about the organization and management of innovation, it has been often presumed that the more radical or "systemic", is innovation, the more appropriate and efficient is vertical integration and the coordination of the change within a single organization.

However, more recently innovation scholars rediscovered the seminal work of Herbert Simon (Simon, 1962 and 2002) on modularity and shift their attention to the wide range of decentralized and "market-based" or "virtual" (e.g., Chesbrough and Teece, 1996) organizations opened up by the vanishing out of large firms (Langlois, 2002 and 2003). Herbert Simon, through his frequently-cited example of Tempus and Hora (Simon, 1962, p. 470) defined the notion of near-decomposability and claimed that a complex system is composed by different modules – or sub-systems – in such a way that interactions between sub-systems are much weaker than interactions within sub-systems (i.e., between elements of the same sub-systems). Modules are almost independent of one another and changes occurring in one element of the system do not affect either the other elements or the overall structure of the system[3].

Elaborating upon Simon's perspective, in recent years the economics and managerial literature on modularity distilled and addressed the benefits that make

[3] This is what Herbert Simon defined as a loosely coupled structure.

modular organizational structures and contracts-based relations between buyer and suppliers more suitable than vertical integration (e.g., Sanchez and Mahoney, 1996; Arora, Gambardella and Rullani, 1998; Ethiraj and Levinthal, 2004; Langlois and Garzarelli, 2008). In particular, Baldwin and Clark (1997) and Langlois (2002), view the organization of production and innovation through modular strategies as the more efficient way the to manage extremely complex and otherwise troublesome organizations and technologies.

When systems grow extensively and the interconnections between the different elements and sub-systems become so numerous, their coordination under an integrated structure is almost unfeasible. In such circumstances, firms can switch from integrated to modular strategies for acquiring and coordinating their productive and innovative capabilities, in relation to the changing characteristics of the technologies and the competencies they build upon in order to introduce novelty (e.g., Chesbrough and Teece, 1996). The more interconnected and articulated are the knowledge bases and technologies necessary to innovate – i.e., according to the view of Herbert Simon, the more complex is the system – the more advantageous is the adoption of a modular organization and the use of formal contracts and market transactions.

However, various contributions highlighted that the literature on modular and contract-based organizations underestimates the important effects that interdependencies between firms (e.g., Kogut and Zander, 1996; Stacey, 1995), as well as inertia (Brusoni and Prencipe, 2001) and high switching costs (Gilson, Sabel and Scott, 2009) have on the coordination of knowledge.

In this respect, innovation scholars are reaching increasing consensus about the fact that inter-firm ties exploit resource heterogeneity and reduce the disadvantages of accessing dispersed and diverse sources of knowledge, enabling therefore new knowledge creation, by combining the flexibility of markets with the visible hand of organization (Powell, 1990; Kogut and Zander, 1992; Powell, Koput and Smith-Doerr, 1996; Uzzi, 1997; Burt, 2000; Kogut, 2000; Ahuja, 2000).

Contributions have paid attention to the qualitative structure of the network and the role played by individual actors, thus identifying different network structures and their relative advantages. In particular, two configurations have been contrasted in the literature: networks characterized by what Coleman (1990) described as structures with strong and redundant ties have been opposed to Burt's (1992) "structural holes" and structures characterized by weak and non-redundant ties[4].

Brusoni and Prencipe (2001) elaborated upon the contrasting evidence about which kind of network is better equipped to organize the accumulation and acquisition of knowledge, and with a special emphasis on complex environments, revisited the notion of loosely coupled networks (Orton and Weick, 1990).

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[4] The purpose of the paper is not to describe and compare the advantages and disadvantages of the different structure. However, for the sake of clarity, Burt (1992) argues that networks with weak links and structural holes - i.e. brokers that arbitrate and flow knowledge between firms and groups of firms that are not tied each other – are more efficient organizational forms and benefits from a kind of hierarchical structure. On the contrary, Coleman (1990) and Uzzi (1997 and 1999), suggest that dense and redundant networks have a clear advantage when firms need to exchange and communicate complex knowledge because they promote trust-based relations and support more effectively cooperative behaviours, since support repeated exchanges and a balanced distribution of power in the network.

Orton and Weick (1990) describe structure of inter-firm networks according to the degree of responsiveness and distinctiveness networks show. They define distinctiveness, as the ability to command and produce a range of complementary technological competences in order to introduce novelty, while responsiveness is the active and intentional management of inter-firms relations to provide the network with cohesion, and to coordinate different sources of learning. "If there is neither responsiveness nor distinctiveness, the system is not really a system and it can be defined as a non-coupled system. If there is responsiveness without distinctiveness, the system is tightly coupled. If there is distinctiveness without responsiveness, the system is decoupled. If there is both distinctiveness and responsiveness, the system is loosely coupled" (Orton and Weick, 1990, p. 205, quoted in Brusoni and Prencipe, 2001, p. 1026).

We argue that innovation platforms share some of the properties of loosely coupled networks in that they combine elements of both modular and integrated systems, as well as of sparse and dense networks. Innovation platforms are characterized by structural holes, arbitrating through a hierarchy the interactions between organizations that are not directly connected. In this regard, for example, system integrators firms (Sturgeon, 2002; Prencipe, Davies and Hobday, 2003), that are well known in a number of sectors such as the automobile, software and PC, microelectronics, aviation industries are defined specific type of structural holes at the center of the recombinatorial flows of different bodies of technological knowledge in complex innovations. However, the increasing division of labour 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 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. Here, 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. 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.

The remainder of the chapter illustrates the case of innovation platforms as organizational forms aimed at the coordination of collective and distributed innovation activities. Because of the coordinating role played by central nodes, innovation platforms combine elements of hierarchical coordination and elements of decentralization of innovative and productive capabilities, based either on modular outsourcing and market transactions, and on collaborations. Let us focus now on their characteristics.

3. Innovation platforms: the building blocks

Innovation platforms are systemic infrastructures for the organisation and coordination of distributed innovation processes that feature high degrees of complexity. The creation of innovation platforms consists in the design and establishment of architectures for inter-organizational coordination (Sah and Stiglitz, 1986 and 1988): these define the levels of engagement of each peripheral units, the characteristics of the flows (i.e. unidirectional or bidirectional) of information and knowledge, and the extent of exchange across organizations.[5] The design of a platform determines *ex-ante* but evaluates (and eventually adapts) *ex-post* the creation and the use of knowledge (Garicano, 2000). Wheelwright and Clark (1992) first talked of platform products whose core design seeks to appeal a large customer base while its openness to marginal modifications attempts to captivate peripheral users with more specific needs. A few years later Kim and Kogut (1996) talked about platform technologies referring to models for the coordination of complementary components such as computers. Rochet and Tirole (2003) first ventured beyond the physical features of artifacts thinking of platforms

[5] The notion of innovation platforms elaborated here differs from that of technological platform. The latter accounts for ICT-based innovations like virtual networks, and the associated infrastructures, and interfaces and standards (Gawer and Cusumano, 2002). Technology platforms facilitate interoperability and coordination between different firms and technologies in the context of high-tech industries (see i.e. Consoli, 2005) as well as scientific clusters (Robinson, Rip and Mangematin, 2007). Innovation platforms are strategic organizational vehicles for coordinating specialised agents. ICTs and virtual networks are thus instrumental and yet subsidiary elements. Common to both technology and innovation platforms is the notion of directed and coordinated organization as opposed to 'spontaneous' organization typical of market processes.

as a design concept and giving them operational functioning with a clear articulation of how products and services stand in functional relation to a collective endeavour, and of the mediating role of leader organisations within such constructs.

The phenomenon of collective structures striving on the participation of multiple business entities is not new, and that platforms are certainly not the first instantiation. Modelling of networks has probably been the archetypal point of reference for this class of phenomena. Network economics approaches propose that increasing returns to scale are at the core of strategic coordination across competing firms (Pennings and Harianto, 1992; Economides, 1996). Networks have higher capacity to manage large-volume transactions compared to closed proprietary circuits, and given a large enough customer base the expected profitability of joining is high and the benefits outweigh the costs (Saloner and Shepard, 1995; Shy, 2001). A critical assumption underpinning this theory is that technologies, like the component organizations, are given and constant. This static view leaves important features out for the observed growth of variety in both the network participants as well as the kinds of interrelations across them (Consoli, 2008).

Innovation platforms differ in some crucial aspects from the above characterisation. In these structures a variety of agents participates 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. The point, though, is that such differences across agents matter to a great degree. In turn, the architectures in which they operate are flexible and can be configured in different ways for different uses, very much akin to computer platforms. A central component for the rationale underpinning platforms is maximising the variety of contributions stemming from a variegated knowledge base while maintaining coherence though a minimum level of hierarchy. As will be discussed further, innovation 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. At the core of the logic of a platform stand three powerful sources of increasing returns: economies of scale due to increased volumes of throughput; economies of scope due to lower costs of producing variations around the core product and services of the platform; and economies of system, that is, the creation of dedicated control procedures to improve utilization of the installed capacity. Another crucial characteristic of platforms is the functional relation in which services and manufacturing activities stand to one another (Suarez and Cusumano, 2009). The provision of some services, in fact, enables closer customer-producer interaction and opens up important feedback mechanisms useful to the effect of adapting the organisation of the platform, or some of its components, towards emerging features such as unmet customer needs, skill gaps, future product developments.

Relevant dynamics within platforms span technological and organisational levels, and bear upon both the static and the dynamic coordination of knowledge. From a static viewpoint, platforms connect and integrate activities and capabilities of relevant agents within an industry, thus supporting specialisation and favouring the accumulation of specific knowledge. From a dynamic viewpoint, platforms stimulate changes in both the structure of the network and the mechanisms for the governance of technological knowledge.

The phenomenon of innovation platforms stirs an intense debate across disciplines. Management scholars connect the latter to the challenges and the strategic implications associated to the emergence of open systems for production, exchange and govern competencies (Gerstein, 1992; Garud and Kuramaswamy, 1996; Ciborra, 1996; Ethiraj and Levinthal, 2004, Jacobides and Billinger, 2006). In the policy realm innovation platforms are looked at as a key reference model for the creation and management of mixed (i.e. public and private) coalitions (European Commission, 2004). In the context of innovation studies Antonelli (2006) argues that platforms are especially appropriate when technological knowledge exhibits levels of compositeness and cumulability that imply too high coordination costs for a single firm. Recent contributions by Baumol (2002) and Von Hippel (2005) further stress the incentives of knowledge-sharing for firms within a platform. Efficiency in knowledge creation, they observe, stems from both internal investments and external learning and is higher than if it relied exclusively on either internal creation (i.e. vertical integration of R&D) or external acquisition (i.e. outsourcing of R&D and design).

Innovation platforms underpin the development of physical technologies too. These integrate a variety of inputs from a range of industries and firms and include innovations such as Internet services, enhanced broadband fibre optics, Asynchronous Digital Subscriber Lines, and Universal Mobile Telecommunications System. As each allows the integration of a variety of content, services, technologies and applications, platform-based technologies are both composite and fungible (Fransman, 2002; Antonelli, 2006).

Let us now draw attention to some of the dynamic properties that characterise innovation platforms, namely: hierarchical causation; coordinated variety; and selective openness. The juxtaposition of these three, it will be further argued, gives way to the texture of connections that make up innovation platforms.

3.1. Hierarchical causation

What stimulates the emergence of collective structures such as innovation platforms? Let us, in answering this question, adopt a functional approach and argue that platforms are purposive responses to specific problems that no individual firm can solve in isolation. The general phenomenon is very common across most modern industries. Each firm possesses a knowledge base which is usually accumulated by blending information inputs, know-how and capabilities while searching for and developing innovative solutions (Nelson and Winter, 1982; Teece, 1986; Cohen and Levinthal, 1989). Industries with a complex knowledge base accelerate the obsolescence of firm-specific knowledge assets thus forcing them to either invest in human capital or sourcing knowledge externally. Each of these solutions however carries its own risk. On the one hand the adaptation of channels for the supply of up-to-date training depends on adjustments within and between complementary institutional domains (Vona and

Consoli, 2009). In practice, highly specialized knowledge is sticky and therefore unlikely to become available through training programs quickly enough, especially knowledge that is close to the frontier. On the other hand significant communication costs stand in the way of latent knowledge spillovers among firms. Such costs are affected by specific characteristics of the competitive environment in which firms operate (Patrucco, 2008). Either way, a firm under pressure needs to adopt effective governance mechanisms to overcome the barriers to creative reaction.

For example, in the auto industry in the Turin area, Fiat experienced strong competitive pressure and risked failure. As a reaction, Fiat adopted governance mechanisms to reconfigure the organization of internal as well as external competencies. In this new system, Fiat retained hierarchical control over the net of suppliers and partners.

The notion of hierarchical causation refers to the fact that the search for knowledge and the associated reorganization of activities are essentially problem-based processes. This carries important consequences. First, newly emerged problems reverberate from past decisions, not necessarily because of a mistake but simply because modified conditions make the current set of activities no longer adequate. In this fundamental sense firms´ knowledge accumulation and learning are path dependent, that is, they are at once directed but also limited by the current knowledge base. Secondly, and related to the former, knowledge growth is an essentially uncertain process. As a result the ability to calculate the outcomes of each individual's decisions as well as the strategies available to others is rather limited. Clearly the sources of complexity and the associated coordination challenges increase when individual actions are drawn together in collective structures like a platform. As Burt (2008) remarks, learning is not an optional attribute of collective structures: in dynamic environments where the scope of collaboration and the operative rules are liable to change, inclusion depends on the ability to remain relevant. That is to say, participation is contingent to learning and adaptation.

3.2. Coordinated variety

Innovation scholars advocate that the growth of knowledge is rarely, if ever, the outcome of isolated action but rather of collective learning and cumulative interactions. On the one hand, the development of tacit knowledge moulds individuals' responses and is a source for new ideas and solutions; on the other, codified and practical knowledge are crucial to facilitate exchange and interactions across individuals. Contrary to the common view that these dimensions are dichotomic, we stress their complementary aspects: new knowledge grows as a result of coordination across individual experiences and the development of shared understanding. At the same time, variety and heterogeneity are not sufficient to replenish the knowledge base and individual specialization is most effective when coordinated through formal and informal standards (Prahalad and Hamel, 1990; Langlois, 2002; Antonelli, 2008). The collective character of knowledge, in turn, elucidates on the importance of establishing sound governance mechanisms (Antonelli 2008). Previous literature sidestepped these points by assuming implicitly that agents learn and adapt swiftly to collective environments. If instead we focus on the juxtaposition of complementary dimensions such as individuals' knowledge bases, routines of communication across them and the criteria that define their collective scope, a great deal of effort is necessary to make these diverse pieces fit together. For, as Nelson (2003) remarks, all such dimensions evolve in a symbiotic, yet uneven, fashion.

The paradigm of the system of Electronic Funds Transfer at the Point of Sale (EFTPOS) in the UK banking industry is a good case in point. After the 1970s the basic rationale of innovation in banking was the replacement of the paper-based regime with automated transactions along the trajectory inspired by the Automated Cash Machines (Consoli, 2005). The EFTPOS concept embodied the grand ambition of implementing a unique system of peripherals which connected directly the point of sale, i.e. the retailer, with the terminals of the bank. This major step change in the management of retail payments was happening at a time when the largest clearing banks had already developed their own proprietary systems for the provision of other automated services. The philosophy underpinning EFTPOS was therefore twofold: increasing the current scale of the network for payments, and expanding the number of services available to customers. Such a purpose required a physical infrastructure of access points, nodes and terminals for the management of the information flow as well as the harmonization of diffuse interests across diverse parties such as financial institutions and retailers. The first step in this direction was the creation of an umbrella organization, EFTPOS Development, under which the major financial institutions were committed to collaborate for the definition of blueprints of the collective network. The initiative however stumbled upon lack of cooperation from its inception as the clearing banks, especially the largest, pursued the expansion of their proprietary schemes. This in turn led to a patchwork of processing systems, front-end terminals and card schemes which was inefficient for both customers and the banking firms. More cogently, individual proprietary schemes discouraged service diversification (Howells and Hine, 1993; Consoli, 2008).

Later in the decade, under the pressure to reduce wasteful dual standards British banks resorted to the collaborative plan in a different fashion, by handing the task of designing a common blueprint over to external organizations like LINK and BACS[6]. These two organizations brought coherence by establishing a semi-hierarchical structure in which proprietary infrastructures and end terminals adapt to a central scheme. Banking firms and retailers are therefore the peripherals of a standardized system whose goal is no longer maximizing traffic (e.g. economies of scale) but rather rationalizing it. In this new framework horizontal entry entails the involvement of previously unrelated organizations, for example supermarkets or specialized intermediaries like Paypal, which in turn stimulate the diversification of retail payment services. Similarly, information processing in the upstream market has evolved into a self-standing business through increasing recourse to outsourcing.

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[6] Bankers Automated Clearing Services Limited (BACS) manages electronic transfer of funds between banks. Since 2003 BACS has become the platform for processing telephone and internet banking payments in the UK. LINK is the network that connects 90% of ATMs in the UK's banking system.

This example illustrates the trade-offs involved in the pursuit of specialization when a large knowledge base is available (Kogut, 2000; Crémér, Garicano and Prat, 2007). In fact, such a trade-off defines the scope, the boundaries and the forms of inter-organizational relations within a platform. On the one hand specialization favours efficient communication within a narrow set of partners but limits both the scope for coordination and accessibility to innovative opportunities. On the other hand the coordination of a bundle of inter-firms and inter-organizations linkages opens up new opportunities but lowers the scope for specialization and the benefits of communication (see Kogut and Zander, 1992). The implementation of innovation platforms contributes to reduce the inefficiencies associated to these trade-offs.

3.3. Selective Openness

The problem based perspective outline so far bears another important consequence for the phenomenon of innovation platforms. Inclusion in collective structures for knowledge sharing does not diminish the uncertainty associated to competition in fast-changing contexts but rather changes the nature of such uncertainty. To be viable infrastructures like innovation platforms require on the one hand a degree of stability that confers coherence to shared goal and, on the other hand, room for further novelty. From this it follows that a necessary condition for the emergence of novelty is that a system maintains a degree of openness to be able to adapt to modified circumstances.

The key point is that the implementation of major technical changes generates new opportunities for learning but in so doing also leads to skill gaps or shortages. Empirical works such as those by Brynolfsson and Hitt (2000) and Bresnahan et al (2002) demonstrate that the large scale diffusion of Information and Communication Technologies (ICTs), often the backbone of innovation platforms, stimulates the emergence of new tasks and of wholly new occupations (Vona and Consoli, 2009). In turn, where matching skills come from and how long does it take to correct for the imbalances depends on the degree of openness of the platform. The case of UK banking is again suggestive in this sense. The growing role of informational and strategic systems entailed an unexpected demand for middle- and back-office technical skills as well as new high-level managerial skills, crucial for business development. In part this skill imbalance has been met by outsourcing of business processing. Such changes need not apply exclusively to physical technologies. The ability of the British National Health System (NHS) to support the development of innovative practices stemming from the front-line of health-care delivery has been a matter of debate for some time. The main culprit, it has been observed, was the lack of appropriate innovation management skills that would facilitate the translation of feedback from patient care into systematic (and systemic) innovation (Cooksey, 2006). The recent creation of the Institute for Innovation and Improvement aims at supporting the connection between basic research and clinical practice (UK Evaluation Forum, 2006), as well as supporting the diffusion of improvements in routine patient care beyond the source unit (Department of Health, 2003). The new organisational platform operates across nine geographical jurisdictions within the UK through local hubs which offer a broad variety of services such as training, technology audits and IP management, to name but a few (Consoli and Patrucco, 2008). By and large the activity of the hubs generate benefits that stretch beyond the life cycle of individual solutions, be they medical products or clinical services. In so doing they ensure a degree of openness towards the screening and the absorption of new skills and forms of knowledge.

As anticipated by Richardson (1972) and reiterated by many others when coordination between closely complementary activities and competencies is essential for the success of innovation firms rely upon a variety of inter-organizational arrangements – such as joint ventures, equity agreement, R&D partnerships, coalitions and consortia – to blend market- and contract-based and integral solutions, strong and weak relations, in order to acquire and coordinate the necessary productive and innovative knowledge. Complex and articulated governance forms emerge when the task is the coordination of knowledge sourced both internally and externally, and multisided learning.

Notions of "architectural knowledge" (Henderson and Clark, 1990), or "architectural capability" (Jacobides, 2006) have been recently put forward precisely to characterize the key ability, possessed by networks' leaders to coordinate and direct the working of increasingly complex organizations, and more precisely to combine and adapt elements of integration, such as authority, with elements of modularity, such as openness, in order to choose which elements and competencies are required to be included in the network.

In the car industry, for instance, this seems precisely to be the case of the design and development of Electric Vehicles (EVs), where large partnerships, often embedding public actors and new comers have been implemented with the scope of learning and acquiring selective technological and market competencies developed outside the car industry strictly considered, as the illustrative evidence of the cooperation between Betterplace and Renault clearly suggests (Aggeri, Elmquist and Pohl, 2009; Beaume and Midler, 2009). The introduction of electric vehicles (EVs) can be depicted as a collective innovation wherein different actors such as traditional OEMs, automobile batteries producers, utilities and system integrators contribute with complementary resources as well as technologies, and converge towards common goals and incentives. Evidence from Israeli and Danish experiences in the introduction of electric vehicles largely supports this view (see Beaume and Midler, 2009).

At the same time, some elements of managerial authority are still likely to characterize such models in that directedness is required in order to guarantee both cohesion within the network and the convergence of the complex system of goals, incentives and interactions that characterizes such an articulated innovation process (Enrietti and Patrucco, 2010). The entry of newcomers like Betterplace in the car industry as well as of car battery producers from the electronic sector that parallel the role of traditional carmakers, and emerge as new platforms' leaders, points in this direction: preliminary evidence on the implementation of EVs indicates that integration, coordination and direction of the different strategies and goals of various organizations that take part in the platform should be a central issue not only for the platform management (Gawer, 2009) but also for the design of innovation and industrial policies that support the formation of broad coalition for innovation in the car industry.

4. Concluding remarks and prospective research

This chapter proposed an integration between elements of the economics of innovation and of complexity theory. This exercise, it has been argued, opens up new interesting avenues for research on the organization of innovative and productive knowledge. In constructing this point we illustrated the empirical case of innovation platforms as emerging form of organization featuring common elements between the two research strands indicated above.

Building upon the pioneering analysis of Nelson and Winter (1982) scholars of innovation made much headway in elaborating a framework based on the analysis of purposeful yet limitedly rational agents; to overcome their intrinsic limitations these engage learning activities and in so doing develop idiosyncratic capabilities and moving goals. Each agent is distinct and unique in relation to the way in which technological knowledge is created and used and, a fortiori, in the ability to succeed. Consistent with the basic tenet of complexity theory interchangeability and substitutability is limited and the emergent patterns of specialization are likely to display significant variety. In such a framework the dynamic acquisition and coordination of new knowledge is the central issue (Teece, Pisano and Shuen, 1997; Winter, 2002).

The concept of coalitions for innovation (Antonelli, 2010) displays its interpretative power precisely in this context and in our opinion deserves to be further developed and understood in the future as a general form of hierarchical networks, among which innovation platforms are a specific manifestation. Coalitions emerge when the diverse incentives and capabilities of a variety of heterogeneous actors are organized so as to display a character of alignment and convergence. In facts, "only the convergence of a plurality of complementary actions aligned though sequential chains of user-producer relations can shape the actual direction and speed of the process. The architecture of coalitions plays a key role here" (Antonelli, 2010, p.515). The inclusion and exclusion of specific actors, characterized by idiosyncratic productive and innovative capabilities, as well as incentives, change the strategic behaviour of the coalition, its objective and the likely actions through which these can be achieved. The need for dynamic coordination, i.e. coordination at each point in time of the heterogeneous actors embedded in the network is clear, if the goal is to be the successful realization of a common innovation. In such a systemic context, dynamic coordination requires some forms of hierarchical organization and yet, for the complexity involved in the system, no single firm commands both the technological and managerial resources necessary to make such coordination effective technologically and efficiently in terms of the coordination costs. Some intermediate forms of organization are required and it is likely that the implementation of coalitions centered on key firms and their strategic action emerges as more appropriate than extreme solutions such as market exchange and vertical integration. Coalitions for innovation as hybrid organizational forms emerge precisely as the appropriate strategy in order to make possible bureaucratic organizations reacting to improvements in product or services by acquiring externally the know-how necessary to innovate.

In a context of distributed capabilities and knowledge often sourced externally, the challenge for individual firms is to enlarge the range of external capabilities that can be accessed and integrated with internal ones, while guaranteeing efficiency and cohesion in access and integration of external knowledge as well as the distinctiveness of capabilities. In this chapter, also through illustrative examples derived from a variety of technologies and industries, we put attention to the implementation of hierarchical networks that integrate the characteristics of distributed markets and directed organizations and qualify the innovation platform as a specific form of hierarchical networks appropriate to govern knowledge interactions and to face that challenge.

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