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Innovation and the evolution of industries

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Abstract The analysis of innovation and the evolution of industries has witnessed major progress in several areas. In the last years, several contributions at the empirical, appreciative, econometric and modelling levels have greatly advanced our understanding of innovation, industrial dynamics and the evolution of industries. This paper reviews these contributions. A discussion follows on four key challenges that are required for a better understanding of the relationship between innovation and the evolution of industries: the analyses of demand, knowledge, networks and coevolution.

Keywords Technological change · Market structure · Firm strategy · Market performance · Industry studies

JEL Classification O3 · L1 · L6

1 Introduction

The relationship between innovation and the evolution of industries is at the core of Schumpeter's work and is one of the major Schumpeterian legacies. It is a central theme in the Schumpeterian approach to economic dynamics, as well in evolutionary and neoclassical theories.

In this address, I will focus on the progress that has been made in the last years and on the challenges that lie ahead in understanding the relationship between innovation and the evolution of industries. In the first part of the paper, I will discuss the progress, while in the second I will focus on four big research challenges that I think lie ahead.

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2 Innovation and the evolution of industry: a key Schumpeterian theme

The relationship between innovation and industrial change has always been central in Schumpeter's work in various ways and specifications. In *The Theory of Economic Development* (Schumpeter 1934), *Business Cycles* (Schumpeter 1939), and *Capitalism Socialism and Democracy* (Schumpeter 1950), Schumpeter was very much interested in innovation either as a process of creative destruction or as a process of creative accumulation (as Keith Pavitt would call it). He placed innovation in the evolution of industries and within the process of economic transformation: for him, innovation was very closely linked to the emergence, growth and decline of industries, which historically marked the development of capitalism. In Schumpeter's work, one may identify several lines of research that have been developed in the following decades at the empirical or at the theoretical level: innovations as clustered historically in specific industries, industrial development and transformation as associated with the emergence and growth of different sectors, dynamic competition as the struggle between new firms that introduce new technologies and products, and incumbents that focus on existing technologies.

After Schumpeter's death, many of the central messages of Schumpeter regarding innovation, industrial development and dynamic competition were put at the margin of mainstream economic research. There was a shift of attention away from transformation and industrial dynamics towards the relationship between innovation and firm size, on the one hand, and innovation and market structure, on the other. The mainstream literature referred to this field of research as the test of the two Schumpeterian hypotheses. But this testing did not have much in common with the original spirit of Schumpeter's work on this issue. The research that emerged and prospered during the 1950s and 1960s had a static flavor, as one may find in the tradition of the Structure–Conduct–Performance Paradigm, and did not pay any attention to industry evolution and transformation. With the advent of game theory, the focus moved to firms' strategies in R–D and licensing. But also in this case, the original message of Schumpeter that had been focused on innovation, industry evolution and transformation got lost.

Since the late 1970s and the early 1980s, however, a new focus of empirical and theoretical research on innovation and the evolution of industries has emerged. Most of this research has developed the original message of Schumpeter on innovation, the evolution of industries and structural transformation in various directions. Of course, not all of this research fits in a truly Schumpeterian framework: indeed the conceptual and theoretical approaches of several of these contributions have been quite different and eclectic. Most of them, however, share two common elements: the recognition of the key role of innovation in economic processes, and the need to use a dynamic analysis.

3 The progress

The progress obtained in the analysis of innovation and the evolution of industries has been on several fronts. First of all, many case studies of innovation and industry evolution have been developed for several industries. The so-called "SPRU tradition" has greatly contributed to the recognition of the major differences that exist across different industries, technologies and countries in the relationship between innovation and the evolution of industries (Freeman 1974; Pavitt 1984).

Second, our appreciative understanding on several aspects of the relationship between innovation and the evolution of industries has greatly increased.

(a) Progress has been obtained in examining the extent and effects of heterogeneity of firms in terms of different knowledge, competences and learning processes. As Richard Nelson, Sidney Winter, Wesley Cohen, Dan Levinthal, Richard Langlois and Giovanni Dosi among others have shown, different agents know how to do different things in different ways. Here the contributions of evolutionary and of organizational theory have been great, by placing emphasis on cognitive aspects such as routines, beliefs, objectives and expectations, in turn affected by previous learning and experience and by the environment in which agents act. Relatedly, heterogeneity and its dynamics have been related to processes of variety generation and selection, which take place in various ways and forms during the evolution of an industry (Nelson 1995; Cohen and Levinthal 1989; Gavetti and Levinthal 2000; Levinthal 1993).

(b) There is now enormous evidence on the contributions of universities, public research organizations, the military, other public actors and financial organizations (such as venture capital) in the generation and diffusion of technological advance in industries. Their roles, however, has been shown to be quite different in different industries (Levin et al. 1987; Cohen et al. 2002).

(c) The role of different institutions—some of them national, other sectoral—has been recognized as relevant. The major point here is that innovative activities in industries are shaped by institutions, which include standards, regulations, norms, routines, common habits, established practices, rules, and so on (Edquist 1997).

(d) Industries have been interpreted as systems, in which actors are related and interact in various ways (formal as well as informal relationships, market and non market interactions, and so on) and are strongly influenced by their competences, learning processes, the knowledge base of sectors and the institutions. In this frame, the notion of sectoral systems of innovation (Malerba 2004) is a useful tool for examining innovation in a sector.

(e) Finally, we know that industries follow specific dynamics of innovation, firm entry and growth and market structure, as the industry life cycle tradition (Abernathy and Utterback 1978; Utterback 1994; Malerba and Orsenigo 1996) shows. We also know that these dynamic sequences are different from one industry to another (Klepper 1997).

Third, econometric work on innovation and industrial dynamics has tremendously progressed in the last thirty years. With the availability of advanced computer technology and new firm level data, econometric analyses have moved from cross sections work during the 1960s and 1970s to panel data and longitudinal analyses since the early 1990s. Great progress has been obtained in identifying, measuring and understanding stylized facts and statistical regularities, and the factors explaining them. This has begun to shed light also on the statistical properties of change in terms of industrial demography, entry and innovation, firm growth, stability of firm size distributions, and persistence in asymmetric firm performance (see the work by Audretsch 1995; Baldwin 1995; Geroski 1994; Bottazzi et al. 2002 among others). All this work has identified robust inter-industry differences in concentration, firm age distribution and the characteristics of innovations.

Fourth, at the modelling level, different strands have developed, in various ways and directions.

(a) At one extreme, one can find models of industry dynamics with rational actors and technological learning by incumbents or entrants or both, and the competitive process weeding out the heterogeneity in firm populations (see for example, Jovanovic 1982; Ericson and Pakes 1995), with not much consistency with some stylized facts such as inertial asymmetric performance, irrational entry processes and so on.
(b) In some models such as Sutton (1998), technological and demand related factors set bounds on industrial structures via no arbitrage conditions, entailing corresponding Nash equilibrium on industry specific entry processes. No attention, however, is paid to the learning processes of firms.
(c) The tradition of population ecology has modelled industrial dynamics as the growth and decline of various groups of firms, each of which with different characteristics (Carroll and Hannan 1999).
(d) More focused on the learning processes of firms and on the general features of industrial dynamics are the evolutionary models à la Nelson–Winter, which have boundedly rational actors, learning and processes of experimentation and imperfect trial and error. Selection processes take place on a heterogeneous population of firms (Nelson and Winter 1982; Dosi et al. 1995), These models have a destrategizing conjecture, in that differences in structures and processes of change are understood as independent from firm micro strategies (Winter et al. 2000).
(e) Then one can find formal models of industry life cycle, analyzing together product and process innovations; rate and type of entrants; selection; firm size and growth; market concentration and market niches (Klepper 1996, 2002; Klepper and Simons 2000). Here there are both a strong link between stylized facts, empirical analyses, econometric analysis and formal theory, and an explanation of different types of industry life cycles.
(f) More attention to the specificities and histories of various industries is paid by history friendly models, which fall into the evolutionary tradition (Malerba et al. 1999; Malerba and Orsenigo 2002). These models pay attention to the evidence and the specific dynamics of the evolution of industries, by modelling the appreciative explanations and historical events that have shaped it.
(g) Finally, progress has been made at a more macro level, by linking innovation and industry evolution to structural change and the changing sectoral composition of the economy, as one can see from the from the early work of Dahmen (1989), Kuznets (1965) and Pasinetti (1981) to the more recent ones by Metcalfe (1998), Dopfer et al. (2004), Dosi (2001), Saviotti (1996), and Montobbio (2002).

4 The challenges

The point to be made in this paper is that, while a lot of ground has been covered in understanding innovation, industrial dynamics and the industry life cycle from an empirical and a theoretical point of view, some key challenges still lie ahead if we want to understand fully the relationship between innovation and the evolution of industries. Some sketchy observations of how industries are structured and how they change over time provide us some questions and hints in this respect. In *telecommunication equipment and services*, a convergence of different technologies, demand and industries has taken place, with processes of knowledge integration. This convergence has been associated with the creation of a wide variety of different specialized and integrated actors, ranging from large equipment producers to new service firms. In this broad sector, innovation is very much affected by standards, the institutional setting and the processes of privatization and liberalization. *In machine tools,* the evolution of the industry has been related to an application-specific knowledge base and has been associated with firm specialization. Here, user-producer interaction, local networks of innovators and in-house experienced human capital are key factors for innovation. However, products are increasingly being modularized and standardized, and suppliers of components are increasingly involved in innovation. In *pharmaceuticals and biotechnology*, a wide variety of science and engineering fields are playing important roles in renewing the search space. Universities, venture capital and national health systems play a major role in the innovative process. Several are the relevant actors—large firms, small firms and new biotech firms (NBFs)—and an extensive division of labor through networks exists. NBFs have entered the sector, competing as well as cooperating with (or being bought up by) the established large pharmaceutical firms. In this sector, demand and institutions (such as regulation, IPR and national health systems) affect the innovation process. In *software,* a highly differentiated knowledge base in which the context of application is relevant has created several different and distinctive product groups. The role of large computer suppliers in developing integrated hardware and software systems has been displaced by many specialized software companies innovating either in package software or in customized software. User–producer interaction, global and local networks and highly mobile skilled human capital are present. The role of the university has become important in the open source domain. IPR, standards and standard setting alliances play a major role in innovation, diffusion and competition. The emergence of *new clusters* that span over several sectors, such as internet–software–telecom, biotechnology–pharmaceuticals, and new materials, is one of the most relevant current transformation processes in sectoral systems. Here, a great role is played by the integration and fusion of previously separated knowledge and technologies and by the new relations involving users, consumers, firms with different specializations and competences, and non-firm organizations grounded in previously separated sectors.

This description points to some additional and quite relevant dimensions of the relationship between innovation and industry evolution. During its evolution, an industry undergoes a process of transformation that involves knowledge, technologies, learning, the features and competences of actors, types of products and processes, and institutions. An industry also changes its structure, where the term “structure” here means not market structure, but rather the network of relationships (competitive and cooperative, market and non market, formal and informal) among actors that affect innovation and performance in an industry.

In this frame, innovation and industry evolution may be seen as:

– the outcome of learning processes by firms and by individuals;
– based on a specific knowledge base which characterizes the industry;
– the result of the competitive and cooperative, market and non market, formal and informal interactions of several actors with different knowledge and competences;
– taking place in specific institutional settings, some of which are national while other are specific to the sector;
– bringing change and transformation not only to products and processes, but also to the actors, links, institutions and knowledge itself.

This view of industries characterized by a specific knowledge base, by firms with different competences, knowledge, learning processes, networks of interactions and a variety of institutions bring to the forefront at least four challenges for research in the analysis of innovation and the evolution of industries: *demand, knowledge, networks and coevolution*. Let me examine these in detail in the following pages.

5 Demand

The first challenge that I want to explore regards the role of demand in the evolution of industries.

As a way of introduction, let me first disagree with the usual complaint that demand has not been studied in its relationships with innovation and industries in the last decades. In the literature, we have various empirical and theoretical strands, from the old debate regarding demand pull vs technology push (Schmookler 1966; Meyers and Marquis 1969 and the SPRU-SAPPHO project), to the analysis of demand, market structure and innovation (from Kamien and Schwartz 1975 to Sutton 1991, 1998), imperfect information among consumers, user initiated innovation (Von Hippel 1986) user–producer interaction (Lundvall 1988) and value networks (Christensen and Rosenbloom 1995). In particular, advertising, bandwagon and networks have been shown to be important factors in influencing the magnitude and orientation of inventive effort and the degree of industry concentration. The presence of submarkets plays a role in affecting the growth and size distribution of firms within an industry, as Klepper and Thompson (2002) show for the laser industry. Demand has been key with respect to the emergence of disruptive technologies, as Christensen (1997) has documented in the case of hard disk drives, earthmoving equipment, retail stores and moto controls. Here, the early development of disruptive technologies serves niche segments that value highly their non standard performance attributes. Further developments in the performance and attributes of the disruptive technologies lead to a level sufficient to satisfy mainstream customers. Finally, when demand and innovation are examined, one has to mention the whole literature on diffusion: all the major empirical advancements and theoretical models regarding diffusion are nothing but contributions regarding the demand of innovation. The same holds for the literature on competing technologies, which pays attention to externalities and increasing returns. In sum, rather than saying that demand has been disregarded by economic studies on innovation, it would be more correct to say that it has been the Schumpeterian tradition that for a long time has kept demand rather marginal, because it has emphasized the supply side. I have to add that Schumpeter himself might have been responsible for that, given his emphasis on the passivity of the consumer in the innovation process.

We also need to recognize that some ground has been covered at the empirical, appreciative and modelling levels of demand with respect to the evolution of industries. At the empirical level, the role of demand during specific stages of the evolution of an industry has been shown to be relevant. In semiconductors and computers, public procurement has been important for innovation in the early stages of industries (Malerba 1985). In computers experimental customers have been major actors in the emergent phase of the industry (Bresnahan and Malerba 1999; Bresnahan and Greenstein 2001). In information technology, user involvement has been key for the development and modification of standards. In pharmaceuticals, demand channelled through agencies, physicians and the health system has played a significant role in the diffusion of new drugs. In instrumentation (Von Hippel 1988) and machine tools, lead users have played a major role in innovation and in shaping both the supplier industry and the user industry.

However, we need to ask analytically in which ways demand affects innovation in specific industries. Standard economic analysis claims that demand provides incentives to innovation during industry evolution. This is indeed a correct statement. The size, growth, structure and composition of demand, differentiation and market segmentation affect innovation in various ways in different stages of the evolution of an industry. One could also add that, in terms of incentives, demand is not homogeneous: it is highly heterogeneous in terms of segments, types of firms (private vs public) and individual customers.

But there is the need to move from this correct claim and to explore new conceptual grounds, as Loasby (1999, 2001), Metcalfe (1998), Witt (2003), Saviotti (2001), Teubal (1979), and others have started to do. In this respect,

(a) Consumer behavior plays a major role in affecting innovation. Consumer behavior may include the presence of information asymmetries and imperfect information with respect to new markets and submarkets, as well as routines, inertia, and habits on the part of consumers.
(b) The knowledge and mental frameworks of consumers and users greatly affect innovation and performance. There is a "knowing that" and knowing how" on the part of consumers. There is also learning and knowledge growth in consumption, much of which is local. Consumers are characterized by routines similar to firms, and deliberative decisions interact with habits when consumers confront new opportunities or new products. However, producers and consumers should not be treated as completely symmetrical because of their different stress on standardization and variety (Langlois 2001; Devetag 1999; Aversi et al. 1999).
(c) Consumer competences play a major role in influencing innovation. One could mention the absorptive capabilities of users, or the role of lead users and

experimental users. In addition, the distribution of competencies among users greatly affects the dynamics of industries.

(d) An analysis of the role of demand framed in the perspective discussed above can be linked to some strong empirical evidence on specific industries. In some industries, users participate intensively in the innovation process. User involvement is more than simple participation in the innovation process. Involvement implies a psychological dimension and a behavioral dimension. It is quite relevant, for example, in participatory design, IT and standard settings. Here the relationship between knowledge and the mental frameworks of producers and of users plays a major role in innovation.

(e) In other industries, coinvention is quite relevant: innovation by sellers and complementary investments and innovation by buyers (in terms of new products, services, applications and investments in human capital). As Timothy Bresnahan and Cristiano Antonelli have shown for IT, coinvention involves the technology of the user as well as that of the supplier. User coinvention is particularly important in explaining technological change in IT applications (package software, semi-custom IT solutions, turn-key solutions). Coinvention pulls technological change in a variety of directions and ways. This means that, in IT, there is not "one" standard type of adoption. Rather, coinventions in IT and its applications represent developments in tightly coupled interconnected technologies (Bresnahan and Greenstein 2001; Antonelli 2003).

(f) In other industries, such as instrumentation as well as IT, lead users play a great role (Von Hippel 1988). Lead users face needs that will be general in a market place but face them months or years before the bulk of the marketplace encounters them. They are also positioned to benefit significantly by obtaining a solution to their needs (Urban and Von Hippel 1988). One has to recognize, however, that the contribution of lead users comes from knowledge related to their experience. Therefore, they have a major role in periods of stability of uses and applications, but they may be less relevant when radical change or instability affects demand.

(g) Finally, in some sectors, as in software (open source software), community of practices are major sources of innovation and change. They act as facilitators of innovation, because members who innovate are able to share their ideas with other members, assist them and even obtain resources to develop their innovations. As Harhoff et al. (2003) show, for innovators it might be beneficial to reveal information inside a community because they may induce improvements by others; be helped in achieving a standard; face low rivalry conditions; and expect reciprocity. Franke and Shah (2003) adds to these four reasons a fifth: the fun and enjoyment that arise through engagement in the task and community. Historically, a similar process can be found in other sectors: for example in machinery (see the case of the development of the Cornish steam engine during the British industrial revolution discussed by Nuvolari 2004).

Such a variety of roles in so many different industries calls for the need to examine systematically consumers and users in different industrial settings, as well as to develop taxonomies of the different role of demand in innovation in industries.

At the modelling level, the challenge is to examine theoretically some of the processes presented above. Broadly, one would like to model the links between demand dynamics, firm dynamics and technology dynamics. In fact, on the one hand, the emergence and development of new technologies create new markets, submarkets and niches. On the other, the dynamics of demand in terms of consumer learning may stimulate technological change and the entry of new firms. This is indeed a challenging task.

In this perspective, one interesting model by Adner and Levinthal (2001) examines the way in which demand in terms of performance thresholds, types of preferences, changing utility and differences across market segments interacts with technological change to guide the evolution of technology and competition during the life cycle of an industry. Adner and Levinthal (2001) model a coevolutionay process in which there is a demand life cycle: early on product innovation increases performance, but then (to the extent to which some performance thresholds are met) process innovation takes over. Later on, a new phase starts in which firms, given a certain willingness to pay by demand, focus again on performance increases and product innovation. In a sense, mature consumers may demand performance, but their appreciation for performance improvements is not reflected in their willingness to pay for the improved product. In addition, demand is also modelled in terms of different market segments. In this was, Adner (2003) shows that technology disruption à la Christensen may be the result of the interplay between the preference overlap of different market segments and preference symmetry. This is a very interesting avenue of research because it takes into account the demand life cycle and demand segments. However, in these models, demand is still static in its basic structure. In fact, thresholds, preferences and decreasing marginal utility are fixed. In reality, contrary to the model, the value consumers derive from performance improvements can change in response to changes in the environment in which products are used (changes in complements and changes in standards and regulations) or to marketing techniques.

With another methodology, similar issues are tackled by models of industry evolution in a "history friendly" fashion (Malerba et al. 2003). Here, various types of customers are present: "standard" customers attracted by established products and guided by product characteristics such as price and performance; experimental customers who crave new technologies in existing products; consumers in new demand segments who look for completely new products. This history-friendly model is inspired by the case of the computer industry, in which experimental users and new demand have played a major role in affecting innovation, competition among technologies and the dynamics of market structure. Here the successful introduction of a radically new technology in an industry, in which a dominant design and a small collection of dominant firms are present, may be dependent upon a group of experimental customers, who are willing to experiment and buy the new products related to new technology. This allows new firms with the new technology to stay around long enough to be viable. A similar dynamics is played by potential customers with different preferences, when potential markets are not served by incumbent firms. Both cases of demand permit new technologies effectively to grow, either within established firms or through new firms. This can have a profound, long-run effect on industry structure. Within this framework, it is also possible to model a convergence among different demand segments and its effects on market structure.

The discussion on modelling brings the coupled dynamics of demand and technology into the forefront of the analysis of industry evolution. In this frame, the interaction between producers and users changes the capabilities and preferences of both producers and users, and sets in motion a coevolution of technology, knowledge, market structure and innovation. Some of these processes have started to be tackled at the conceptual and appreciative levels, by examining learning and specialization in consumption and the increasing variety of goods and services offered in the market (Witt 2001; Saviotti 2001). These processes are indeed evolutionary in the sense that they imply learning, routinized behavior and selection (Metcalfe 2001).

One of the most evident examples of coevolution is coinvention. As Bresnahan and Greenstein (2001) show for IT, coinventions generate new trajectories of improvements in the original technology, new organizational change and new institutions, which in turn generate new coinventions between users and suppliers. For example, the rise in demand for the world wide web has set in motion entirely new waves of coinventions, with new application developments, new business models and new institutions, which in turn feed back on demand, changing it in various ways and so on.

In conclusion, the progress in understanding the relationship between demand, innovation and industry evolution calls for new challenges in terms of richer and more detailed empirical analyses, deeper appreciative understanding and formal modelling. They have to include feedbacks, coevolution and processes of specialization in consumption, proliferation of niches and convergence in demand.

6 Knowledge

A different reasoning could be employed for the second challenge: knowledge. Here we face one of the key building blocks of the evolutionary approach: the key role of knowledge and learning by agents in innovation. The work done on knowledge by Richard Nelson, Paul David, Stan Metcalfe, Sidney Winter, Brian Loasby, Giovanni Dosi, Bengt Ake Lundvall and Dominique Foray, among others, in the last twenty years has greatly enriched our understanding of what knowledge is and of its role, properties and relevant dimensions in innovation and change. In particular, the evolutionary literature has proposed that sectors and technologies differ greatly in terms of the knowledge base and learning processes related to innovation. In some sectors, science is the force driving knowledge growth, while in others, learning by doing and cumulativeness of advancements are the major forces. We also know that knowledge differs across sectors in terms of sources (firms, universities, and so on), domains (i.e. the specific scientific and technological fields at the base of innovative activities in a sector), and applications (Cowan et al. 2000). Knowledge has also different degrees of accessibility (i.e. opportunities of gaining knowledge that are external to firms and may be internal or external to the sector) with major consequences on entry and concentration, and may be more or less cumulative (i.e. the degree by which the generation of new knowledge builds upon current knowledge). In addition, knowledge may flow more or less intentionally across individuals and organizations, as the huge literature on knowledge spillovers (see for example Jaffe et al. 2000) and the work on knowledge and mobility of inventors shows (Kogut 2000; Balconi et al. 2004; Breschi and Lissoni 2004).

Given this progress, the challenge here is to move from the broad identification of the main characteristics and effects of knowledge across sectors to a detailed understanding of the specific type and structure of knowledge, of its various effects on innovation and the organization of innovative activities, and on the two-way relationship between knowledge evolution and industry evolution in different sectors.

In this respect, several issues emerge clearly. First, finer grained dimensions of knowledge (such as the ones mentioned for example in Winter 1987) and links and complementarities have to be taken into account (Malerba 1992). Links and complementarities may refer to scientific, technological or application knowledge. These complementarities are often a major source of increasing returns. Related major areas of inquiry include knowledge transmission, flows and spillovers within industries and across industries, the coordination and integration of knowledge, and the relevance of modularity of knowledge, as in the work by Loasby (1999, 2001), Foray (2004), and Brusoni et al. (2001).

This calls also for the use of appropriate indicators of knowledge, knowledge flows and knowledge structure. Patents and patent citations are one indicator, and have been used to describe knowledge flows among people, organizations and sectors. Patent citations represent indeed relational data, and identify a paper trail left by the knowledge flowing from the inventor/applicant of the cited document to the inventor/applicant to the citing one. But criticism may be advanced for the use of patent citations as an exact measure of interpersonal or interorganizational knowledge flows. In fact, often the flow comes from the patent examiner rather than the inventor. When the inventor cites a patent, it is not necessarily the case that there is an interpersonal knowledge flow (but more simply the inventor may retrieve information on the cited patent directly from a database). However, I remain convinced of the importance of patent citations in providing some evidence of a paper trail about knowledge links, and in describing some features of knowledge and knowledge networks of an industry, as flows of knowledge can be captured by patent citations even when inventors are unaware of those citations. The analyses by Jaffe and Trajtenberg (2002) and by Thompson and Fox-Kean (2005) show that patent citations are a noisy signal of the presence of spillovers, and that aggregate citations flows can be used as a proxy for knowledge spillover intensity. In any case, the use of patent citations in order to examine knowledge flows and networks is a very fruitful research direction, provided that one is aware of their limitations and uses them jointly with other qualitative and quantitative indicators.

Second, a deeper understanding of the effects of the type of knowledge on the organization of innovative activities and the relationships among firms in various sectors is required. This may be accomplished in various ways. One is to link one specific dimension of knowledge with the organization of knowledge production. For example, one could link codified knowledge, the specialization in knowledge production and the division of innovative labor, as Arora et al. (2001) do. Another is to link the leaning and knowledge environment to the patterns of innovative activities in a sector. The identification of some key properties of knowledge such as accessibility, opportunity and cumulativeness can be related to the notion of technological and learning regimes (dating back to Nelson and Winter 1982), providing a description of the knowledge environment in which firms operate. Malerba and Orsenigo (1995, 1997) have proposed that a technological regime is composed by opportunity and appropriability conditions, degrees of cumulativeness of technological knowledge and characteristics of the relevant knowledge base. Then one could advance and test empirically some general propositions on the relationship between technological regimes and patterns of innovation in industries, related to a fundamental distinction between the Schumpeter Mark I and the Schumpeter Mark II models—the first is characterized by "creative destruction" with technological ease of entry and a major role played by entrepreneurs and new firms in innovative activities, the second by "creative accumulation" with the prevalence of a stable core of few large firms and the presence of relevant barriers to entry for new innovators (Breschi et al. 2000). Although rather archetypical, these analyses show that knowledge and learning regimes indeed affect the way innovative activities take place in industries (Marsili and Verspagen 2002). Finally, one could go into much more depth and relate the structure of knowledge in a sector to the type of actors and their relationships. As an example, let me mention here the work that Orsenigo et al. (1997) have done in pharmaceuticals and biotechnology. They have found that there is an isomorphism between the cognitive structure underlying the dynamics of knowledge and the structure of the network. The impact of science has been the proliferation of more specialized and new hypotheses that have generated new subdisciplines, requiring new sets of search techniques, testing procedures and skills. Over time, entrants tend to be more specialized in terms of the scientific hypotheses they are trying to test and the search techniques they are employing. The intrinsic characteristics of the search techniques and the patterns of learning in pharmaceutical R–D explain simultaneously why the network expands over time, why it remains relatively stable in its core-periphery profile and why entrants make agreements with incumbents or older NBF, rather than with firms of the same generation.

A third issue refers to the boundaries of knowledge in an industry and their effects on innovation and industry evolution. A focus on boundaries means highlighting all the interdependencies and complementarities outside the industry in related sectors or scientific fields. Think for example of multimedia, in which the convergence of different types of technologies and demand has originated a new sector with continuously expanding knowledge boundaries. A focus on boundaries also means that there are some bounds to knowledge growth which are related to the specificity of the technologies and the sector. This is in the notion of technological regimes discussed above, and is present in the evolutionary literature and, from a different perspective, also in the notion of bounds, as seen in the work of Sutton (1998). If we take this view of knowledge, the specificities of technological regimes and the knowledge base of an industry provide a powerful restriction on the patterns of firms' learning, competencies, behavior and organization of innovative and production activities. In general, a given knowledge base, technological environment or demand defines the nature of the problems firms have to solve in their innovative and production activities and the types of incentives and constraints to particular behavior and organizations. Within these constraints, however, great and persistent heterogeneity in firm innovative and productive behavior and organization is possible.

One last issue concerns the processes of change in knowledge and the knowledge base during the evolution of an industry. This goes to the heart of the evolution of industries and of the factors affecting the changes in industrial structure. This is a very difficult task to accomplish, even for a single case study, let alone the identification of regularities and laws of knowledge change in sectors.

7 Networks

Let me move to the next challenge: networks. This challenge starts from the recognition that innovation and industry evolution are highly affected by the interaction of heterogeneous actors with different knowledge, competences and specialization, with relationships that may range from competitive to cooperative, from formal to informal, from market to non-market.

Recently, the literature on networks among economic actors has boomed, and networks have been studied in a variety of ways. Tremendous progress has been made on various fronts by social networks analysis. Major developments have been achieved in the organizational and strategic studies of networks, the examination of the specific role and strategy of actors within networks, the analysis of firms and industries as networks, and the approach of social embeddedness. In a similar vein, great progress has been obtained in modelling networks in various ways. One may go from static models regarding the effects of different network architectures on performance, to dynamics of networks (in which the structure influences individual actions and performance and attention is paid to the efficiency and stability of networks and the feedback mechanisms), to network evolution in which the focus is on processes and rules. Similarly, the types of models are quite different, from small world models, to evolutionary game theory, percolation theory, neural networks and so on.

Within this burgeoning interest on networks, one major area of research has been that related to networks and innovation in an evolutionary perspective and with a system view. The innovation system literature has put the role of links and relationships among various actors at the center of the analysis (see Lundvall 1993; Edquist 1997; Teubal et al. 1991). In a similar vein, evolutionary theory has stressed that, in uncertain and changing environments, networks emerge because agents are different, thus integrating complementarities in knowledge, capabilities and specialization (see Nelson 1995). Along these lines, progress has been made in the analysis of the characteristics and structure of networks in several industries: biotechnology (Powell et al. 1996; Arora and Gambardella 1998; McKelvey et al. 2004; Orsenigo et al. 2001; Nesta and Mangematin 2002); ICT (Saxenian 1994; Langlois and Robertson 1995); automobiles (Dyer 1996); aircraft (Bonaccorsi and Giuri 2001); flight simulation (Rosenkopt and Tushman 1998); steel (Rowley et al. 2000); semiconductors (Stuart 1998).

Progress has been obtained by the recognition that the emergence of certain types of networks is a function of specific knowledge, industrial settings, demand and institutions, and their evolution is the result of the interplay between firms' internal capabilities and technological, social and institutional factors (Kogut

2000). Therefore, the types and structures of relationships and networks differ from industry to industry. If we go along this line, it will be seen as relevant to develop taxonomies of network structures for groups of industries (as the useful one by Kogut 2000).[1]

However, the empirical enquiry on networks has to be accompanied by answers to some basic questions. What is a network for the purpose of the analysis of innovation and industry evolution? How might we define it in such a way that is understandable and useful for research on innovation and industry evolution? This was the question that Freeman (1991) posed some years ago and which has not been fully resolved yet. Freeman wrote about networks of innovators as driven by technological complementarities, and pointed to the relevance of formal as well as informal networks. Once the domain of a network is clarified for the purpose of the analysis of innovation and industrial dynamics, the identification of the relevant interactions among actors, the indicators of these interactions and the measures of their structure and evolution can be developed (avoiding accepting uncritically the measures of social network analysis, often created for another purpose of analysis).

A related issue is how and why the specific features and characteristics of networks affect innovation, profitability and growth in an industry. In this respect, we are still at the beginning of the research agenda. From exploratory empirical analyses it seems that strong ties favor exploitation and weak ties favor exploration (as it has been found in longitudinal analyses for the chemical, semiconductor and steel industries). But additional robust evidence and deep appreciative theorizing on this and other connected issues are needed.

And a final, broader question regards the role of networks in different stages of industry evolution, and the related coevolutionary processes. At the general level, we know that networks show stability and change over the evolution of an industry, as longitudinal data for some industries show. Stable networks are often formed early in the industry life cycle. The evidence also shows that major industry specific events shape indeed the structure of networks (see for example Rosenkopf and Thusman 1998). Again, a lot of ground needs to be covered by moving from general statements to the analyses of specific network evolutions and coevolutionary processes. In this respect, the work by Lundgren (1995) on digital image processing and by Bonaccorsi and Giuri (2001) for aircraft are good examples of the coupled dynamics of networks and technology.

At the formal theoretical level, only few models explore the relationship between the dynamics of networks and the dynamics of industries. Among them, Cowan et al. (2004) show that, in industries in which tacit knowledge is relevant and technological opportunities are high, regular structures generate higher knowledge growth, while in industries in which knowledge is codified and technological opportunities are lower, communication without any structure performs better. Although very promising, this line of research is in its infancy, and needs to be developed further. For example, under which conditions early on in the life cycle of a sector do certain types of collaborations (for example to explore knowledge) emerge? And under what conditions in industry maturity do other

[1] Kogut relates the type of network to factors such as technology, resource bottleneck, competing and regulatory rules and strength of property rights, and does it for broad industries such as microprocessors, information technology, software operating systems, pharmaceuticals and biotechnology, automobile and financial markets.

types of collaborations (for example to exploit knowledge) gain in importance? Also, when and why at certain stages of industry evolution do large informal networks rather than formal ones become major sources of knowledge generation (see for example Pyka 2000). Finally, what is the relationship between different types of industry life cycles and different types of network dynamics?

These remarks bring us directly to the last point of the paper: the need to understand the coevolutionary processes that take place during industry evolution.

8 Coevolution

Coevolution goes to the very heart of the dynamic analysis of innovation and the evolution of industries, and more broadly addresses the issue of transformation and structural change. In a broad sense, coevolutionary processes involve knowledge, technology, actors, demand and institutions, and are often path-dependent (David 2000). Moreover, local learning, interactions among agents, and networks may generate increasing returns and irreversibilities that lock sectoral systems into inferior technologies, as Richard Nelson, Stan Metcalfe, Paul David and Richard Langlois among others have shown.

These coevolutionary processes are indeed sector-specific. And discussions of on the joint change of several variables during industry evolution have been proposed (Nelson 1994). For example, just looking at three elements such as technology, demand and firms, one could claim that, in sectors characterized by a system product and consumers with a rather homogeneous demand, coevolution leads to the emergence of a dominant design and industrial concentration (Klepper 1996). However in sectors with either a heterogeneous demand or competing technologies with lock-ins, specialized products and a more fragmented market structure may emerge. In general, one could say that changes in the specific knowledge base of an industry or in the features of demand may affect the specific characteristics of the actors, the type of organization of R–D, the features of the innovative process and of networks, the structure of the market and the specific role of the institutions. All these changes may in turn lead to further modifications in the technology, the knowledge base, demand, and so on. The cases of specific industries provide interesting examples. In chemicals, Arora and Gambardella (1998) have discussed the long run coevolution of technology, organization of innovative activities and market structure, and Murman (2003) has examined the joint interrelated evolution of the dye technology, the population of firms and market structure, national organizations (such as universities and firms), and the international leadership and decline of specific countries. In computers, coevolutionary processes involving technology, demand, market structure, institutions and firm organization and strategies have differed greatly in mainframes, minicomputers, personal computers and computer networks, involving different actors, mechanisms, entry processes and producer–customers relationships (Bresnahan and Malerba 1999). In pharmaceuticals and biotechnology, the interactions between knowledge, technology, institutions and country-specific factors have shaped the evolution of the industry. Changes in the knowledge base and in the relevant learning processes of firms have induced deep transformations in the behavior, structure and interaction of agents. These, in turn, have changed the knowledge and learning processes, leading to new products and so on (as McKelvey 1997; McKelvey et al. 2004). Another case refers to telecom equipment and services. The convergence within ICT and between ICT and broadcasting-audio-visual and the emergence of the internet produced a more fluid market structure with a lot of different actors with different specializations and capabilities, and new types of users. This, in turn, greatly expanded the boundaries of the sector by creating new segments and new opportunities, and also by creating national differences in the organization of innovation. Moreover, the emergence of the internet has generated more pressure in favor of open standards and has led to the rise of new actors (such as ISP and content providers) (Dalum and Villumsen 2003). In software, since the early 1980s, the spread of networked computing, embedded software, the internet, the development of open system architecture and open source, and the growth of web-based network computing has led to the decline of large computer producers as developers of integrated hardware and software systems and to the emergence of many specialized software companies, and to changes in software distribution from licensing agreements in the early days, to the rise of independent software vendors, to price discounts for package software, and, with the diffusion of the CD-ROM and the internet, to shareware and freeware (D'Adderio 2004).

The challenge for research here is to go to a much finer analysis at both empirical and theoretical levels, and to move from the statement that everything is coevolving with everything else to the identification of what is coevolving with what, how intense is this process and whether indeed there is a bi-direction of causality.

A very interesting case of coevolution can be found in vertically related industries. The empirical work by Bonaccorsi and Giuri (2001) for the aircraft industry has already been mentioned. At a more theoretical level, one could find a first discussion of these vertical interdependent processes in the contribution by Young (1928), in which the size of the market depends on prices, which in turn depend upon the cost of production, which depends on the extent of the division of labor. In other words, ultimately the division of labor is limited not by the extent of the market but by the division of labor itself.

In terms of appreciative theorizing and modelling, such coevolutionary processes between vertically related industries can be tackled in various ways. Arora and Bokhari (2000) examine vertical integration and specialization as driven by the interplay of the Babbage effect, the division of labor effect and coordination advantages. Jacobides and Winter (2005) explain the vertical scope of firms in terms of the coevolution of firms' capabilities and transaction costs, and focus their analysis on four factors - knowledge accumulation, capability differences, selection processes and endogenous transaction costs. Finally, in Malerba et al. (2005), vertical integration and specialization is driven by firm capabilities, the rate of technological change and the size and structure of markets, and it is the result of the coevolutionary processes of these variables in the upstream and downstream industries.

9 Conclusions

In this paper, I have suggested that the analysis of innovation and industry evolution has progressed in several areas. Contributions at the empirical, appreciative, econometric and modelling levels have greater advanced our understanding of innovation, industrial dynamics and the different evolution of industries. However, the main part of the paper is centered around the point that a full understanding of the relationship between innovation and the evolution of industries has also to cope with a finer grained analysis of demand, knowledge, networks and coevolution.

I have implicitly stressed that the challenge has to be faced by using a methodology that is quite common to researchers in the Schumpeterian and evolutionary tradition: identify some empirical regularities, stylized facts or puzzles that need to be explained, develop appreciative theorizing, do quantitative analyses and then formal modelling. Consistency between cases-appreciative theorizing-econometrics and modelling has to be present. In a sense, research should not be guided by techniques, but theory should be driven by empirical questions and facts.

In addition, in the realm of innovation and the evolution of industries, research needs to be interdisciplinary. This means that the full understanding of topics such as innovation and the evolution of industries requires the integration of economics, history, sociology, technology, management and organization. Interdisciplinarity means eclecticism and openness to new contributions coming from different field of research. Schumpeter might, I think, have approved, as he was after all as much a sociologist as he was an economist.

Being myself an economist, I may add that a major task is also to have very fruitful confrontation between different approaches within economics, as Schumpeter did with his fellow mainstream economists. I think that a fruitful confrontation is possible because the Schumpeterian approach and the evolutionary research paradigm have developed rich enough contributions to be shared with others and discussed openly.

In conclusion, I am convinced that the strength of a scientific society does not lie only in the discussion of the achievements of the past but in the intellectual challenges it is willing to take. It has to look ahead and not behind. Be bold in the challenges it takes. I am sure many, particularly the new generations, will enthusiastically take up some of the challenge that I have discussed in this paper.

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