department of economics
"S. Cognetti de Martiis"

Via Po, 53 – 10124 Torino (Italy)
Tel. (+39) 011 6704917 - Fax (+39) 011 6703895
URL: http//www.de.unito.it

WORKING PAPER SERIES

THE ECONOMICS OF KNOWLEDGE INTERACTION AND THE CHANGING ROLE OF UNIVERSITIES

Cristiano Antonelli, Pier Paolo Patrucco e Federica Rossi

Dipartimento di Economia "S. Cognetti de Martiis"

LEI & BRICK - Laboratorio di economia dell'innovazione "Franco Momigliano"
Bureau of Research in Innovation, Complexity and Knowledge, Collegio Carlo Alberto

Working paper No. 02/2008

Università di Torino

THE ECONOMICS OF KNOWLEDGE INTERACTION AND THE CHANGING ROLE OF UNIVERSITIES

CRISTIANO ANTONELLI
PIER PAOLO PATRUCCO
FEDERICA ROSSI

LABORATORIO DI ECONOMIA DELL'INNOVAZIONE "FRANCO MOMIGLIANO"
DIPARTIMENTO DI ECONOMIA
UNIVERSITÀ DI TORINO
VIA PO 53 – 10124 TORINO

1. INTRODUCTION

The key role of interactions in order to understand the dynamics of economic systems is increasingly appreciated. Interactions among agents are at the origin of the endogenous change of both preferences and technologies (Lane, 1993; Lane and Maxfield, 2005; Durlauf, 2005).

Within advanced economies, based upon the production and use of services, the organization and implementation of interactions between a variety of business partners and institutions becomes a central issue in the generation and dissemination of knowledge. Within economic systems, agents do more than exchange and trade: they interact, in that they share and barter tacit knowledge and specific competencies. Such knowledge interactions take place vertically in the context of user-producer transactions that parallel market transactions, horizontally among firms engaged in competitive relationships, and diagonally among firms and other institutions. The intentional pursuit of qualified interactions, their organization and exploitation are increasingly seen as effective innovative strategies that enable the generation of new knowledge by allowing access to external complementary knowledge (Antonelli, 2008b).

The new understanding of the dynamics of knowledge generation parallels major institutional and organizational changes in the universities' characteristics and modes of operation. The traditional "open science" and "knowledge mode 1" models are being challenged by new organisational forms of the university, as described by the "mode 2", the "entrepreneurial science" and the "triple helix" models. These models have revisited an array of elements that typically characterize different systems of scientific knowledge creation and distribution: 1) the characteristics of knowledge flowing from universities (i.e., knowledge as a public good vs. knowledge as a private good); 2) the nature of the research activity itself (i.e., basic research vs. applied and contract research); 3) the processes through which knowledge is created and distributed (i.e., publication and teaching vs. patenting, consulting, scientific entrepreneurship and more generally “third stream activities”); 4) the organizational and governance forms through which knowledge is created and disseminated (academic self-governance vs. university industry interactions).

Precisely, the current shift in the organization of science and knowledge production from Mode 1 (Bush, 1945) and “open science” (Dasgupta and David, 1994) to Mode 2 (Gibbons et al., 1994; Nowotny et al., 2001), Triple Helix and entrepreneurial science (Etzkowitz, 2002; Etzkowitz and Leyedesdorff, 2000) and university-industry networks (Lawton-Smith, 2006) seems to support the idea that scientific production benefits from agglomeration and concentration of different research organizations and from interaction between firms and universities. In Mode 1 and the “open science” model, research was conducted in an individualistic way, within a single organization, within the boundaries of a single discipline, with few if any collaborations with industry. The scientific output of such research activity was then possibly and subsequently applied to the productive activities of industries and firms, so that the innovation process itself was conceptualized as a linear process. This model had its day between the 1950s and the 1980s, but it became less efficient following the decline of the innovative model based on large corporations. On the contrary, in Mode 2, the triple helix model and entrepreneurial science, research involves wider connections and collaborations across institutions, scientific fields, industrial sectors and countries. This supports the emergence of multidisciplinary science, vertical and horizontal integration across institutions, and scientific diversification. This also favours the view that the organization of scientific activity and the growth in knowledge production may benefit from consolidation and collaboration not only within the academic system but also and especially between universities and firms. This model acquired increasing relevance both in the literature and in practice since the mid-1980s.

The objective of this contribution is to understand, both analytically and empirically, this shift in the organization of knowledge production. The integration between information economics, the economics of knowledge and the economics of interactions provide the basic tools to elaborate an appropriate framework to understand the closer relationship between university and industry. In this perspective, the economics of interactions and social networks is emerging as a fruitful field of analysis that qualifies communication among agents within economic systems as an essential determinant of knowledge dynamics. University-industry relationships gain relevance in the economics of innovation as an interesting case where the market provision of knowledge-based services and the sharing of localized competence and idiosyncratic expertise among heterogeneous agents with distinct and limited competencies provide the foundations for the generation of further new knowledge. Elaborating upon data for Italian regions, we provide evidence of a positive relationship between scientific production in universities and private R&D performed by firms. Our argument supports the increasing emphasis given to university-industry collaborations as appropriate strategies aiming at the exploitation of the positive feedbacks between academic research and industrial R&D.

This contribution is structured as follows. Section 2 analyses the characteristics and implications of the shift in the organization of scientific production, from the traditional open science model to the new understanding based on the entrepreneurial activity of scientists and the collaboration between university and industry. Interactions support the emergence of quasi-markets for knowledge-based services, where universities are new entrepreneurial players. Section 3, elaborating upon the Italian case, provides preliminary and descriptive evidence for the positive relationship between scientific publications and private R&D activity. The conclusions summarize and put the main results into perspective.

2. THE NEW ORGANIZATION OF SCIENTIFIC PRODUCTION: FROM OPEN SCIENCE, TO UNIVERSITY ENTREPRENEURSHIP, MARKETS FOR SCIENCE AND UNIVERSITY-INDUSTRY INTERACTIONS

Institutional and organizational characteristics of universities are at the centre of the economic analysis of the academic system. In particular, the effect that different organisational and governance forms have on the quantity, quality and efficiency of research activity has been an object of analysis in the economics of science (see, for instance, Bonaccorsi and Daraio, 2007; Geuna et al., 2003; Von Tunzelmann et al., 2003).

However - while it has long been appreciated that the distribution of scientific production across individuals as well as institutions, is by no means normal but it is well described by a Pareto distribution, where the largest proportion of output is accounted for by very few researchers and institutions (Lotka, 1926; Katz, 1999; Merton, 1968) - the large body of empirical and theoretical literature investigating whether specific organizational and institutional forms have positive effects on scientific production has generated controversial results. Results are nuanced, with a set of studies that support the idea of positive effects of industry-university interactions, agglomeration of R&D and the commercialization of science on scientific production, but only under precise specifications and assumptions; while a different set of studies are more critical, finding that “third stream activities” are not only not relevant to explain the amount of scientific production, but that they are negatively related to its quality.

In particular, the relationship between publicly and privately funded science, the progressive commercialisation of research, and the effects that contract research has on scientific production are the object of ongoing debate. On the one hand, criticisms to contract research are based on the idea that scientists would be less and less committed to publication activities and would substitute the creation of public knowledge and basic research with private consulting to firms. In turn, this would harm the traditional academic ethos based on the publicity of scientific results, the circulation of information and the sharing of knowledge among colleagues, who would instead be seen as competitors in the market for private consulting and contract research (see for instance, Nelson, 2004). Moreover, according to this view, not only the rise of entrepreneurial activity at universities is detrimental to the traditional academic ethos and culture, but the introduction of intellectual property rights and commercial exploitation of basic research also undermine the transfer of knowledge from university to industry, by restricting the upstream diffusion of knowledge (Mowery and Ziedonis, 2002; Sampat, 2006). This argument is used to support the claim that the increasing commercialization of science may even hamper the economy’s overall rate of innovation (Florida, 1999).

On the other hand however, it has been stressed that the generation of public science and contract research are complementary rather than substitute, and that the production of basic research would benefit from scientists closely interacting with firms.

In this respect, the seminal study by Mansfield (1995) points to the idea that the academics' scientific production benefits from their interactions with industrial partners. Moreover, in some sectors like biotechnology, higher levels of scientific knowledge production often result from the presence of social networks between 'star scientists' and industry (Zucker et al., 1998; Zucker and Darby, 2001). Van Looy et al. (2004) and Lowe and Gonzalez-Brambila (2007) find that the combination of basic research, patenting and entrepreneurial activity by academic scientists is beneficial for the intensity of publication.

The specific characteristics of different scientific fields and disciplines seem to matter in explaining to what extent "third stream activities" and university-industry interactions may favour or not scientific productivity. For instance, applied sciences seem to benefit from the agglomeration of and the collaboration between public and private R&D organizations, because of the greater endowment of technical equipment and the need to rely upon external technological resources in order to develop experimental research activities. The benefits seem to stem also from easier access to financial resources and the sharing of equipment costs among a larger number of partners. These, in turn, generate greater efficiency in scientific production (Bordons at al., 1996; Bordons and Zulueta, 1997). Similarly, Van Looy et al. (2004) and Lowe and Brambila-Gonzalez (2007) find specific differences between, for instance, engineering, where entrepreneurial activities of academic scientists exert a stronger positive effect on scientific productivity, and chemistry and biomedicine where such effects are much weaker. Their results seem to point to the fact that in certain disciplines, the setting up of university-industry collaborations and the development of university entrepreneurship are more time-consuming and less mutually advantageous. This produces a misallocation of resources and efforts in favour of "third stream activities" that is detrimental to scientific production.

2.1. The Open Science Model

In the traditional "open science" model (Dasgupta and David, 1994), the academic system provides the institutional context appropriate to combine the incentives to both the creation of new knowledge and its dissemination. Publication activity is the keystone of this model. Researchers compete for collective reputation within the international scientific community through peer-review and the process of selection. On the basis of the reputation achieved internationally, academics are rewarded in both hierarchical and monetary terms. At the same time, clearly, publications are the main channel through which knowledge can be created and disseminated. In such context, well-described by the famous metaphor of the "ivory tower", research is generally conducted in an individualistic way, within a single organization, within the boundaries of a single discipline, with few collaborations with industry. Interactions between university and industry are possible but limited to large firms able to undertake large R&D projects in their laboratories, and also to hire young PhDs and scientists. The scientific output of such research is applied to the productive activity of industries and firms in a "linear" way.

The functioning of the system, and more specifically the possibility of interaction between universities and large firms performing R&D internally, is possible only as long as the State intermediates between universities and firms. Such an indirect relationship between the business sector and the academic system is based upon the following circular scheme: 1) firms agree to pay taxes that the State re-allocates to the funding of universities; 2) the academic system assesses the quality of scientific publication and the creativity of scientists, on the basis of the peer-review mechanism, and provides them with the appropriate rewards by financing chairs and tenured positions using State funds; 3) academics create and disseminate scientific knowledge by both publishing and teaching; 4) firms access knowledge produced externally by universities through the hiring of highly-educated workers and PhDs able to absorb and build upon the scientific contents of publications.

The basic tenets of the economics of knowledge as they have been put forward by Kenneth Arrow and Richard Nelson provide the conceptual tools to analyse the characteristics, processes and institutional forms that qualify scientific knowledge production in the open science system.

Knowledge created in such a system is public in nature and its characteristics are consistent with the notion of information as a typical public good (Arrow, 1962): it is non-rival, since more than one person can use it at the same time, and non-exclusive, since it can be shared easily and rapidly, and it is difficult to prevent potential free riders from accessing it. Non-rivalry and non-excludability imply that information cannot be appropriated – or at least it cannot be appropriated completely - by the agents that have invested resources in order to produce it. Information is moreover indivisible and there is a fundamental asymmetry in the assessment of its content: the potential buyer cannot appreciate the value of information without knowing its content, but if the content is disclosed the buyer no longer needs to purchase it. Scientific knowledge shares many of the economic properties of information, and in particular it has the character of a durable public good, since " (i) it does not lose validity due to use or the passage of time per se, (ii) it can be enjoyed jointly, and (iii) costly measures must be taken to restrict access to those who do not have a "right" to use it" (Dasgupta and David, 1994, p. 493).

Focusing more specifically on the production of scientific knowledge, Nelson (1959) pointed out that the amount of basic research activities performed by private agents competing in a market setting is likely to be inferior to the socially optimal amount. This is due to several features of basic research. First, the outcomes of basic research are characterized by fundamental Knightian uncertainty (there is no known probability distribution over their attainment); and even when scientific discoveries are made, the realization of economic payoffs may require a very long time. As a consequence, the economic value of basic research is difficult to quantify. Second, the discoveries that stem from basic research tend to produce large externalities: results and applications may be obtained that are far from those that were expected ex ante ("serendipity") and hence they may benefit economic agents that are different from those that have invested in their production. Therefore, social returns to basic research are larger than private returns, and this divergence causes a systematic market failure which, in the absence of remedial actions, would result in private underinvestment in science: in order to guarantee that the socially optimal amount of basic research is performed, public investment becomes necessary. This "market failure" argument has constituted the main economic rationale for public intervention in stimulating scientific production since it was first formulated (Mowery, 1983): it has provided economic justification either for direct public funding of research, or for the design of appropriate incentives and constraints able to induce individuals to behave in ways that lead to globally efficient solutions.

In this context, one of the most fruitful applications of the Arrovian economics of information and knowledge to the analysis of university activities relates to the study of the norms that govern the production and transmission of academic knowledge. An early influential account of the incentives and norms that guide the behaviour of research scientists was provided by Merton (1973), who identified the main institutional goal of science as "the extension of certified knowledge", and described four interrelated norms that govern its production: scientific findings are the product of social collaboration and should be made available to the scientific community ("communalism"); the truthfulness of claimed observations is to be determined on the basis of impersonal criteria without regard to the identity of the scientist who makes the observation ("universalism"); scientists should be seeking truth, rather than seek to further their own interests by advancing unfounded claims ("disinterestedness"); the scientific community should subject the claims and beliefs of its members to empirical scrutiny before accepting them ("organized scepticism").

These norms imply the autonomy of science in setting its own goals and in pursuing objective knowledge without outside pressures. This was at the basis of the well- known 'university of culture' model, which developed the ideas of Humboldt and the German idealists, and which was closely interlinked with the "open science" model of scientific production. The norm of self-governance and control over the research agenda exercised by the scientific community rely precisely on this view. This norm is justified on the basis of the asymmetric information problem due to society's inability to appreciate the quality of scientists and of their publications, as well as to identify the most promising directions of research (Cowan, 2006).

However, as Antonelli (2008a) pointed out, the system works only if the inventor is rewarded appropriately, so that he or she is induced to make the results of his or her work public, if scientific publication is an effective form of knowledge dissemination, and if some form of economic compensation is granted also to the losers in the priority race. In the absence of such rewards no individuals would be encouraged to undertake uncertain and costly research activities. In this respect, the great ingenuity of the academic system is that it is based on a two-part payment schedule. This consists of a flat salary for entering science, supplemented by rewards to winners of scientific competitions. The flat salary is paid even in absence of research activity, but it is economically justified because it is tied to a complementary productive activity, teaching. The reward for academic priority is instead granted by indexing career advancements and/or wages to publication performance.

Over time, a set of external and internal forces has induced important changes in the academic system, pushing universities towards new organizational configurations. First, the decline in the amount of R&D funded and performed directly within large corporations has been paralleled by the increased division of innovative labor between specialized and often small firms, often able to command high technologies and scientific knowledge, and to combine these with more tacit and practical skills. This decline in the well-established innovation model - based on large corporation performing R&D in their own labs and receiving scientific knowledge from universities - alters the conditions that justify the funding structure of the open science model. Secondly and relatedly, following the Anglo-Saxon model[1], evaluation and accountability schemes have been progressively introduced in the majority of academic systems in developed countries in order to assess the scientific and organizational performances of academic institutions. These are now compelled to achieve well-defined goals in terms of scientific productivity and administrative efficiency. Thirdly, some inefficiencies of the "open science" system itself have progressively become apparent. The model appears to provide poor guidance to identify both the correct amount of public funds and the criteria to distribute these funds among disciplines and among institutions. The reward system sets up a tension between compliance with the norm of full disclosure and the competition for priority. Competition among researchers may encourage rival teams to undertake a too risky set of research projects within a given program. It may also induce them to choose too similar projects within the program; and if the program involves projects that do not display large fixed costs, too many research teams may be attracted to a given research area, to the possible neglect of other areas.

In sum, it seems clear that the lack of actual communication between the generation of knowledge and its usage lies at the heart of the demise of the "ivory tower" model. In the "ivory tower" model, the university is expected to perform the function of issuing "knowledge signals" without paying any attention to their actual reception on the business side. At the same time universities are not expected to listen to the knowledge signals emitted from the business community. In the new model, industrial R&D feeds academic research and vice versa, both with the bilateral provision of intermediary knowledge inputs and with better signals about the emerging direction of the needs and opportunities of both parties.

2.2. The University-Industry Interaction Model

The interpretation of technological knowledge as a collective activity provides the foundations to appreciate the role of knowledge interactions, as well as to qualify the shift in the role and functions performed by universities within economic systems. In this approach, in fact, knowledge is regarded as fragmented and dispersed among a

[1] In Europe, for instance, the UK introduced the first research assessment exercise in 1986, while the Netherlands first developed a research evaluation method in 1983, which was then upgraded into a systemic assessment exercise in 1993; in Germany the first attempts to link funds to research evaluation date back to 1990, and were developed to a fuller extent in 1998. Finland and Denmark carried out their first systemic national research evaluations in 1994, although in Finland measures of scientific assessment were present already in the early '80s (Geuna and Martin, 2003). In Italy, the first national research assessment exercise has been implemented in 2003, on a three-year basis.

variety of heterogeneous agents where each possesses complementary bits. Their communication by means of both knowledge transactions and knowledge interactions, and their eventual integration, enables the generation of new knowledge (Antonelli, 2008a). The generation of scientific knowledge is not an exception to this general view. Both scientific and technological knowledge are the result of qualified knowledge communication among agents that have access to dispersed fragments of the general knowledge. For communication to take place it is clear that both parties need to take an active role: both the emission and the reception of signals are necessary. The analysis of university-industry relationships provides an interesting perspective from which to understand the role of both knowledge-based services transactions and interactions as vehicles for knowledge dissemination and as central sources in the innovation process. Interaction and transactions are complementary aspects of a broader process of communication. Communications benefit from the concentration of organizations that are heterogeneous in terms of scientific and technological domains. In this context geographical and institutional proximity are seen as means for more efficient knowledge-based interactions.

Two distinct strands of literature contribute this approach. On the one hand the analysis of limited knowledge appropriability (Arrow, 1962) has led to the identification of knowledge spillovers (Griliches, 1992) and eventually of knowledge absorption costs (Cohen, Levinthal, 1990). This line of enquiry has made it possible to identify knowledge transactions as sources of knowledge creation and dissemination because they provide economic actors with the opportunity to access external knowledge at costs that are below equilibrium levels because of the well-known effects of pecuniary knowledge externalities (Antonelli, 2009). On the other hand the appreciation of the role of user-producer interactions – which were originally understood within the limited context of market transactions between customers and suppliers of well identified goods – has progressively lead to identify and emphasize the broader flows of knowledge interactions including those between firms and universities (Lundvall, 1985; Russo, 1985; Von Hippel, 1988 and 2005). The merging of these lines of enquiry into an integrated framework has stressed the key role of knowledge communication, consisting both of knowledge transactions and knowledge interactions, as a key source of the generation of new knowledge. Knowledge transactions and knowledge interactions are strictly intertwined and parallel each other. They are often complementary: knowledge interactions add on and qualify knowledge transactions. The identification of the interaction content of transactions becomes crucial in this approach.

In this perspective, universities are progressively emerging as new and crucial partners of business firms in the innovation process, since they are performing an increasingly important role as providers of knowledge-based services supplied in the marketplace and as actors in the organization and implementation of qualified interactions with firms.

It is generally acknowledged that the substantial shift towards both new organizational forms and new (“third stream”) activities performed within universities has been supported by four complementary processes: 1) the introduction of accountability and assessment criteria for academic scientists and their research outcomes; 2) the approval on the part of governments of legislative measures aimed at facilitating the commercialization of university research and at fostering industry-university collaborations, of which the most important and the most questioned was the Bayh-Dole Act (1980) approved by the U.S. Congress; 3) the emergence of biotechnology, a scientific discipline that, more than other disciplines, produces results for which commercial applications can be found quite rapidly and profitably; 4) the assignment to universities, in addition to their traditional missions of research and teaching, of an economic development mandate, with a particular emphasis on the generation of benefits for firms' R&D performances, especially in the case of small and technology-based firms. In particular, university-industry interactions as strategies through which universities exert entrepreneurial activity have recently experienced a dramatic rise through increasing patenting, licensing, research joint ventures with private firms, university spin-offs and technological consultancy (Rothaermel et al., 2007).

A visible qualitative effect of the increased interaction with industry on the part of academia has been, in the 1980s and 1990s, the flourishing of new organizational forms based on both formal and informal university-industry interactions and communication of scientific knowledge. While traditional university-industry interactions and the commercialization of scientific results were based upon licensing (Siegel et al., 2003), universities are now progressively enlarging the range of strategies devoted to transferring and marketing their scientific outcomes. In this respect, formal interactions and university technology transfer mechanisms rely upon academic-industrial liaison and technology licensing offices, industry-university joint research centres and, more recently, university spin-offs, and generally result in a legal instrument such as a patent, license or royalty agreement. Informal interactions are instead based on the transfer of commercial technology, joint publications and industrial consulting (Link et al., 2007).

Firms create various linkages with universities and other R&D organizations, with clear benefits for technology-based firms, especially in terms of firm productivity, R&D capability and R&D output (Medda et al., 2005). The involvement in technology and innovation platforms, through various channels such as formal and informal collaborations, facility sharing, joint R&D projects and the development of university incubators (Zucker and Darby, 2001; Zucker et al., 2002; Rothaermael and Thursby, 2005a,b) enable interaction and coordination processes between firms, public laboratories and universities and support the development of scientific clusters, such as in the case of biotechnology (Robinson, Rip and Mangematin, 2007). Technology and innovation platforms emerge as directed governance forms for the provision of new knowledge-intensive activities based on the interactions between different organizations, and as institutions that are distinct from the spontaneous organization of economic activities such as in the traditional notion of markets for knowledge (Consoli and Patrucco, 2009).

In the models based on the interactions between university and industry, such as Mode 2, the triple helix and the academic entrepreneurship models, research is the outcome of collaborations across organizations, disciplines, sectors and technologies (Mowery et al., 2004; Siegel, 2006). The importance given to the implementation of vertical and horizontal linkages across institutions supports the idea that the organization of scientific production benefits from agglomeration effects. Consistently with the 'Triple Helix' and 'entrepreneurial science' approach to innovation processes, the spatial concentration of technology centres, R&D laboratories and of academic infrastructures (Abramovski et al., 2007) - which characterizes successful regional innovation systems - provides the suitable endowment to generate opportunities for co-localized firms to take advantage from the diversity of science- and technology-based knowledge, as well as from better opportunities to transfer efficiently both codified and tacit knowledge. A well-established empirical literature confirms that the local diffusion of scientific and technological complementary knowledge bases is increased via the knowledge externalities which stem from human capital in university and R&D laboratories, e.g. by means of postgraduates, researchers mobility and personal contacts among them (Audretsch and Feldman, 1996; Audretsch and Stephan, 1996; Feldman and Audretsch, 1999).

Here, regions can be loci where effectual industry-related R&D infrastructures are built around new activities and functions of the academic system, such as patenting and licensing, consulting, research outsourcing, scientific spin-offs. Small and medium firms, especially those located on the innovation frontier, can also benefit from academic research.

University and the R&D system at large (i.e., R&D centres, technology experts and consultants, regional agencies for innovation and research) now contribute the knowledge outputs of industry providing new inputs in three major ways. First, firms can receive new inputs in terms of codified knowledge through individuals, both in the form of highly and formally educated human capital and in the form of scientists and senior researchers. Second, the academic system diffuses new knowledge that can be used in the industrial process of knowledge creation through publications. Third, co-operative R&D projects focused on the development of specific technological applications for industrial needs are more and more characterized by the strategic presence of universities (Geuna, 1999)[2]. The university emerges as a first interface among the variety of knowledge bases, not only favouring the effective introduction of generic and scientific knowledge in the activities of business firms, but also creating the conditions that support the application of new knowledge in different contexts.

Formal and informal university-industry interactions are based also on the personal relationships and social networks between academics, industry scientists, and managers and entrepreneurs in local firms. Social networks in fact can account for a better local exploitation of the most excellent skills of each academic vintage. Academics and scholars can provide appropriate consultancy and research support for local firms, even benefiting from close interaction with firms in terms of reputation, new chances and stimuli for academic research, and also in terms of the diffusion of knowledge through the creation of students' job opportunities and placement on the local labor markets. From the firm's point of view, pursuing their research processes in collaboration with universities may be preferable to funding them all internally for several reasons: easier access to a wider range of already existing competences, lower costs of personnel training and internal competence creation, greater cognitive heterogeneity, and, in an increasingly fast-paced economic system, more opportunities for "shaping" their environment by at least partially influencing the actions of potential competitors in

[2] While the first two features are common to both the open science and university-industry interaction models, the third qualifies the difference between the two approaches.

research. Firms can also benefit from the access to new knowledge in the form of infrastructures (such as laboratories and databases) and from the opportunity to temporarily post researchers and scientists in academic infrastructures, establishing new chances for learning and research.

In this perspective, university-based spin-offs might be a most appropriate entrepreneurial strategy. University spin-offs can benefit from knowledge transfer embodied in academic scientists and researchers, eventually leading to the development of university-based technology and science parks where small firms and especially new technology-based firms (NTBFs) are not simply tenants or mechanisms to generate financial returns from academic intellectual property (Lockett et al., 2003). NTBFs can be an effective mechanism to foster innovation and the generation of technological knowledge in the region when they can benefit from a common pool of scientific and technological knowledge and from social networks, in turn increasing the rate of survival of new, technology-based firms and supporting the persistence of their innovative activity (Murray, 2004). Financial institutions at large and venture capitalists in particular can foster the creation of new technology-based entrepreneurship. Interactions between venture capitalists, new high tech firms often resulting from academic spin-offs, their clients and prospective investors, enable a more effective screening and a better assessment of the value and reliability of new ventures' knowledge (Antonelli and Teubal, 2008). Venture capitalism supports, on the one hand, the growth of new business ideas and academic entrepreneurship through the funding of technology-based and university spin-offs companies, and, on the other, the diffusion of successful knowledge.

Also in the new approach, scientific reputation based upon publication is a key element in the implementation of effective university-industry interactions (Antonelli, 2008a). As a matter of fact, academic scientists need to publish so as to reinforce their reputation, signal their competencies in the markets for research services and therefore attract new funds for their activity. Scientific reputation built upon publication now engenders rewards that can be earned in the market for research and professional activities. The interplay between epistemic communities and local communities of practice as new markets for scientists is most important in this context, and the direction of scientific and basic research is strongly affected by developments in existing technologies and products. Very often, basic research provides scientific explanations of technological artefacts that are already in use (Rosenberg, 1994). The greater the overlapping between scientific recognition and the reputation in the professional community, and the closer the interplay between local academic and professional communities, the more efficient is the role of publication as a system of incentives (Knorr-Cetina, 1999; Feldman and Desrochers, 2004).

In this context, the boundaries between knowledge as a public good and knowledge as a private good are blurry. Knowledge flowing from universities can be seen as quasi-public good, to some extent similar to knowledge flowing from national laboratories, where, such as in the case of the development of standards and technical measurement and methods, it involves close collaborations with industry. Knowledge is now understood as an essential facility that enters the creation of further scientific and technological developments (Antonelli, 2007).

In this new context, the more intensive is the communication between business and academic research, implemented by means of both knowledge transactions and knowledge interactions and favoured by geographic proximity and organizational interfacing, and the larger the productivity of the resources invested in research is expected to be.

3. PRELIMINARY EVIDENCE ON UNIVERSITY-INDUSTRY INTERACTIONS IN ITALY

According to the interactionist approach developed so far, scientific activity within universities and R&D investments by business firms are interdependent elements in the innovation process. Collaborations between academic scientists and industrial researchers, for instance in the forms of technological consultancy or joint publications, are crucial means through which external knowledge can be accessed and knowledge-based services provided. The creation of scientific knowledge in universities and the undertaking of R&D within private firms are complementary and closely related, rather than substitute, and reinforce each other in the creation of further new knowledge.

This leads us to advance the hypothesis that the intensity of knowledge transactions and interactions between universities and firms should increase the amount of technological and scientific knowledge that can be generated with a given level of resources. The preliminary empirical analysis presented in this section will show the distribution of both academic scientific production and private R&D investments for Italian regions so as to provide some tentative evidence about the positive relationships between the two.

This section elaborates upon an original database made of 2,673 Italian researchers (assistant, associate and full professors), distributed across 61 universities, active in the fields of chemistry (Physical chemistry; General and inorganic chemistry; Organic chemistry), engineering (Metallurgy; Material engineering; Electronics measurement), earth sciences (Petrology) and physics (Theoretical physics). These scientific fields were chosen first and foremost because in these fields, with the exception of physics, Italy has a scientific impact higher than the European average. Such fields can be thought of as 'best practices' or 'scientific champions' in Italian science. Secondly, they mirror quite well the traditional distinction between theoretical science (Physics), applied science (Chemistry and), and technical or technology-oriented science (Petrology and Engineering)[3].

This database has been implemented using data from the Italian Ministry of University, Research and Technology (MIUR), and the 2673 researchers included in the database represent the universe of the researchers in those fields. For each researcher, the database provides information on their position (assistant, associate and full professor), the institution in which they are employed (university level), and the region in which the university is located.

[3] Such classification has been confirmed by interviews with researchers in the fields.

In order to analyse scientific production for the different fields, two indicators for output will be used, namely the number of publications cited by articles published in ISI journals, and the number of citations received by such publications. Such output indicators will be then correlated with an input indicator represented by the number of researchers per University and region. In particular, in order to account for the variability of output due to scale effects, we used the number of researchers as a proxy for the dimension of the resources available in a given university. The number of publications and citations is referred to the period 1990-2004 and it is based on the Science Citation Index elaborated by the ISI.

Table 1 shows the distribution of researchers, publications and citations across the different scientific fields (Patrucco, 2006). Here, the larger fields are those in chemistry, which represent 25%, 23% and 18.5% of the population of researchers, respectively. On the contrary, engineering sectors are the smallest, covering 8%, 4% and 3% of the total researchers. These relative weights are, quite obviously, reflected also in the shares of publications and citations. More interestingly, when considering simple productivity measures such as the number of publications per researcher, researchers in physics are the most productive, with 62 publications per researcher. When looking at the citation impact (N° citations/N° publications), chemistry, and in particular the field of General and inorganic chemistry has the highest impact (6.79).

Table 1. The distribution of researchers, publications and citations across the different scientific fields

Scientific field	N□res	% res	N□publ	% publ	N□cit	% cit	Publ/res	Cit/res	Cit/publ
Metallurgy	88	3.29	2,365	1.68	9,874	1.17	26.88	112.20	4.18
Material engineering	220	8.23	7,375	5.24	31,680	3.74	33.52	144.00	4.30
Electronics measurement	108	4.04	1,890	1.34	4,949	0.58	17.50	45.82	2.62
Petrology	117	4.38	3,889	2.76	18,860	2.23	33.24	161.20	4.85
Physical chemistry	493	18.44	27,715	19.70	157,915	18.63	56.22	320.31	5.70
General and inorganic chemistry	621	23.23	37,598	26.73	255,292	30.12	60.54	411.10	6.79
Organic chemistry	670	25.07	37,871	26.92	234,397	27.66	56.52	349.85	6.19
Theoretical physics	356	13.32	21,956	15.61	134,494	15.87	61.67	377.79	6.13
TOTAL	2,673	100.00	140,659	100.00	847,461	100.00	52.62	317.04	6.02

Table 2. The distribution of researchers, publications and citations across the Italian regions

Region	N□res	% res	N□publ	% publ	N□cit	% cit	Publ/res	Cit/res	Cit/publ
EMILIA-ROMAGNA	376	14.07	22167	15.76	149955	17.69	58.95	398.82	6.76
LOMBARDIA	346	12.94	18634	13.25	116200	13.71	53.86	335.84	6.24
TOSCANA	248	9.28	15513	11.03	100052	11.81	62.55	403.44	6.45
LAZIO	256	9.58	13229	9.41	77500	9.14	51.68	302.73	5.86
CAMPANIA	232	8.68	11050	7.86	63558	7.50	47.63	273.96	5.75
VENETO	182	6.81	9483	6.74	55365	6.53	52.10	304.20	5.84
PIEMONTE	152	5.69	9143	6.50	55815	6.59	60.15	367.20	6.10
SICILIA	207	7.74	7748	5.51	45357	5.35	37.43	219.12	5.85
PUGLIA	119	4.45	5460	3.88	25164	2.97	45.88	211.46	4.61
FRIULI	89	3.33	5436	3.86	34765	4.10	61.08	390.62	6.40
UMBRIA	75	2.81	4823	3.43	25439	3.00	64.31	339.19	5.27
SARDEGNA	97	3.63	4351	3.09	25739	3.04	44.86	265.35	5.92
LIGURIA	80	2.99	3621	2.57	16236	1.92	45.26	202.95	4.48
MARCHE	63	2.36	3396	2.41	16752	1.98	53.90	265.90	4.93
CALABRIA	54	2.02	2116	1.50	11115	1.31	39.19	205.83	5.25
TRENTINO-A.A.	30	1.12	1709	1.21	10775	1.27	56.97	359.17	6.30
ABRUZZO	32	1.20	1656	1.18	10505	1.24	51.75	328.28	6.34
BASILICATA	28	1.05	887	0.63	5771	0.68	31.68	206.11	6.51
MOLISE	7	0.26	237	0.17	1398	0.16	33.86	199.71	5.90
TOTAL	2,673	100.00	140,659	100.00	847,461	100.00	52.62	317.04	6.02

Table 2 shows instead the distribution of researchers, publications and citations by region. Emilia Romagna is the region with the largest proportion of researchers (14%), publications (15.76%) and citations (17.69%), and also with the highest citation impact (6.76). in terms of scientific productivity, that is to say the ratio between publications and researchers, however, Tuscany and Piedmont are, among the largest regions, the most productive ones, with 62.55 and 60 publications per researcher respectively.

Table 3 shows the distribution of total, public and private R&D expenditures across Italian regions and compares these with the number of publications.

Table 3. R&D expenditures and publications across Italian regions (,000 Euros; constant prices 1995; 1990-2001 mean values)

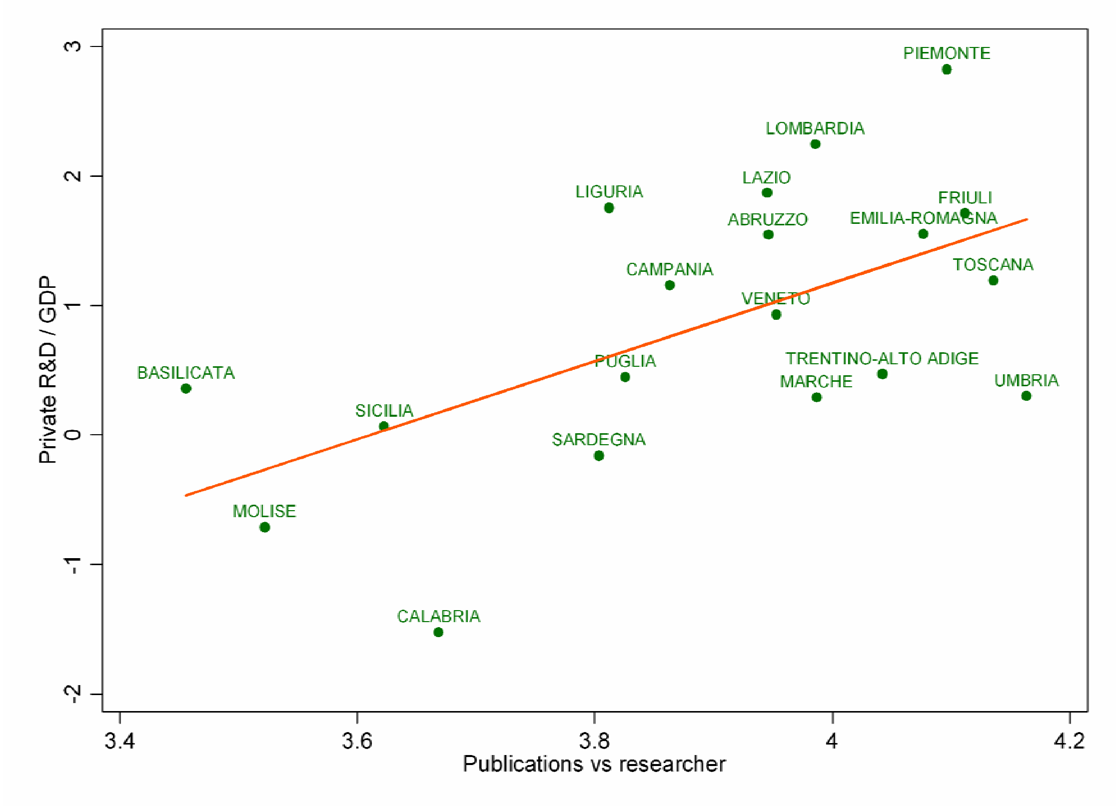
Region	**N° Publications**	**Total R&D**	**Private R&D**	**Public R&D**
EMILIA-ROMAGNA	22,167.00	711,752.58	379,880.17	331,872.67
LOMBARDIA	18,634.00	2,329,485.25	1,808,760.58	520,724.58
TOSCANA	15,513.00	558,687.58	206,042.25	352,645.25
LAZIO	13,229.00	1,904,128.17	606,956.08	1,297,171.75
CAMPANIA	11,050.00	500,306.83	191,737.92	308,569.00
VENETO	9,483.00	423,185.33	213,965.83	209,219.25
PIEMONTE	9,143.00	1,567,384.17	1,367,001.75	200,382.25
SICILIA	7,748.00	311,484.67	59,695.00	251,789.50
PUGLIA	5,460.00	205,285.08	68,893.08	136,392.25
FRIULI	5,436.00	222,353.50	119,898.08	102,455.42
UMBRIA	4,823.00	84,283.17	17,613.50	66,669.92
SARDEGNA	4,351.00	117,888.08	17,461.33	100,426.75
LIGURIA	3,621.00	332,267.25	166,293.00	165,974.17
MARCHE	3,396.00	96,425.67	31,421.08	65,004.17
CALABRIA	2,116.00	49,656.25	4,463.67	45,333.92
TRENTINO-A. A.	1,709.00	75,325.58	31,990.83	43,334.50
ABRUZZO	1,656.00	150,082.92	84,504.83	65,578.00
BASILICATA	887.00	37,495.42	9,772.33	27,723.08
MOLISE	237.00	10,239.17	2,067.00	8,171.92
*ITALY**	*140,659.00*	*509,879.82*	*283,600.96*	*226,286.23*

*Mean values for R&D expenditures

Figure 4 shows the relationship between the intensity of private R&D expenditures (see Table 3) and the effectiveness of academic research activity in each region. The log specification of both variables implies the existence of a power functional relationship. The regression line fits the data quite well, supporting the idea that there is a mutually reinforcing relationship between private and academic research. The position of each region with respect to the regression line reflects the extent to which they are above or below average. Out of the virtuous regions, Piedmont is located at the top-right in the diagram, showing the highest combination of the two variables. Then one can find Lombardy, followed by some North-Eastern regions like Friuli and Emilia Romagna. Finally, two central regions, i.e. Lazio and Abruzzi, deserve to be mentioned as contexts in which industrial and academic research are mutually reinforcing. Moreover, it is hardly surprising to note that most of the less developed Southern regions are in the bottom-left part of the box.

The preliminary evidence gathered confirms that the productivity of research activities is larger where there is an agglomeration and concentration of different research organizations and, hence, a closer interaction between firms and universities.

Figure 4. The relation between private R&D expenditures and scientific productivity



4. CONCLUSIVE REMARKS

The academic system is undergoing a deep transformation in the way in which it creates and disseminates knowledge, as well as in the characteristics of the knowledge it produces. The new academic system emerging from such transformation seems to be able to fill the gap between the two, extreme and traditional cases of knowledge production: on the one hand, the public provision of knowledge through basic research, and, on the other, the private provision of knowledge as a (quasi) proprietary good on the part of firms.

Inter-organizational and qualified interactions are an intermediate knowledge governance mode between the extremes of pure market transactions and vertical integration. Knowledge interaction consists of the intentional implementation of selective and preferential communication between providers of interdependent knowledge-based services. Because of the peculiar characteristics of knowledge as partially appropriable, excludable and indivisible, in a context where transactions are not completely efficient, knowledge interactions emerge as the appropriate strategy pursued by innovators in order to endogenize the effects of positive knowledge externalities and complementarities.

The emergence of a (quasi)market for scientific knowledge and research-based services and the ensuing flows of knowledge interactions are the result of the interdependence among numerous elements: 1) the typical non-exclusivity that characterizes academic employment and the freedom to enter professional markets traditionally accepted for academics; 2) the enhanced knowledge transactions made possible by increasing knowledge appropriability and tradability through licensing, patenting and consultancy; 3) the rise of venture capitalism and of dedicated financial markets for knowledge and innovation; 4) the development of a complementary knowledge intensive business services (KIBS) sector able to intermediate between universities and firms, especially new ones; 5) the improved mutual understanding between academics and firms with respect both to the demand for knowledge and to the identification of local pools of knowledge characterized by high levels of complementarity: 6) the implementation of technology infrastructures, such as research consortia and technological platforms as specific forms of qualified interactions that support technology and knowledge sharing between firms and universities; 7) the faster pace of innovation and the increasing uncertainty confronted by firms, which are therefore increasingly incentivated to liaise with external agents in order to attempt to "control" their environment.

It has been highlighted that there is an inherent conflict between the set of incentives and rewards in the traditional open science system, based on peer-reviewed publication of basic research, and the incentives and rewards that are at the core of the new entrepreneurial university model, focused on the revenue generated from commercial application of basic research.

However, the two different approaches are not only and not merely historically specific, divergent and substitute. The two approaches can be understood also as localised and more or less appropriate according to the nature of the knowledge (e.g., tacit vs. codified) and of the innovations (disruptive vs. incremental) that are being created, or according to the relationship between technological and scientific knowledge that characterizes different fields (Nelson and Rosenberg, 2004). For instance, while "knowledge mode 1" and "ivory-towerism" can be useful for the creation of codified knowledge in the case of radical innovations, interactions and close collaboration between university and industry can be appropriate in the case of more applied, tacit and incremental innovations. The integration between the economics of information, the economics of knowledge and the interactionist approach provides an analytical framework able to clarify the variety of organizational and governance systems in the research sector. In this framework, open science and university-industry interactions coexist as two complementary modes of knowledge production whose synergies are beneficial to the overall innovative and scientific development (Rossi, 2007). Open science enables the rapid advancement of the scientific frontier and the opening up of a wide range of scientific possibilities and opportunities. Interactions between firms and universities allow for such findings not only to find useful applications, but also to be constantly ameliorated and adjusted according to users' needs.

In this perspective, knowledge is increasingly viewed as a collective good based upon the integration of external resources by means of interactions and communication, where the division of knowledge renders networks and platforms appropriate coordinating forms. The importance progressively given to intentional interactions and communication in the new economic understanding of knowledge production, requires to consider: 1) the way in which different knowledge bases require different institutional patterns especially in terms of learning and communication norms, and 2) the way in which these patterns and norms imply different forms of organisation and governance of knowledge production (Patrucco, 2008 and 2009).

The economics of interactions and social networks provides the elementary principles to understand the role of external resources in the overall process of innovation and knowledge creation. Knowledge transactions and knowledge interactions are often complementary: knowledge transactions add to and qualify knowledge transactions. Connections and interactions between actors emerge as a crucial institutional element to understand the dynamic properties of innovation systems and the governance of knowledge creation and dissemination. The growing array of relationships between university and industry are only a specific, and yet increasingly important, case of the more general properties recognized by the economics of interactions and social networks.

In sum, the economics of social interactions provides the economics of knowledge with a powerful tool of analysis to understand and guide the evolution of the organization and governance of knowledge generation. Specifically, the grasping of key role of knowledge interactions provides basic guidance in understanding the evolution of the organization of the academic system. Much work is necessary in order to qualify the actual amount of knowledge communication and knowledge generation that transactions and interactions actually produce and to qualify the characteristics of the context into which they take place most effectively. The identification and valorization of knowledge transactions that are rich in knowledge interactions and the sorting of transactions with a low interactionist content become central issues in the organization of effective knowledge governance mechanisms.

REFERENCES

Abramovski, L., R. Harrison and H. Simpson (2007), 'University research and the location of business R&D', *Economic Journal*, 117 (3), 114-141.

Antonelli, C. (2007), 'Technological knowledge as an essential facility', *Journal of Evolutionary Economics*, 17 (4), 451-471.

Antonelli, C. (2008a), 'The new economics of the university: A knowledge governance approach', *Journal of Technology Transfer*, 33 (1), 1-22.

Antonelli, C. (2008b), *Localized Technological Change: Towards the Economics of Complexity*, London: Routledge.

Antonelli, C. (2009), 'Pecuniary externalities: The convergence of directed technological change and the emergence of innovation systems', *Industrial and Corporate Change*, forthcoming

Antonelli, C. and Teubal, M. (2008), 'Knowledge-intensive property rights and the evolution of venture capitalism', *Journal of Institutional Economics* 4, 163-182.

Arrow, K. J. (1962), 'Economic welfare and the allocation of resources for invention', in R. R. Nelson (ed), *The Rate and Direction of Inventive Activity: Economic and Social Factors*, Princeton: Princeton University Press for N.B.E.R, pp. 609-629.

Audretsch, D. B. and M. P. Feldman (1996), 'Spillovers and the geography of innovation and production', *American Economic Review*, 86 (3), 630-642.

Audretsch, D. B. and P. E. Stephan (1996), 'Company-scientist locational links: the case of biotechnology', *American Economic Review*, 86 (3), 641-652.

Bonaccorsi, A. and C. Daraio (2007), *Universities and Strategic Knowledge Creation: Specialization and Performance in Europe*, Cheltenham: Edward Elgar.

Bush, V. (1945), *Science: The Endless Frontier*, Report to The President on a Program for Postwar Scientific Research, Washington, D.C., Department of Defence.

Bordons, M., I. Gomez, M. T. Fernandez, M. A. Zulueta and A. Mendez (1996), 'Local, domestic and international scientific collaboration in biomedical research', *Scientometrics*, 37 (2), 279-295.

Bordons, M. and M. A. Zulueta (1997), 'Comparison of research team activity in two biomedical fields', *Scientometrics,* 40 (3), 423-436.

Cohen, W.M. and D. A. Levinthal (1990), 'Absorptive capacity: a new perspective on learning and innovation', *Administrative Science Quarterly*, 35 (1), 128-152.

Consoli, D. and Patrucco, P. P. (2009), ‘Innovation platforms and the governance of knowledge: Evidence from Italy and the UK’, *Economics of Innovation and New Technology*, 18 (2), forthcoming.

Cowan, R. (2006), ‘Universities and the knowledge economy’, in B. Kahin and D. Foray (eds), *Advancing Knowledge ad the Knowledge Economy*, Cambridge, MA.: MIT Press, pp. 135-149.

Dasgupta, P, and P. A. David (1994), ‘Towards a new economics of science’, *Research Policy*, 23 (5), 487-521.

Durlauf, S. (2005), ‘Complexity and empirical economics’, *Economic Journal*, 115 (504), 225-243.

Etzkowitz, H. (2002), *MIT and the Rise of Entrepreneurial Science*, London: Routledge.

Etzkowitz, H., and L. Leydesdorff (2000), ‘The dynamics of innovation: from national systems and “Mode 2” to triple helix of university-industry-government relations’, *Research Policy*, 29 (2), 109-123.

Feldman, M. P. and D. B. Audtretsch (1999), ‘Innovation in cities: science-based diversity, specialization and competition’, *European Economic Review*, 43 (2), 409-429.

Feldman, M. P. and P. Desrochers (2004), ‘Truth for its own sake: academic culture and technology transfer at Johns Hopkins University’, *Minerva*, 42 (2), 105-126.

Florida, R. (1999), ‘The role of the University: leveraging talent, not technology’, *Issues in Science and Technology*, 15 (4), 67-73.

Lockett, A., M. Wright and S. Franklin (2003), ‘Technology transfer and universities’ spin-out strategies’, *Small Business Economico*, 20 (2), 185–200.

Geuna, A. (1999), *The Economics of Knowledge Production*, Cheltenham: Edward Elgar.

Geuna, A. and B. Martin (2003), ‘University research evaluation and funding: an international comparison’, *Minerva*, 41 (4), 277-304.

Geuna, A., A. Salter and E. Steinmueller (eds) (2003), *Science and Innovation: Rethinking the Rationales for Funding and Governance*, Cheltenham: Edward Elgar.

Gibbons, M., C. Limoges, H. Nowotny, S. Schwarzman, P. Scott and M. Trow (1994), *The New Production of Knowledge: The Dynamics of Research in Contemporary Societies*, London: Sage Publications.

Griliches, Z. (1992), ‘The search for R&D spillovers’, *Scandinavian Journal of Economics*, 94, 29-47.

Katz, J. S. (1999), ‘The self-similar science’, *Research Policy* 28 (5), 501-518.

Knorr-Cetina, K. (1999), *Epistemic Cultures: How the Sciences Make Knowledge*, Cambridge, MA.: Harvard University Press.

Lane, D. A. (1993), ‘Artificial worlds and economics, part II’, *Journal of Evolutionary Economics*, 3 (3), 177-197

Lane, D. A. and R. R. Maxfield (2005), ‘Ontological uncertainty and innovation’, *Journal of Evolutionary Economics*, 15 (1), 3-50.

Lawton-Smith, H. (2006), *Universities, Innovation and the Economy*, London: Routledge.

Link, A. N., D.S. Siegel and B. Bozeman (2007), ‘An empirical analysis of the propensity of academics to engage in informal university technology transfer’, *Industrial and Corporate Change*, 16 (4), 641-655.

Lotka, A. J. (1926), ‘The frequency distribution of scientific productivity’, *Journal of the Washington Academy of Sciences*, 16(12), 317-323.

Lowe, R. and C. Gonzalez-Brambila (2007), ‘Faculty entrepreneurs and research productivity: a first look’, *Journal of Technology Transfer*, 32 (3), 173-194.

Lundvall, B.A. (1985), *Product Innovation and User-Producer Interaction*, Aalborg: Aalborg University Press.

Mansfield, E. (1995), ‘Academic research underlying industrial innovations: sources, characteristics and financing’, *Review of Economics and Statistics*, 77 (1), 55-65.

Medda, G., C. Piga and D. S. Siegel (2005), ‘University R&D and firm productivity: evidence from Italy’, *Journal of Technology Transfer* 30 (1/2), 199-205.

Merton, R. K. (1968), ‘The Matthew effect in science: the reward and communication systems of science are considered’, *Science* 5 (159), 56-63.

Merton, R. K., (1973), *The Sociology of Science. Theoretical and Empirical Investigations*, Chicago: University of Chicago Press.

Mowery, D. (1983), ‘Economic theory and government technology policy’, *Policy Science*, 16 (1), 27-43.

Mowery, D. C. and A. A. Ziedonis (2002), ‘Academic patent quality and quantity before and after the Bayh-Dole Act in the United States’, *Research Policy* 31 (3), 366-418.

Mowery, D. C., R.R. Nelson, B. Sampat and A. A. Ziedonis (2004), *Ivory Tower and Industrial Innovation. University-Industry Technology Transfer Before and After the Bayh-Dole Act,* Stanford: Stanford University Press.

Murray, F. (2004), 'The role of academic inventors in entrepreneurial firms: sharing the laboratory life', *Research Policy*, 33 (4), 643-659.

Nelson, R.R. (1959), 'The simple economics of basic scientific research', *The Journal of Political Economy*, 67 (3), 297-306.

Nelson, R. R. (2004), 'The market economy and the scientific commons', *Research Policy*, 33 (3), 455-471.

Nelson, R. R. and N. Rosenberg (2004), 'American universities and technical advance in industry', *Research Policy*, 23 (3), 323–348.

Nowotny, H., P. Scott and M. Gibbons (2001), *Re-Thinking Science: Knowledge and the Public in an Age of Uncertainty*, Cambridge: Polity Press.

Patrucco, P.P. (2006), 'The production of scientific knowledge in Italy: evidence in theoretical, applied and technical sciences', European University Institute Working Papers RSCAS No. 2006/12.

Patrucco, P. P. (2008), 'The economics of collective knowledge and technological communication', *Journal of Technology Transfer*, forthcoming.

Patrucco, P. P. (2009), 'Collective knowledge production costs and the dynamics of technological systems', *Economics of Innovation and New Technology*, 18 (3), forthcoming.

Robinson, D. K. R., A. Rip and V. Mangematin (2007), 'Technological agglomeration and the emergence of clusters and networks in nanotechnology', *Research Policy*, 36 (6), 871-879.

Rosenberg, N. (1994), *Exploring the Black Box*, Cambridge: University Press.

Rossi, F. (2007), 'Understanding the organization of scientific production: from the economics of information and knowledge to dynamic interactionism', Department of Economics, University of Torino, mimeo.

Rothaermel, F. T. and M. C. Thursby (2005a), 'University-incubator firm knowledge flows: assessing their impact on incubator firm performance', *Research Policy*, 34 (3), 305-320.

Rothaermel, F. T. and M. C. Thursby (2005b), 'Incubator firms failure or graduation? The role of university linkages', *Research Policy*, 34 (7), 1076-1090.

Rothaermel, F. T., S. D. Agung and L. Jiang (2007), 'University entrepreneurship: a taxonomy of the literature', *Industrial and Corporate Change*, 16 (4), 691-791.

Russo, M. (1985), 'Technical change and the industrial district: the role of interfirm relations in the growth and transformation of ceramic tile production in Italy', *Research Policy*, 14 (6), 329-343.

Sampat, B. N. (2006), 'Patenting and U.S. academic research in the 20th century: The world before and after Bayh-Dole', *Research Policy*, 35 (6), 772-789.

Siegel, D. S. (ed) (2006), *Technology Entrepreneurship: Institutions and Agents Involved in University Technology Transfer*, Vol. I. Cheltenham: Edward Elgar.

Siegel, D. S., D. Waldman and A. N. Link (2003), 'Assessing the impact of organizational practices on the relative productivity of university technology transfer offices: an exploratory study', *Research Policy*, 32 (1), 27-48.

Siegel, D. S., M. Wright and A. Lockett (2007), 'The rise of entrepreneurial activity at universities: organizational and societal implications', *Industrial and Corporate Change*, 16 (4), 489-504.

Van Looy, B., M. Ranga, J. Callaert, K. Debackere and E. Zimmerman (2004), 'Combining entrepreneurial and scientific performance in academia: towards a compound and reciprocal Matthew-effect?', *Research Policy*, 33 (3), 425-441.

Von Hippel, E. (1988), *The Sources of Innovation*, Oxford: Oxford University Press.

Von Hippel, E. (2005), *Democratizing Innovation*, Cambridge, MA.: The MIT Press.

Von Tunzelmann, N . M. Ranga, B. Martin and A. Geuna (2003), The effects of size on research performance: a SPRU review, SPRU, University of Sussex, Brighton.

Zucker, L. G. and M. R. Darby (2001), 'Capturing technological opportunity via Japan's star scientists: evidence from Japanese firms' biotech patents and products', *Journal of Technology Transfer*, 26 (1-2), 37-58.

Zucker, L. G., M. R. Darby and M. B. Brewer (1998), 'Intellectual human capital and the birth of US biotechnology enterprises', *American Economic Review*, 88 (11), 290-306.

THE ECONOMICS OF KNOWLEDGE INTERACTION AND THE CHANGING ROLE OF UNIVERSITIES[1]

Cristiano Antonelli[1,2], Pier Paolo Patrucco[1,2] and Federica Rossi[3]

[1] *Laboratorio di Economia dell'Innovazione "Franco Momigliano"*, Dipartimento di Economia, Università di Torino

[2] *BRICK* (*Bureau of Research on Innovation, Complexity and Knowledge*), Collegio Carlo Alberto, Moncalieri

[3] Dipartimento di Economia, Università di Torino

ABSTRACT. Within advanced economies, based upon the production and use of services, the organization and implementation of interactions between a variety of business partners and institutions becomes a central issue in the generation and dissemination of knowledge. The new understanding of the dynamics of knowledge generation parallels major institutional and organizational changes in the universities' characteristics and modes of operation. University-industry relationships gain relevance in the economics of innovation as an interesting case where the market provision of knowledge-based services and the sharing of localized competence and idiosyncratic expertise among heterogeneous agents with distinct and limited competencies provide the foundations for the generation of further new knowledge. Elaborating upon data for Italian regions, we provide evidence of a positive relationship between scientific production in universities and private R&D performed by firms. Our argument supports the increasing emphasis given to university-industry collaborations as appropriate strategies aiming at the exploitation of the positive feedbacks between academic research and industrial R&D.

KEYWORDS: knowledge production; networks; open science; scientific productivity; university-industry interactions

JEL CODES: O30; 031

[1] Authors' names appear in alphabetical order. For the purpose of assignation, each author contributes equally to this paper.

1. INTRODUCTION

The key role of interactions in order to understand the dynamics of economic systems is increasingly appreciated. Interactions among agents are at the origin of the endogenous change of both preferences and technologies (Lane, 1993; Lane and Maxfield, 2005; Durlauf, 2005).

Within advanced economies, based upon the production and use of services, the organization and implementation of interactions between a variety of business partners and institutions becomes a central issue in the generation and dissemination of knowledge. Within economic systems, agents do more than exchange and trade: they interact, in that they share and barter tacit knowledge and specific competencies. Such knowledge interactions take place vertically in the context of user-producer transactions that parallel market transactions, horizontally among firms engaged in competitive relationships, and diagonally among firms and other institutions. The intentional pursuit of qualified interactions, their organization and exploitation are increasingly seen as effective innovative strategies that enable the generation of new knowledge by allowing access to external complementary knowledge (Antonelli, 2008b).

The new understanding of the dynamics of knowledge generation parallels major institutional and organizational changes in the universities' characteristics and modes of operation. The traditional "open science" and "knowledge mode 1" models are being challenged by new organisational forms of the university, as described by the "mode 2", the "entrepreneurial science" and the "triple helix" models. These models have revisited an array of elements that typically characterize different systems of scientific knowledge creation and distribution: 1) the characteristics of knowledge flowing from universities (i.e., knowledge as a public good vs. knowledge as a private good); 2) the nature of the research activity itself (i.e., basic research vs. applied and contract research); 3) the processes through which knowledge is created and distributed (i.e., publication and teaching vs. patenting, consulting, scientific entrepreneurship and more generally "third stream activities"); 4) the organizational and governance forms through which knowledge is created and disseminated (academic self-governance vs. university industry interactions).

Precisely, the current shift in the organization of science and knowledge production from Mode 1 (Bush, 1945) and "open science" (Dasgupta and David, 1994) to Mode 2 (Gibbons et al., 1994; Nowotny et al., 2001), Triple Helix and entrepreneurial science (Etzkowitz, 2002; Etzkowitz and Leyedesdorff, 2000) and university-industry networks (Lawton-Smith, 2006) seems to support the idea that scientific production benefits from agglomeration and concentration of different research organizations and from interaction between firms and universities. In Mode 1 and the "open science" model, research was conducted in an individualistic way, within a single organization, within the boundaries of a single discipline, with few if any collaborations with industry. The scientific output of such research activity was then possibly and subsequently applied to the productive activities of industries and firms, so that the innovation process itself was conceptualized as a linear process. This model had its day between the 1950s and the 1980s, but it became less efficient following the decline of the innovative model based on large corporations. On the contrary, in Mode 2, the triple helix model and entrepreneurial science, research involves wider connections and collaborations across institutions, scientific fields, industrial sectors and countries. This supports the emergence of multidisciplinary science, vertical and horizontal integration across institutions, and scientific diversification. This also favours the view that the organization of scientific activity and the growth in knowledge production may benefit from consolidation and collaboration not only within the academic system but also and especially between universities and firms. This model acquired increasing relevance both in the literature and in practice since the mid-1980s.

The objective of this contribution is to understand, both analytically and empirically, this shift in the organization of knowledge production. The integration between information economics, the economics of knowledge and the economics of interactions provide the basic tools to elaborate an appropriate framework to understand the closer relationship between university and industry. In this perspective, the economics of interactions and social networks is emerging as a fruitful field of analysis that qualifies communication among agents within economic systems as an essential determinant of knowledge dynamics. University-industry relationships gain relevance in the economics of innovation as an interesting case where the market provision of knowledge-based services and the sharing of localized competence and idiosyncratic expertise among heterogeneous agents with distinct and limited competencies provide the foundations for the generation of further new knowledge. Elaborating upon data for Italian regions, we provide evidence of a positive relationship between scientific production in universities and private R&D performed by firms. Our argument supports the increasing emphasis given to university-industry collaborations as appropriate strategies aiming at the exploitation of the positive feedbacks between academic research and industrial R&D.

This contribution is structured as follows. Section 2 analyses the characteristics and implications of the shift in the organization of scientific production, from the traditional open science model to the new understanding based on the entrepreneurial activity of scientists and the collaboration between university and industry. Interactions support the emergence of quasi-markets for knowledge-based services, where universities are new entrepreneurial players. Section 3, elaborating upon the Italian case, provides preliminary and descriptive evidence for the positive relationship between scientific publications and private R&D activity. The conclusions summarize and put the main results into perspective.

2. THE NEW ORGANIZATION OF SCIENTIFIC PRODUCTION: FROM OPEN SCIENCE, TO UNIVERSITY ENTREPRENEURSHIP, MARKETS FOR SCIENCE AND UNIVERSITY-INDUSTRY INTERACTIONS

Institutional and organizational characteristics of universities are at the centre of the economic analysis of the academic system. In particular, the effect that different organisational and governance forms have on the quantity, quality and efficiency of research activity has been an object of analysis in the economics of science (see, for instance, Bonaccorsi and Daraio, 2007; Geuna et al., 2003; Von Tunzelmann et al., 2003).

However - while it has long been appreciated that the distribution of scientific production across individuals as well as institutions, is by no means normal but it is well described by a Pareto distribution, where the largest proportion of output is accounted for by very few researchers and institutions (Lotka, 1926; Katz, 1999; Merton, 1968) - the large body of empirical and theoretical literature investigating whether specific organizational and institutional forms have positive effects on scientific production has generated controversial results. Results are nuanced, with a set of studies that support the idea of positive effects of industry-university interactions, agglomeration of R&D and the commercialization of science on scientific production, but only under precise specifications and assumptions; while a different set of studies are more critical, finding that “third stream activities” are not only not relevant to explain the amount of scientific production, but that they are negatively related to its quality.

In particular, the relationship between publicly and privately funded science, the progressive commercialisation of research, and the effects that contract research has on scientific production are the object of ongoing debate. On the one hand, criticisms to contract research are based on the idea that scientists would be less and less committed to publication activities and would substitute the creation of public knowledge and basic research with private consulting to firms. In turn, this would harm the traditional academic ethos based on the publicity of scientific results, the circulation of information and the sharing of knowledge among colleagues, who would instead be seen as competitors in the market for private consulting and contract research (see for instance, Nelson, 2004). Moreover, according to this view, not only the rise of entrepreneurial activity at universities is detrimental to the traditional academic ethos and culture, but the introduction of intellectual property rights and commercial exploitation of basic research also undermine the transfer of knowledge from university to industry, by restricting the upstream diffusion of knowledge (Mowery and Ziedonis, 2002; Sampat, 2006). This argument is used to support the claim that the increasing commercialization of science may even hamper the economy’s overall rate of innovation (Florida, 1999).

On the other hand however, it has been stressed that the generation of public science and contract research are complementary rather than substitute, and that the production of basic research would benefit from scientists closely interacting with firms.

In this respect, the seminal study by Mansfield (1995) points to the idea that the academics’ scientific production benefits from their interactions with industrial partners. Moreover, in some sectors like biotechnology, higher levels of scientific knowledge production often result from the presence of social networks between ‘star scientists’ and industry (Zucker et al., 1998; Zucker and Darby, 2001). Van Looy et al. (2004) and Lowe and Gonzalez-Brambila (2007) find that the combination of basic research, patenting and entrepreneurial activity by academic scientists is beneficial for the intensity of publication.

The specific characteristics of different scientific fields and disciplines seem to matter in explaining to what extent “third stream activities” and university-industry interactions may favour or not scientific productivity. For instance, applied sciences seem to benefit from the agglomeration of and the collaboration between public and private R&D

organizations, because of the greater endowment of technical equipment and the need to rely upon external technological resources in order to develop experimental research activities. The benefits seem to stem also from easier access to financial resources and the sharing of equipment costs among a larger number of partners. These, in turn, generate greater efficiency in scientific production (Bordons at al., 1996; Bordons and Zulueta, 1997). Similarly, Van Looy et al. (2004) and Lowe and Brambila-Gonzalez (2007) find specific differences between, for instance, engineering, where entrepreneurial activities of academic scientists exert a stronger positive effect on scientific productivity, and chemistry and biomedicine where such effects are much weaker. Their results seem to point to the fact that in certain disciplines, the setting up of university-industry collaborations and the development of university entrepreneurship are more time-consuming and less mutually advantageous. This produces a misallocation of resources and efforts in favour of "third stream activities" that is detrimental to scientific production.

2.1. The Open Science Model

In the traditional "open science" model (Dasgupta and David, 1994), the academic system provides the institutional context appropriate to combine the incentives to both the creation of new knowledge and its dissemination. Publication activity is the keystone of this model. Researchers compete for collective reputation within the international scientific community through peer-review and the process of selection. On the basis of the reputation achieved internationally, academics are rewarded in both hierarchical and monetary terms. At the same time, clearly, publications are the main channel through which knowledge can be created and disseminated. In such context, well-described by the famous metaphor of the "ivory tower", research is generally conducted in an individualistic way, within a single organization, within the boundaries of a single discipline, with few collaborations with industry. Interactions between university and industry are possible but limited to large firms able to undertake large R&D projects in their laboratories, and also to hire young PhDs and scientists. The scientific output of such research is applied to the productive activity of industries and firms in a "linear" way.

The functioning of the system, and more specifically the possibility of interaction between universities and large firms performing R&D internally, is possible only as long as the State intermediates between universities and firms. Such an indirect relationship between the business sector and the academic system is based upon the following circular scheme: 1) firms agree to pay taxes that the State re-allocates to the funding of universities; 2) the academic system assesses the quality of scientific publication and the creativity of scientists, on the basis of the peer-review mechanism, and provides them with the appropriate rewards by financing chairs and tenured positions using State funds; 3) academics create and disseminate scientific knowledge by both publishing and teaching; 4) firms access knowledge produced externally by universities through the hiring of highly-educated workers and PhDs able to absorb and build upon the scientific contents of publications.

The basic tenets of the economics of knowledge as they have been put forward by Kenneth Arrow and Richard Nelson provide the conceptual tools to analyse the characteristics, processes and institutional forms that qualify scientific knowledge production in the open science system.

Knowledge created in such a system is public in nature and its characteristics are consistent with the notion of information as a typical public good (Arrow, 1962): it is non-rival, since more than one person can use it at the same time, and non-exclusive, since it can be shared easily and rapidly, and it is difficult to prevent potential free riders from accessing it. Non-rivalry and non-excludability imply that information cannot be appropriated – or at least it cannot be appropriated completely - by the agents that have invested resources in order to produce it. Information is moreover indivisible and there is a fundamental asymmetry in the assessment of its content: the potential buyer cannot appreciate the value of information without knowing its content, but if the content is disclosed the buyer no longer needs to purchase it. Scientific knowledge shares many of the economic properties of information, and in particular it has the character of a durable public good, since " (i) it does not lose validity due to use or the passage of time per se, (ii) it can be enjoyed jointly, and (iii) costly measures must be taken to restrict access to those who do not have a "right" to use it" (Dasgupta and David, 1994, p. 493).

Focusing more specifically on the production of scientific knowledge, Nelson (1959) pointed out that the amount of basic research activities performed by private agents competing in a market setting is likely to be inferior to the socially optimal amount. This is due to several features of basic research. First, the outcomes of basic research are characterized by fundamental Knightian uncertainty (there is no known probability distribution over their attainment); and even when scientific discoveries are made, the realization of economic payoffs may require a very long time. As a consequence, the economic value of basic research is difficult to quantify. Second, the discoveries that stem from basic research tend to produce large externalities: results and applications may be obtained that are far from those that were expected ex ante ("serendipity") and hence they may benefit economic agents that are different from those that have invested in their production. Therefore, social returns to basic research are larger than private returns, and this divergence causes a systematic market failure which, in the absence of remedial actions, would result in private underinvestment in science: in order to guarantee that the socially optimal amount of basic research is performed, public investment becomes necessary. This "market failure" argument has constituted the main economic rationale for public intervention in stimulating scientific production since it was first formulated (Mowery, 1983): it has provided economic justification either for direct public funding of research, or for the design of appropriate incentives and constraints able to induce individuals to behave in ways that lead to globally efficient solutions.

In this context, one of the most fruitful applications of the Arrovian economics of information and knowledge to the analysis of university activities relates to the study of the norms that govern the production and transmission of academic knowledge. An early influential account of the incentives and norms that guide the behaviour of research scientists was provided by Merton (1973), who identified the main institutional goal of science as "the extension of certified knowledge", and described four interrelated norms that govern its production: scientific findings are the product of social collaboration and should be made available to the scientific community ("communalism"); the truthfulness of claimed observations is to be determined on the basis of impersonal criteria without regard to the identity of the scientist who makes the observation ("universalism"); scientists should be seeking truth, rather than seek to further their own interests by advancing unfounded claims ("disinterestedness"); the scientific community should subject the claims and beliefs of its members to empirical scrutiny before accepting them ("organized scepticism").

These norms imply the autonomy of science in setting its own goals and in pursuing objective knowledge without outside pressures. This was at the basis of the well- known 'university of culture' model, which developed the ideas of Humboldt and the German idealists, and which was closely interlinked with the "open science" model of scientific production. The norm of self-governance and control over the research agenda exercised by the scientific community rely precisely on this view. This norm is justified on the basis of the asymmetric information problem due to society's inability to appreciate the quality of scientists and of their publications, as well as to identify the most promising directions of research (Cowan, 2006).

However, as Antonelli (2008a) pointed out, the system works only if the inventor is rewarded appropriately, so that he or she is induced to make the results of his or her work public, if scientific publication is an effective form of knowledge dissemination, and if some form of economic compensation is granted also to the losers in the priority race. In the absence of such rewards no individuals would be encouraged to undertake uncertain and costly research activities. In this respect, the great ingenuity of the academic system is that it is based on a two-part payment schedule. This consists of a flat salary for entering science, supplemented by rewards to winners of scientific competitions. The flat salary is paid even in absence of research activity, but it is economically justified because it is tied to a complementary productive activity, teaching. The reward for academic priority is instead granted by indexing career advancements and/or wages to publication performance.

Over time, a set of external and internal forces has induced important changes in the academic system, pushing universities towards new organizational configurations. First, the decline in the amount of R&D funded and performed directly within large corporations has been paralleled by the increased division of innovative labor between specialized and often small firms, often able to command high technologies and scientific knowledge, and to combine these with more tacit and practical skills. This decline in the well-established innovation model - based on large corporation performing R&D in their own labs and receiving scientific knowledge from universities - alters the conditions that justify the funding structure of the open science model. Secondly and relatedly, following the Anglo-Saxon model[2], evaluation and accountability schemes have been progressively introduced in the majority of academic

[2] In Europe, for instance, the UK introduced the first research assessment exercise in 1986, while the Netherlands first developed a research evaluation method in 1983, which was then upgraded into a systemic assessment exercise in 1993; in Germany the first attempts to link funds to research evaluation date back to 1990, and were developed to a fuller extent in 1998. Finland and Denmark carried out their first systemic national research evaluations in 1994, although in Finland measures of scientific assessment were present already in the early '80s (Geuna and Martin, 2003). In Italy, the first national research assessment exercise has been implemented in 2003, on a three-year basis.

systems in developed countries in order to assess the scientific and organizational performances of academic institutions. These are now compelled to achieve well-defined goals in terms of scientific productivity and administrative efficiency. Thirdly, some inefficiencies of the "open science" system itself have progressively become apparent. The model appears to provide poor guidance to identify both the correct amount of public funds and the criteria to distribute these funds among disciplines and among institutions. The reward system sets up a tension between compliance with the norm of full disclosure and the competition for priority. Competition among researchers may encourage rival teams to undertake a too risky set of research projects within a given program. It may also induce them to choose too similar projects within the program; and if the program involves projects that do not display large fixed costs, too many research teams may be attracted to a given research area, to the possible neglect of other areas.

In sum, it seems clear that the lack of actual communication between the generation of knowledge and its usage lies at the heart of the demise of the "ivory tower" model. In the "ivory tower" model, the university is expected to perform the function of issuing "knowledge signals" without paying any attention to their actual reception on the business side. At the same time universities are not expected to listen to the knowledge signals emitted from the business community. In the new model, industrial R&D feeds academic research and vice versa, both with the bilateral provision of intermediary knowledge inputs and with better signals about the emerging direction of the needs and opportunities of both parties.

2.2. The University-Industry Interaction Model

The interpretation of technological knowledge as a collective activity provides the foundations to appreciate the role of knowledge interactions, as well as to qualify the shift in the role and functions performed by universities within economic systems. In this approach, in fact, knowledge is regarded as fragmented and dispersed among a variety of heterogeneous agents where each possesses complementary bits. Their communication by means of both knowledge transactions and knowledge interactions, and their eventual integration, enables the generation of new knowledge (Antonelli, 2008a). The generation of scientific knowledge is not an exception to this general view. Both scientific and technological knowledge are the result of qualified knowledge communication among agents that have access to dispersed fragments of the general knowledge. For communication to take place it is clear that both parties need to take an active role: both the emission and the reception of signals are necessary. The analysis of university-industry relationships provides an interesting perspective from which to understand the role of both knowledge-based services transactions and interactions as vehicles for knowledge dissemination and as central sources in the innovation process. Interaction and transactions are complementary aspects of a broader process of communication. Communications benefit from the concentration of organizations that are heterogeneous in terms of scientific and technological domains. In this context geographical and institutional proximity are seen as means for more efficient knowledge-based interactions.

Two distinct strands of literature contribute this approach. On the one hand the analysis of limited knowledge appropriability (Arrow, 1962) has led to the identification of knowledge spillovers (Griliches, 1992) and eventually of knowledge absorption costs (Cohen, Levinthal, 1990). This line of enquiry has made it possible to identify knowledge transactions as sources of knowledge creation and dissemination because they provide economic actors with the opportunity to access external knowledge at costs that are below equilibrium levels because of the well-known effects of pecuniary knowledge externalities (Antonelli, 2009). On the other hand the appreciation of the role of user-producer interactions – which were originally understood within the limited context of market transactions between customers and suppliers of well identified goods – has progressively lead to identify and emphasize the broader flows of knowledge interactions including those between firms and universities (Lundvall, 1985; Russo, 1985; Von Hippel, 1988 and 2005). The merging of these lines of enquiry into an integrated framework has stressed the key role of knowledge communication, consisting both of knowledge transactions and knowledge interactions, as a key source of the generation of new knowledge. Knowledge transactions and knowledge interactions are strictly intertwined and parallel each other. They are often complementary: knowledge interactions add on and qualify knowledge transactions. The identification of the interaction content of transactions becomes crucial in this approach.

In this perspective, universities are progressively emerging as new and crucial partners of business firms in the innovation process, since they are performing an increasingly important role as providers of knowledge-based services supplied in the marketplace and as actors in the organization and implementation of qualified interactions with firms.

It is generally acknowledged that the substantial shift towards both new organizational forms and new ("third stream") activities performed within universities has been supported by four complementary processes: 1) the introduction of accountability and assessment criteria for academic scientists and their research outcomes; 2) the approval on the part of governments of legislative measures aimed at facilitating the commercialization of university research and at fostering industry-university collaborations, of which the most important and the most questioned was the Bayh-Dole Act (1980) approved by the U.S. Congress; 3) the emergence of biotechnology, a scientific discipline that, more than other disciplines, produces results for which commercial applications can be found quite rapidly and profitably; 4) the assignment to universities, in addition to their traditional missions of research and teaching, of an economic development mandate, with a particular emphasis on the generation of benefits for firms' R&D performances, especially in the case of small and technology-based firms. In particular, university-industry interactions as strategies through which universities exert entrepreneurial activity have recently experienced a dramatic rise through increasing patenting, licensing, research joint ventures with private firms, university spin-offs and technological consultancy (Rothaermel et al., 2007).

A visible qualitative effect of the increased interaction with industry on the part of academia has been, in the 1980s and 1990s, the flourishing of new organizational forms based on both formal and informal university-industry interactions and communication of scientific knowledge. While traditional university-industry interactions and the commercialization of scientific results were based upon licensing (Siegel et al., 2003), universities are now progressively enlarging the range of strategies devoted to transferring and marketing their scientific outcomes. In this respect, formal interactions and university technology transfer mechanisms rely upon academic-industrial liaison and technology licensing offices, industry-university joint research centres and, more recently, university spin-offs, and generally result in a legal instrument such as a patent, license or royalty agreement. Informal interactions are instead based on the transfer of commercial technology, joint publications and industrial consulting (Link et al., 2007).

Firms create various linkages with universities and other R&D organizations, with clear benefits for technology-based firms, especially in terms of firm productivity, R&D capability and R&D output (Medda et al., 2005). The involvement in technology and innovation platforms, through various channels such as formal and informal collaborations, facility sharing, joint R&D projects and the development of university incubators (Zucker and Darby, 2001; Zucker et al., 2002; Rothaermael and Thursby, 2005a,b) enable interaction and coordination processes between firms, public laboratories and universities and support the development of scientific clusters, such as in the case of biotechnology (Robinson, Rip and Mangematin, 2007). Technology and innovation platforms emerge as directed governance forms for the provision of new knowledge-intensive activities based on the interactions between different organizations, and as institutions that are distinct from the spontaneous organization of economic activities such as in the traditional notion of markets for knowledge (Consoli and Patrucco, 2009).

In the models based on the interactions between university and industry, such as Mode 2, the triple helix and the academic entrepreneurship models, research is the outcome of collaborations across organizations, disciplines, sectors and technologies (Mowery et al., 2004; Siegel, 2006). The importance given to the implementation of vertical and horizontal linkages across institutions supports the idea that the organization of scientific production benefits from agglomeration effects. Consistently with the 'Triple Helix' and 'entrepreneurial science' approach to innovation processes, the spatial concentration of technology centres, R&D laboratories and of academic infrastructures (Abramovski et al., 2007) - which characterizes successful regional innovation systems - provides the suitable endowment to generate opportunities for co-localized firms to take advantage from the diversity of science- and technology-based knowledge, as well as from better opportunities to transfer efficiently both codified and tacit knowledge. A well-established empirical literature confirms that the local diffusion of scientific and technological complementary knowledge bases is increased via the knowledge externalities which stem from human capital in university and R&D laboratories, e.g. by means of postgraduates, researchers mobility and personal contacts among them (Audretsch and Feldman, 1996; Audretsch and Stephan, 1996; Feldman and Audretsch, 1999).

Here, regions can be loci where effectual industry-related R&D infrastructures are built around new activities and functions of the academic system, such as patenting and licensing, consulting, research outsourcing, scientific spin-offs. Small and medium firms, especially those located on the innovation frontier, can also benefit from academic research.

University and the R&D system at large (i.e., R&D centres, technology experts and consultants, regional agencies for innovation and research) now contribute the knowledge outputs of industry providing new inputs in three major ways. First, firms can receive new inputs in terms of codified knowledge through individuals, both in the form of highly and formally educated human capital and in the form of scientists and senior researchers. Second, the academic system diffuses new knowledge that can be used in the industrial process of knowledge creation through publications. Third, co-operative R&D projects focused on the development of specific technological applications for industrial needs are more and more characterized by the strategic presence of universities (Geuna, 1999)[3]. The university emerges as a first interface among the variety of knowledge bases, not only favouring the effective introduction of generic and scientific knowledge in the activities of business firms, but also creating the conditions that support the application of new knowledge in different contexts.

Formal and informal university-industry interactions are based also on the personal relationships and social networks between academics, industry scientists, and managers and entrepreneurs in local firms. Social networks in fact can account for a better local exploitation of the most excellent skills of each academic vintage. Academics and scholars can provide appropriate consultancy and research support for local firms, even benefiting from close interaction with firms in terms of reputation, new chances and stimuli for academic research, and also in terms of the diffusion of knowledge through the creation of students' job opportunities and placement on the local labor markets. From the firm's point of view, pursuing their research processes in collaboration with universities may be preferable to funding them all internally for several reasons: easier access to a wider range of already existing competences, lower costs of personnel training and internal competence creation, greater cognitive heterogeneity, and, in an increasingly fast-paced economic system, more opportunities for "shaping" their environment by at least partially influencing the actions of potential competitors in research. Firms can also benefit from the access to new knowledge in the form of infrastructures (such as laboratories and databases) and from the opportunity to temporarily post researchers and scientists in academic infrastructures, establishing new chances for learning and research.

In this perspective, university-based spin-offs might be a most appropriate entrepreneurial strategy. University spin-offs can benefit from knowledge transfer embodied in academic scientists and researchers, eventually leading to the development of university-based technology and science parks where small firms and especially new technology-based firms (NTBFs) are not simply tenants or mechanisms to generate financial returns from academic intellectual property (Lockett et al., 2003). NTBFs can be an effective mechanism to foster innovation and the generation of technological knowledge in the region when they can benefit from a common pool of scientific and technological knowledge and from social networks, in turn increasing the rate of survival of new, technology-based firms and supporting the persistence of their innovative activity (Murray, 2004). Financial institutions at large and venture capitalists in particular can foster the creation of new technology-based entrepreneurship.

[3] While the first two features are common to both the open science and university-industry interaction models, the third qualifies the difference between the two approaches.

Interactions between venture capitalists, new high tech firms often resulting from academic spin-offs, their clients and prospective investors, enable a more effective screening and a better assessment of the value and reliability of new ventures' knowledge (Antonelli and Teubal, 2008). Venture capitalism supports, on the one hand, the growth of new business ideas and academic entrepreneurship through the funding of technology-based and university spin-offs companies, and, on the other, the diffusion of successful knowledge.

Also in the new approach, scientific reputation based upon publication is a key element in the implementation of effective university-industry interactions (Antonelli, 2008a). As a matter of fact, academic scientists need to publish so as to reinforce their reputation, signal their competencies in the markets for research services and therefore attract new funds for their activity. Scientific reputation built upon publication now engenders rewards that can be earned in the market for research and professional activities. The interplay between epistemic communities and local communities of practice as new markets for scientists is most important in this context, and the direction of scientific and basic research is strongly affected by developments in existing technologies and products. Very often, basic research provides scientific explanations of technological artefacts that are already in use (Rosenberg, 1994). The greater the overlapping between scientific recognition and the reputation in the professional community, and the closer the interplay between local academic and professional communities, the more efficient is the role of publication as a system of incentives (Knorr-Cetina, 1999; Feldman and Desrochers, 2004).

In this context, the boundaries between knowledge as a public good and knowledge as a private good are blurry. Knowledge flowing from universities can be seen as quasi-public good, to some extent similar to knowledge flowing from national laboratories, where, such as in the case of the development of standards and technical measurement and methods, it involves close collaborations with industry. Knowledge is now understood as an essential facility that enters the creation of further scientific and technological developments (Antonelli, 2007).

In this new context, the more intensive is the communication between business and academic research, implemented by means of both knowledge transactions and knowledge interactions and favoured by geographic proximity and organizational interfacing, and the larger the productivity of the resources invested in research is expected to be.

3. PRELIMINARY EVIDENCE ON UNIVERSITY-INDUSTRY INTERACTIONS IN ITALY

According to the interactionist approach developed so far, scientific activity within universities and R&D investments by business firms are interdependent elements in the innovation process. Collaborations between academic scientists and industrial researchers, for instance in the forms of technological consultancy or joint publications, are crucial means through which external knowledge can be accessed and knowledge-based services provided. The creation of scientific knowledge in universities and the undertaking of R&D within private firms are complementary and closely related, rather than substitute, and reinforce each other in the creation of further new knowledge.

This leads us to advance the hypothesis that the intensity of knowledge transactions and interactions between universities and firms should increase the amount of technological and scientific knowledge that can be generated with a given level of resources. The preliminary empirical analysis presented in this section will show the distribution of both academic scientific production and private R&D investments for Italian regions so as to provide some tentative evidence about the positive relationships between the two (Patrucco, 2006).

This section elaborates upon an original database made of 2,673 Italian researchers (assistant, associate and full professors), distributed across 61 universities, active in the fields of chemistry (Physical chemistry; General and inorganic chemistry; Organic chemistry), engineering (Metallurgy; Material engineering; Electronics measurement), earth sciences (Petrology) and physics (Theoretical physics). These scientific fields were chosen first and foremost because in these fields, with the exception of physics, Italy has a scientific impact higher than the European average. Such fields can be thought of as 'best practices' or 'scientific champions' in Italian science. Secondly, they mirror quite well the traditional distinction between theoretical science (Physics), applied science (Chemistry and), and technical or technology-oriented science (Petrology and Engineering)[4].

This database has been implemented using data from the Italian Ministry of University, Research and Technology (MIUR), and the 2673 researchers included in the database represent the universe of the researchers in those fields. For each researcher, the database provides information on their position (assistant, associate and full professor), the institution in which they are employed (university level), and the region in which the university is located.

In order to analyse scientific production for the different fields, two indicators for output will be used, namely the number of publications cited by articles published in ISI journals, and the number of citations received by such publications. Such output indicators will be then correlated with an input indicator represented by the number of researchers per University and region. In particular, in order to account for the variability of output due to scale effects, we used the number of researchers as a proxy for the dimension of the resources available in a given university. The number of publications and citations is referred to the period 1990-2004 and it is based on the Science Citation Index elaborated by the ISI.

Table 1 shows the distribution of researchers, publications and citations across the different scientific fields. Here, the larger fields are those in chemistry, which represent 25%, 23% and 18.5% of the population of researchers, respectively. On the contrary, engineering sectors are the smallest, covering 8%, 4% and 3% of the total researchers. These relative weights are, quite obviously, reflected also in the shares of publications and citations. More interestingly, when considering simple productivity measures such

[4] Such classification has been confirmed by interviews with researchers in the fields.

as the number of publications per researcher, researchers in physics are the most productive, with 62 publications per researcher. When looking at the citation impact (N° citations/N° publications), chemistry, and in particular the field of General and inorganic chemistry has the highest impact (6.79).

Table 1. The distribution of researchers, publications and citations across the different scientific fields

Scientific field	N° res	% res	N° publ	% publ	N° cit	% cit	Publ/res	Cit/res	Cit/publ
Metallurgy	88	3.29	2,365	1.68	9,874	1.17	26.88	112.20	4.18
Material engineering	220	8.23	7,375	5.24	31,680	3.74	33.52	144.00	4.30
Electronics measurement	108	4.04	1,890	1.34	4,949	0.58	17.50	45.82	2.62
Petrology	117	4.38	3,889	2.76	18,860	2.23	33.24	161.20	4.85
Physical chemistry	493	18.44	27,715	19.70	157,915	18.63	56.22	320.31	5.70
General and inorganic chemistry	621	23.23	37,598	26.73	255,292	30.12	60.54	411.10	6.79
Organic chemistry	670	25.07	37,871	26.92	234,397	27.66	56.52	349.85	6.19
Theoretical physics	356	13.32	21,956	15.61	134,494	15.87	61.67	377.79	6.13
TOTAL	2,673	100.00	140,659	100.00	847,461	100.00	52.62	317.04	6.02

Table 2. The distribution of researchers, publications and citations across the Italian regions

Region	N° res	% res	N° publ	% publ	N° cit	% cit	Publ/res	Cit/res	Cit/publ
EMILIA-ROMAGNA	376	14.07	22167	15.76	149955	17.69	58.95	398.82	6.76
LOMBARDIA	346	12.94	18634	13.25	116200	13.71	53.86	335.84	6.24
TOSCANA	248	9.28	15513	11.03	100052	11.81	62.55	403.44	6.45
LAZIO	256	9.58	13229	9.41	77500	9.14	51.68	302.73	5.86
CAMPANIA	232	8.68	11050	7.86	63558	7.50	47.63	273.96	5.75
VENETO	182	6.81	9483	6.74	55365	6.53	52.10	304.20	5.84
PIEMONTE	152	5.69	9143	6.50	55815	6.59	60.15	367.20	6.10
SICILIA	207	7.74	7748	5.51	45357	5.35	37.43	219.12	5.85
PUGLIA	119	4.45	5460	3.88	25164	2.97	45.88	211.46	4.61
FRIULI	89	3.33	5436	3.86	34765	4.10	61.08	390.62	6.40
UMBRIA	75	2.81	4823	3.43	25439	3.00	64.31	339.19	5.27
SARDEGNA	97	3.63	4351	3.09	25739	3.04	44.86	265.35	5.92
LIGURIA	80	2.99	3621	2.57	16236	1.92	45.26	202.95	4.48
MARCHE	63	2.36	3396	2.41	16752	1.98	53.90	265.90	4.93
CALABRIA	54	2.02	2116	1.50	11115	1.31	39.19	205.83	5.25
TRENTINO-A.A.	30	1.12	1709	1.21	10775	1.27	56.97	359.17	6.30
ABRUZZO	32	1.20	1656	1.18	10505	1.24	51.75	328.28	6.34
BASILICATA	28	1.05	887	0.63	5771	0.68	31.68	206.11	6.51
MOLISE	7	0.26	237	0.17	1398	0.16	33.86	199.71	5.90
TOTAL	2,673	100.00	140,659	100.00	847,461	100.00	52.62	317.04	6.02

Table 2 shows instead the distribution of researchers, publications and citations by region. Emilia Romagna is the region with the largest proportion of researchers (14%), publications (15.76%) and citations (17.69%), and also with the highest citation impact (6.76). in terms of scientific productivity, that is to say the ratio between publications and researchers, however, Tuscany and Piedmont are, among the largest regions, the most productive ones, with 62.55 and 60 publications per researcher respectively.

Table 3 shows the distribution of total, public and private R&D expenditures across Italian regions and compares these with the number of publications.

Table 3. R&D expenditures and publications across Italian regions (,000 Euros; constant prices 1995; 1990-2001 mean values)

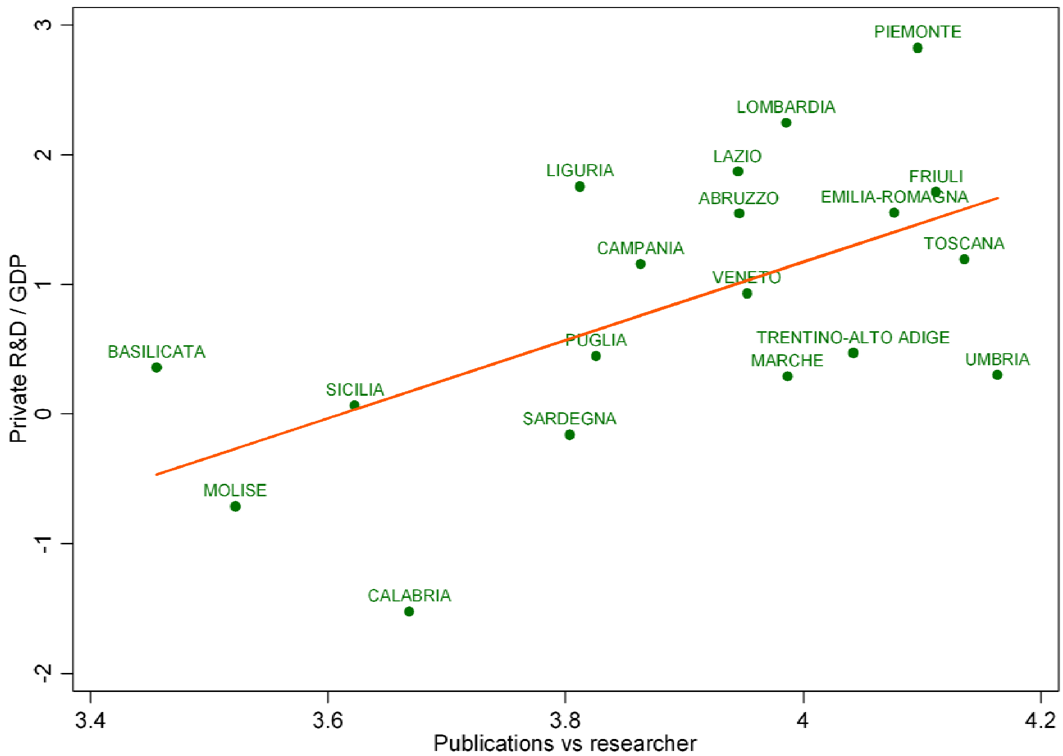
Region	N Publications	Total R&D	Private R&D	Public R&D
EMILIA-ROMAGNA	22,167.00	711,752.58	379,880.17	331,872.67
LOMBARDIA	18,634.00	2,329,485.25	1,808,760.58	520,724.58
TOSCANA	15,513.00	558,687.58	206,042.25	352,645.25
LAZIO	13,229.00	1,904,128.17	606,956.08	1,297,171.75
CAMPANIA	11,050.00	500,306.83	191,737.92	308,569.00
VENETO	9,483.00	423,185.33	213,965.83	209,219.25
PIEMONTE	9,143.00	1,567,384.17	1,367,001.75	200,382.25
SICILIA	7,748.00	311,484.67	59,695.00	251,789.50
PUGLIA	5,460.00	205,285.08	68,893.08	136,392.25
FRIULI	5,436.00	222,353.50	119,898.08	102,455.42
UMBRIA	4,823.00	84,283.17	17,613.50	66,669.92
SARDEGNA	4,351.00	117,888.08	17,461.33	100,426.75
LIGURIA	3,621.00	332,267.25	166,293.00	165,974.17
MARCHE	3,396.00	96,425.67	31,421.08	65,004.17
CALABRIA	2,116.00	49,656.25	4,463.67	45,333.92
TRENTINO-A. A.	1,709.00	75,325.58	31,990.83	43,334.50
ABRUZZO	1,656.00	150,082.92	84,504.83	65,578.00
BASILICATA	887.00	37,495.42	9,772.33	27,723.08
MOLISE	237.00	10,239.17	2,067.00	8,171.92
*ITALY**	*140,659.00*	*509,879.82*	*283,600.96*	*226,286.23*

*Mean values for R&D expenditures

Figure 4 shows the relationship between the intensity of private R&D expenditures (see Table 3) and the effectiveness of academic research activity in each region. The log specification of both variables implies the existence of a power functional relationship. The regression line fits the data quite well, supporting the idea that there is a mutually reinforcing relationship between private and academic research. The position of each region with respect to the regression line reflects the extent to which they are above or below average. Out of the virtuous regions, Piedmont is located at the top-right in the diagram, showing the highest combination of the two variables. Then one can find Lombardy, followed by some North-Eastern regions like Friuli and Emilia Romagna. Finally, two central regions, i.e. Lazio and Abruzzi, deserve to be mentioned as contexts in which industrial and academic research are mutually reinforcing. Moreover, it is hardly surprising to note that most of the less developed Southern regions are in the bottom-left part of the box.

The preliminary evidence gathered confirms that the productivity of research activities is larger where there is an agglomeration and concentration of different research organizations and, hence, a closer interaction between firms and universities.

Figure 4. The relation between private R&D expenditures and scientific productivity



4. CONCLUSIVE REMARKS

The academic system is undergoing a deep transformation in the way in which it creates and disseminates knowledge, as well as in the characteristics of the knowledge it produces. The new academic system emerging from such transformation seems to be able to fill the gap between the two, extreme and traditional cases of knowledge production: on the one hand, the public provision of knowledge through basic research, and, on the other, the private provision of knowledge as a (quasi) proprietary good on the part of firms.

Inter-organizational and qualified interactions are an intermediate knowledge governance mode between the extremes of pure market transactions and vertical integration. Knowledge interaction consists of the intentional implementation of selective and preferential communication between providers of interdependent knowledge-based services. Because of the peculiar characteristics of knowledge as partially appropriable, excludable and indivisible, in a context where transactions are not completely efficient, knowledge interactions emerge as the appropriate strategy pursued by innovators in order to endogenize the effects of positive knowledge externalities and complementarities.

The emergence of a (quasi)market for scientific knowledge and research-based services and the ensuing flows of knowledge interactions are the result of the interdependence among numerous elements: 1) the typical non-exclusivity that characterizes academic employment and the freedom to enter professional markets traditionally accepted for academics; 2) the enhanced knowledge transactions made possible by increasing knowledge appropriability and tradability through licensing, patenting and consultancy; 3) the rise of venture capitalism and of dedicated financial markets for knowledge and innovation; 4) the development of a complementary knowledge intensive business services (KIBS) sector able to intermediate between universities and firms, especially new ones; 5) the improved mutual understanding between academics and firms with respect both to the demand for knowledge and to the identification of local pools of knowledge characterized by high levels of complementarity: 6) the implementation of technology infrastructures, such as research consortia and technological platforms as specific forms of qualified interactions that support technology and knowledge sharing between firms and universities; 7) the faster pace of innovation and the increasing uncertainty confronted by firms, which are therefore increasingly incentivated to liaise with external agents in order to attempt to "control" their environment.

It has been highlighted that there is an inherent conflict between the set of incentives and rewards in the traditional open science system, based on peer-reviewed publication of basic research, and the incentives and rewards that are at the core of the new entrepreneurial university model, focused on the revenue generated from commercial application of basic research.

However, the two different approaches are not only and not merely historically specific, divergent and substitute. The two approaches can be understood also as localised and more or less appropriate according to the nature of the knowledge (e.g., tacit vs. codified) and of the innovations (disruptive vs. incremental) that are being created, or according to the relationship between technological and scientific knowledge that characterizes different fields (Nelson and Rosenberg, 2004). For instance, while "knowledge mode 1" and "ivory-towerism" can be useful for the creation of codified knowledge in the case of radical innovations, interactions and close collaboration between university and industry can be appropriate in the case of more applied, tacit and incremental innovations. The integration between the economics of information, the economics of knowledge and the interactionist approach provides an analytical framework able to clarify the variety of organizational and governance systems in the research sector. In this framework, open science and university-industry interactions coexist as two complementary modes of knowledge production whose synergies are beneficial to the overall innovative and scientific development (Rossi, 2007). Open science enables the rapid advancement of the scientific frontier and the opening up of a wide range of scientific possibilities and opportunities. Interactions between firms and universities allow for such findings not only to find useful applications, but also to be constantly ameliorated and adjusted according to users' needs.

In this perspective, knowledge is increasingly viewed as a collective good based upon the integration of external resources by means of interactions and communication, where the division of knowledge renders networks and platforms appropriate coordinating forms. The importance progressively given to intentional interactions and communication in the new economic understanding of knowledge production, requires to consider: 1) the way in which different knowledge bases require different institutional patterns especially in terms of learning and communication norms, and 2) the way in which these patterns and norms imply different forms of organisation and governance of knowledge production (Patrucco, 2008 and 2009).

The economics of interactions and social networks provides the elementary principles to understand the role of external resources in the overall process of innovation and knowledge creation. Knowledge transactions and knowledge interactions are often complementary: knowledge transactions add to and qualify knowledge transactions. Connections and interactions between actors emerge as a crucial institutional element to understand the dynamic properties of innovation systems and the governance of knowledge creation and dissemination. The growing array of relationships between university and industry are only a specific, and yet increasingly important, case of the more general properties recognized by the economics of interactions and social networks.

In sum, the economics of social interactions provides the economics of knowledge with a powerful tool of analysis to understand and guide the evolution of the organization and governance of knowledge generation. Specifically, the grasping of key role of knowledge interactions provides basic guidance in understanding the evolution of the organization of the academic system. Much work is necessary in order to qualify the actual amount of knowledge communication and knowledge generation that transactions and interactions actually produce and to qualify the characteristics of the context into which they take place most effectively. The identification and valorization of knowledge transactions that are rich in knowledge interactions and the sorting of transactions with a low interactionist content become central issues in the organization of effective knowledge governance mechanisms.

REFERENCES

Abramovski, L., R. Harrison and H. Simpson (2007), ‘University research and the location of business R&D’, *Economic Journal*, 117 (3), 114-141.

Antonelli, C. (2007), ‘Technological knowledge as an essential facility’, *Journal of Evolutionary Economics*, 17 (4), 451-471.

Antonelli, C. (2008a), ‘The new economics of the university: A knowledge governance approach’, *Journal of Technology Transfer*, 33 (1), 1-22.

Antonelli, C. (2008b), *Localized Technological Change: Towards the Economics of Complexity*, London: Routledge.

Antonelli, C. (2009), ‘Pecuniary externalities: The convergence of directed technological change and the emergence of innovation systems’, *Industrial and Corporate Change*, forthcoming

Antonelli, C. and Teubal, M. (2008), ‘Knowledge-intensive property rights and the evolution of venture capitalism’, *Journal of Institutional Economics* 4, 163-182.

Arrow, K. J. (1962), ‘Economic welfare and the allocation of resources for invention’, in R. R. Nelson (ed), *The Rate and Direction of Inventive Activity: Economic and Social Factors*, Princeton: Princeton University Press for N.B.E.R, pp. 609-629.

Audretsch, D. B. and M. P. Feldman (1996), ‘Spillovers and the geography of innovation and production’, *American Economic Review*, 86 (3), 630-642.

Audretsch, D. B. and P. E. Stephan (1996), ‘Company-scientist locational links: the case of biotechnology’, *American Economic Review*, 86 (3), 641-652.

Bonaccorsi, A. and C. Daraio (2007), *Universities and Strategic Knowledge Creation: Specialization and Performance in Europe*, Cheltenham: Edward Elgar.

Bush, V. (1945), *Science: The Endless Frontier*, Report to The President on a Program for Postwar Scientific Research, Washington, D.C., Department of Defence.

Bordons, M., I. Gomez, M. T. Fernandez, M. A. Zulueta and A. Mendez (1996), ‘Local, domestic and international scientific collaboration in biomedical research’, *Scientometrics*, 37 (2), 279-295.

Bordons, M. and M. A. Zulueta (1997), ‘Comparison of research team activity in two biomedical fields’, *Scientometrics,* 40 (3), 423-436.

Cohen, W.M. and D. A. Levinthal (1990), ‘Absorptive capacity: a new perspective on learning and innovation’, *Administrative Science Quarterly*, 35 (1), 128-152.

Consoli, D. and Patrucco, P. P. (2008), 'Innovation platforms and the governance of knowledge: Evidence from Italy and the UK', *Economics of Innovation and New Technology*, 17 (7/8), forthcoming.

Cowan, R. (2006), 'Universities and the knowledge economy', in B. Kahin and D. Foray (eds), *Advancing Knowledge ad the Knowledge Economy*, Cambridge, MA.: MIT Press, pp. 135-149.

Dasgupta, P, and P. A. David (1994), 'Towards a new economics of science', *Research Policy*, 23 (5), 487-521.

Durlauf, S. (2005), 'Complexity and empirical economics', *Economic Journal*, 115 (504), 225-243.

Etzkowitz, H. (2002), *MIT and the Rise of Entrepreneurial Science*, London: Routledge.

Etzkowitz, H., and L. Leydesdorff (2000), 'The dynamics of innovation: from national systems and "Mode 2" to triple helix of university-industry-government relations', *Research Policy*, 29 (2), 109-123.

Feldman, M. P. and D. B. Audtretsch (1999), 'Innovation in cities: science-based diversity, specialization and competition', *European Economic Review*, 43 (2), 409-429.

Feldman, M. P. and P. Desrochers (2004), 'Truth for its own sake: academic culture and technology transfer at Johns Hopkins University', *Minerva*, 42 (2), 105-126.

Florida, R. (1999), 'The role of the University: leveraging talent, not technology', *Issues in Science and Technology*, 15 (4), 67-73.

Lockett, A., M. Wright and S. Franklin (2003), 'Technology transfer and universities' spin-out strategies', *Small Business Economico*, 20 (2), 185–200.

Geuna, A. (1999), *The Economics of Knowledge Production*, Cheltenham: Edward Elgar.

Geuna, A. and B. Martin (2003), 'University research evaluation and funding: an international comparison', *Minerva*, 41 (4), 277-304.

Geuna, A., A. Salter and E. Steinmueller (eds) (2003), *Science and Innovation: Rethinking the Rationales for Funding and Governance*, Cheltenham: Edward Elgar.

Gibbons, M., C. Limoges, H. Nowotny, S. Schwarzman, P. Scott and M. Trow (1994), *The New Production of Knowledge: The Dynamics of Research in Contemporary Societies*, London: Sage Publications.

Griliches, Z. (1992), 'The search for R&D spillovers', *Scandinavian Journal of Economics*, 94, 29-47.

Katz, J. S. (1999), 'The self-similar science', *Research Policy* 28 (5), 501-518.

Knorr-Cetina, K. (1999), *Epistemic Cultures: How the Sciences Make Knowledge*, Cambridge, MA.: Harvard University Press.

Lane, D. A. (1993), 'Artificial worlds and economics, part II', *Journal of Evolutionary Economics*, 3 (3), 177-197

Lane, D. A. and R. R. Maxfield (2005), 'Ontological uncertainty and innovation', *Journal of Evolutionary Economics*, 15 (1), 3-50.

Lawton-Smith, H. (2006), *Universities, Innovation and the Economy*, London: Routledge.

Link, A. N., D.S. Siegel and B. Bozeman (2007), 'An empirical analysis of the propensity of academics to engage in informal university technology transfer', *Industrial and Corporate Change*, 16 (4), 641-655.

Lotka, A. J. (1926), 'The frequency distribution of scientific productivity', *Journal of the Washington Academy of Sciences*, 16(12), 317-323.

Lowe, R. and C. Gonzalez-Brambila (2007), 'Faculty entrepreneurs and research productivity: a first look', *Journal of Technology Transfer*, 32 (3), 173-194.

Lundvall, B.A. (1985), *Product Innovation and User-Producer Interaction*, Aalborg: Aalborg University Press.

Mansfield, E. (1995), 'Academic research underlying industrial innovations: sources, characteristics and financing', *Review of Economics and Statistics*, 77 (1), 55-65.

Medda, G., C. Piga and D. S. Siegel (2005), 'University R&D and firm productivity: evidence from Italy', *Journal of Technology Transfer* 30 (1/2), 199-205.

Merton, R. K. (1968), 'The Matthew effect in science: the reward and communication systems of science are considered', *Science* 5 (159), 56-63.

Merton, R. K., (1973), *The Sociology of Science. Theoretical and Empirical Investigations*, Chicago: University of Chicago Press.

Mowery, D. (1983), 'Economic theory and government technology policy', *Policy Science*, 16 (1), 27-43.

Mowery, D. C. and A. A. Ziedonis (2002), 'Academic patent quality and quantity before and after the Bayh-Dole Act in the United States', *Research Policy* 31 (3), 366-418.

Mowery, D. C., R.R. Nelson, B. Sampat and A. A. Ziedonis (2004), *Ivory Tower and Industrial Innovation. University-Industry Technology Transfer Before and After the Bayh-Dole Act,* Stanford: Stanford University Press.

Murray, F. (2004), 'The role of academic inventors in entrepreneurial firms: sharing the laboratory life', *Research Policy*, 33 (4), 643-659.

Nelson, R.R. (1959), 'The simple economics of basic scientific research', *The Journal of Political Economy*, 67 (3), 297-306.

Nelson, R. R. (2004), 'The market economy and the scientific commons', *Research Policy*, 33 (3), 455-471.

Nelson, R. R. and N. Rosenberg (2004), 'American universities and technical advance in industry', *Research Policy*, 23 (3), 323–348.

Nowotny, H., P. Scott and M. Gibbons (2001), *Re-Thinking Science: Knowledge and the Public in an Age of Uncertainty*, Cambridge: Polity Press.

Patrucco, P.P. (2006), 'The production of scientific knowledge in Italy: evidence in theoretical, applied and technical sciences', European University Institute Working Papers RSCAS No. 2006/12.

Patrucco, P. P. (2008), 'The economics of collective knowledge and technological communication', *Journal of Technology Transfer* 33 (6), forthcoming.

Patrucco, P. P. (2009), 'Collective knowledge production costs and the dynamics of technological systems', *Economics of Innovation and New Technology*, 18 (3), forthcoming.

Robinson, D. K. R., A. Rip and V. Mangematin (2007), 'Technological agglomeration and the emergence of clusters and networks in nanotechnology', *Research Policy*, 36 (6), 871-879.

Rosenberg, N. (1994), *Exploring the Black Box*, Cambridge: University Press.

Rossi, F. (2007), 'Understanding the organization of scientific production: from the economics of information and knowledge to dynamic interactionism', Department of Economics, University of Torino, mimeo.

Rothaermel, F. T. and M. C. Thursby (2005a), 'University-incubator firm knowledge flows: assessing their impact on incubator firm performance', *Research Policy*, 34 (3), 305-320.

Rothaermel, F. T. and M. C. Thursby (2005b), 'Incubator firms failure or graduation? The role of university linkages', *Research Policy*, 34 (7), 1076-1090.

Rothaermel, F. T., S. D. Agung and L. Jiang (2007), 'University entrepreneurship: a taxonomy of the literature', *Industrial and Corporate Change*, 16 (4), 691-791.

Russo, M. (1985), 'Technical change and the industrial district: the role of interfirm relations in the growth and transformation of ceramic tile production in Italy', *Research Policy*, 14 (6), 329-343.

Sampat, B. N. (2006), 'Patenting and U.S. academic research in the 20th century: The world before and after Bayh-Dole', *Research Policy*, 35 (6), 772-789.

Siegel, D. S. (ed) (2006), *Technology Entrepreneurship: Institutions and Agents Involved in University Technology Transfer*, Vol. I. Cheltenham: Edward Elgar.

Siegel, D. S., D. Waldman and A. N. Link (2003), 'Assessing the impact of organizational practices on the relative productivity of university technology transfer offices: an exploratory study', *Research Policy*, 32 (1), 27-48.

Siegel, D. S., M. Wright and A. Lockett (2007), 'The rise of entrepreneurial activity at universities: organizational and societal implications', *Industrial and Corporate Change*, 16 (4), 489-504.

Van Looy, B., M. Ranga, J. Callaert, K. Debackere and E. Zimmerman (2004), 'Combining entrepreneurial and scientific performance in academia: towards a compound and reciprocal Matthew-effect?', *Research Policy*, 33 (3), 425-441.

Von Hippel, E. (1988), *The Sources of Innovation*, Oxford: Oxford University Press.

Von Hippel, E. (2005), *Democratizing Innovation*, Cambridge, MA.: The MIT Press.

Von Tunzelmann, N . M. Ranga, B. Martin and A. Geuna (2003), The effects of size on research performance: a SPRU review, SPRU, University of Sussex, Brighton.

Zucker, L. G. and M. R. Darby (2001), 'Capturing technological opportunity via Japan's star scientists: evidence from Japanese firms' biotech patents and products', *Journal of Technology Transfer*, 26 (1-2), 37-58.

Zucker, L. G., M. R. Darby and M. B. Brewer (1998), 'Intellectual human capital and the birth of US biotechnology enterprises', *American Economic Review*, 88 (11), 290-306.