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Knowledge, complexity, uncertainty and the governance of industry-university interactions

Federica Rossi

PhD Student

Dipartimento di Economia

Università degli Studi di Torino

Via Po 53

Torino (Italy)

Email: rossi.federica@unito.it

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Abstract

In the course of the last few decades, firms and universities have been increasingly involved in mutual interactions with the purpose to create, disseminate and exploit knowledge.
The purpose of this paper is to develop a comprehensive framework in order to understand the economic incentives underpinning the increased interactions between universities and firms, from the perspective of all the agents involved – firms, universities, governments. We show how the tools of the economics of knowledge and the conceptualization of knowledge production as an activity characterized by complexity, uncertainty, path dependency, idiosyncrasy, can fulfill these objectives.

Keywords: economics of information, economics of knowledge, knowledge governance, university-industry relationships, third stream activities

1. Introduction

Although the historical roots of the relationships between industry and academia have been traced back to late eighteen and early nineteenth–century England and Germany (Lawton Smith, 2006; Etzkowitz, 1998), this phenomenon has become more widespread in the second half of the XX century, and particularly since the 1980s, first in the US and then in Europe. Besides quantitative effects - measured by increases in the number of university-assigned patents (Geuna and Nesta, 2006), in the number of papers co-authored by academic and industrial scientists (Hicks and Hamilton, 1999), in universities' income from royalties (Feller, 1990, AUTM, 2002) and in the amount of industry funds assigned to academic research - a visible qualitative effect of the increased interaction between industry and academia has been the flourishing of new organizational forms[1]. The European Commission (EC, 2005) reports a trend towards greater outsourcing of R&D from firms to universities, in parallel with a reduction in the overall share of business R&D. US data highlight similar trends (Slaughter and Rhoades, 1996). Empirical evidence confirms that interactions among universities and firms involve activities of knowledge production as well as just transfer and application of existing knowledge[2].

At the same time, governments in many countries have modified their institutional frameworks in order to provide incentives for universities to more effectively transfer academic knowledge to the economic system. The commercialization of research outcomes has been stimulated by the approval of legislative measures such as the Bayh-Dole Act (1980), which has permitted US universities to patent federally funded research results, and by similar measures adopted in many countries in the course of the 1980s and 1990s (Agyres and Liebeskind, 1998). Governments have also supported a wide range of new programmes designed to encourage universities to interact with industry (Cohen et al., 2002), for example through the provision of public funds explicitly directed at financing the development of third stream activities (such as the Higher Education Innovation Fund in the UK), and the creation of fiscal and monetary incentives promoting industry funding of academic research and the setup of academic spinoffs (DTI, 2003; OECD 2000).

The purpose of this paper is to develop a comprehensive framework in order to understand the economic incentives underpinning the interactions between universities and firms, from the perspective of all the agents involved: firms, universities, and governments. The economic understanding of knowledge has undergone major changes in the second part of the XX century (Antonelli, 2005; Dosi, Malerba, Ramello and Silva, 2006). While knowledge was initially considered as equivalent to information – that is, the symbolic representation of knowledge content, intangible and transmissible – a range of contributions from different sources has progressively led to a widely diffused conceptualization of knowledge as path dependent, localized, complex, idiosyncratic. This has led to a progressively shared emphasis on the role of interactions among economic agents as fundamental for the production and exchange of knowledge to take place. In section 2, the evolution in the

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[1] Among these, academic-industrial liaison offices, technology licensing offices, industry-university research centres, research joint ventures, university spin-offs and technological consultancies (Onida and Malerba, 1989; Peters and Etzkowitz, 1990; Cohen et al, 2002; Link et al., 2007; Rothaermel et al., 2007).

[2] Data show that universities increasingly engage in co-operative R&D projects focused on the development of technological applications for industrial needs (Geuna, 1999).

economic view of knowledge and of knowledge production activities is briefly described, showing how, in the so-called "knowledge-based economy" interactions among different organizations are increasingly important for knowledge to be produced and exchanged. It is also argued that the increasing rapidity of technological and organizational change further exacerbates the incentives for economic agents to engage in qualified interactions – where this term indicates any form of relationship that is longer lasting than a spot market transaction, and hence requires the establishment of durable communication patterns[3].

Having articulated this framework, the paper then applies it to the understanding of the more specific incentives that underpin the interactions among industry and academia, first by looking at the incentives that firms confront with respect to the choice of governance modes for knowledge exchange and production, in section 3, then by looking at the rationales that underpin the promotion of government incentives for universities to interact with firms, in section 4. Section 5 claims that the understanding of knowledge creation as a complex, uncertain, path dependent process can help make sense of another important role played by university-industry interactions, that of promoting dynamic coordination in the academic system, and hence benefit universities as well as firms. Section 6 concludes.

2. Interactions in knowledge production and exchange: a theoretical framework

2.1. From the economics of information to the economics of knowledge

The properties of information as an economic good were first studied by Arrow (1962), who highlighted the appropriability issues that stem from information's non-rivalry, non-excludability and from the asymmetry in the assessment of its content leading to the so-called "Arrow's paradox". The approach developed in order to study the economic properties of information as a public good has then been applied to scientific knowledge, which shares many of these properties[4].

Nelson (1959) was the first to show how several features of basic research activities – its serendipity, the large externalities associated with its production, the uncertainty characterizing its outcomes – cause social returns to basic research to be larger than private returns, and this discrepancy leads, in the absence of remedial actions, to suboptimal private investment in science.

This market failure argument has constituted the main economic rationale for public intervention in stimulating scientific production since it was first formulated (Mowery, 1983). To overcome the market inefficiencies associated with knowledge production, in fact, the government can either engage directly in the production of knowledge, making it freely available for use, or it can offer public subsidies to private knowledge producers, who agree to make their research outcomes public (Dasgupta and David, 1994). The latter, triangular scheme corresponds to the academic research system: businesses accept to pay some taxes that are transferred by

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[3] Qualified interactions therefore comprise a range of governance structures that goes from coordinated transactions to constructed interactions to quasi-hierarchies, and a variety of hybrid forms in between (Antonelli, 2005).

[4] According to Dasgupta and David (1994), scientific knowledge possesses many features that are typical of durable public goods, 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".

the State to academia, which in turn manages the open science system of knowledge production (Antonelli, 2008).

Using the tools of the economics of asymmetric and incomplete information (Akerlof, 1970, Arrow, 1971, Stiglitz, 2002), the new economics of science approach (Dasgupta and David, 1987, 1994), has successfully explained the economic rationale underpinning the organization of academic knowledge production in the open science system. The latter consists in a system of rules – of which the most important are the rule of priority, the rule of open dissemination, the rule of autonomy (or self-determination) – which efficiently solve the so-called "knowledge tradeoff" between the need to create incentives for the production of scientific knowledge and the need to maximize its dissemination in order to foster the production of further knowledge.

Besides the direct public funding of research, the assignment of property rights to innovators is another effective scheme in order to guarantee that an efficient amount of knowledge is produced in the economic system: society grants intellectual property rights to private producers for their discoveries, and permits them to charge fees for their use by others, thus creating private markets for the exchange of knowledge (Dasgupta and David, 1994). The possibility to protect knowledge through the enforcement of the patent system renders knowledge a quasi-private good with high levels of appropriability and limited externalities, increasing the incentives for private production. The argument that markets for knowledge - underpinned by the enforcement of intellectual property rights and by innovative institutions such as financial markets for high-tech companies (Antonelli, 2005; Antonelli and Teubal, 2008) - provide an efficient model for the governance of knowledge production and exchange, has gained widespread acceptance, particularly since the early 1980s.

At the same time, a view has progressively emerged according to which knowledge is most often characterized by economic properties that are different and more complex than those of either fully public or fully private goods.

A first important step towards greater understanding of the complex features of knowledge has been made when economists[5] have begun to shift their attention from the concept of information to the more general concept of knowledge, which includes all forms of intangible artifacts, whether codified and hence easily transmissible, like information, or more tacit in nature, difficult to transmit from one person to another, such as various kinds of individual crafts and skills.

Already before the 1970s, studies of human learning had shown that individual learning always includes a tacit, non-expressible dimension (Polanyi, 1966) and that consequently knowledge is often not exchanged instantaneously but its acquisition requires practice and the active participation of the learning individual (Ryle, 1949; Polanyi, 1966). A lively debate on the nature and implications of "tacit knowledge" has taken place (Cowan, David and Foray, 2000): typologies of knowledge, positioned between the two extremes of "full codification" and "tacitness", have been proposed, generally referred to the knowledge possessed by the organization rather than by the individual (Nonaka and Takeuchi, 1995; Blackler, 1995; Lam, 2001).

[5] Dosi, Llerena and Sylos Labini (2006) refer to this body of interpretation as the "Stanford–Yale–Sussex (SYS) synthesis", represented by authors such as Nathan Rosenberg, Christopher Freeman, Keith Pavitt. This interpretation takes on board the original Arrow–Nelson intuitions on the economics of information and their further refinements (see for example David, 2004), and integrates them with developments in the analysis of the specific features of technological knowledge.

Recognizing that knowledge cannot be reduced to information undermines some of the assumptions that underpin the conventional economic interpretation of knowledge-producing activities.

First, since knowledge is often specific to the context where it is generated, it may be difficult to transfer it without the assistance of its creator, and as a consequence imitation costs can be high: certain forms of knowledge can be regarded as having quite high levels of natural appropriability and exclusivity, without the need to enforce patent protection (Levin, Klevoric, Nelson and Winter, 1987).

Secondly, attention for the tacit dimension of knowledge has led scholars to re-examine the nature of scientific research activities. It has in fact been acknowledged that scientific knowledge and, even more so, technological knowledge share some degrees of tacitness, drawing upon skills and techniques "that are acquired experientially, and transferred by demonstration, by personal instruction and by the provision of expert services (advice, consultations, and so forth), rather than being reduced to conscious and codified methods and procedures" (Dasgupta and David, 1994). As a consequence, the distinction between scientific and technological knowledge is blurred: both types of knowledge combine tacit and codified elements, which may be more or less prevalent in different cases[6].

Third, the interpretation of individual knowledge as situated in the context of the actions and interactions that the individual performs - a claim that has been supported by empirical evidence and by the most recent developments in cognitive science (Suchman, 1987; Clarke, 1997) – has led to an increasing appreciation for the role played by interactions in knowledge creation and transmission.

2.2. Complexity, uncertainty and the role of inter-organizational interactions

Another important advance in the understanding of knowledge is the acknowledgement that the production of new knowledge often requires the recombination of knowledge from different sources. The increasing appreciation that innovation depends upon the integration and recombination of different sources of knowledge, often external to the firm, results from the convergence of different strands of research. The competence theory of the firm (Penrose, 1959; Hodgson, 1988) has laid the foundations for an understanding of knowledge creation and transformation as key economic activities performed by the firm, opening the way for an appreciation of interactions as sources of competence creation and regeneration. The study of user-producer interactions as a source of innovation, originated in the organizational literature and in the literature on industrial districts (Lundvall, 1985; Russo, 1985; Von Hippel, 1988), has also highlighted the importance of flows of inter-organizational knowledge. Interactions among agents possessing heterogeneous cognitive resources are considered crucial for the production of new knowledge (Nooteboom, 2004; Lane and Maxfield, 1997; 2005): the semantic ambiguity that emerges from these relationships is a powerful mechanism for innovation (Lane and Maxfield, 1997; Fonseca, 2002). At the same time, such interactions must be longer lasting than spot market transactions so that it can be ensured that cognitive distance among the agents involved is not so wide as to prevent communication (Nooteboom,

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[6] This has been confirmed by numerous studies in the history and sociology of science and technology, which have shown that technology and science are mutually dependent and that it is often difficult to distinguish between them (Mokyr, 1990, McKenzie and Wajcman, 1999, Nelson and Rosenberg, 2004).

2004). The literature on knowledge spillovers (Griliches, 1992) - which provide economic actors with the opportunity to access external knowledge at costs that are below equilibrium levels because of pecuniary knowledge externalities (Antonelli, 2009) – has led scholars to further appreciate the economic role of external knowledge and to pay attention to the features of organizations which foster the creation and absorption of such spillovers (Jaffe, 1989; Jaffe and Trajtenberg, 1996; Audretsch and Feldman, 1996). Proximity among agents – cognitive, geographical, cultural, social – is required for knowledge transmission (Balconi, Breschi, Lissoni, 2003).

With the term "complexity" of knowledge we refer to the extent to which the production of new knowledge requires the integration and recombination of existing sources of knowledge. The knowledge base that firms need to innovate is more complex the more it is characterized by cumulativity (building upon pre-existing knowledge), complementarity (requiring the integration of different, complementary types of knowledge), compositeness (requiring the combination of different "bits" of knowledge that are held by many different agents). Numerous studies support the claim that, as technological knowledge cumulates and expands, firms are becoming increasingly dependent on a wider range of knowledge fields in order to develop their innovations (Powell et al, 1996, Pavitt, 1998; Nesta and Saviotti, 2006) and that industrial production has a growing scientific and technological content (Geuna, 1999). Over time, the increased complexity of products and processes induces firms to increasingly seek complementary competences outside their boundaries. The degree to which a firm's knowledge base is more or less complex is also, to some extent, a matter of managerial choice: firms can choose to draw upon a greater number of sources of external knowledge by adopting more "open" search strategies (Laursen and Salter, 2004).

Thanks to these theoretical advances, knowledge is increasingly conceptualized as partly tacit, sticky, complex, idyosincratic - as in the notion of localized technological knowledge proposed by Antonelli (2001). Knowledge creation is seen as a collective, localized and path dependent process (Antonelli, 2005).

In these conditions, the transmission of knowledge is fundamental in order to produce new knowledge, but often it is not easily regulated by demand and supply mechanisms in the context of impersonal markets. For knowledge to be easily traded through arms' length transactions, it should be fully appropriable, so that opportunistic behaviour due to the "Arrow paradox" is avoided; it should be fully codified, so it can be disseminated without the assistance of its original holder; and uncertainty about its content and applicability should be minimum, so that comprehensive contracts can be drawn. Under these conditions, "quasi-markets for knowledge" (Guilhon, 2001) can arise, where different kinds of organizations can specialize in the production and exchange of knowledge as an economic good. But very often, instead, knowledge is characterized by tacitness, high uncertainty and by limited appropriability conditions, (Levin, Klevoric, Nelson and Winter, 1987; Dosi, Marengo and Pasquali, 2006). In this case, the setup of qualified interactions among different organizations allow the various agents to create a context conducive to knowledge sharing and transmission, thanks to the setting up of appropriate communication channels and the development of appropriate languages and communication codes.

Besides facilitating the transmission of existing knowledge, qualified interactions are often necessary for the creation of new knowledge to take place. Vertical integration of knowledge production activities within the firm often fails. On the one hand, the inability to fully appropriate the returns of internal research activities means that the firm may be reluctant to finance their full cost; this is especially true for research whose outcomes is difficult to anticipate in terms both of rate and of direction, and which can occasionally open up many more opportunities than those that the individual firm, because of coordination costs, can realistically exploit (Arrow, 1974)[7]. On the other hand, the firm incurs high agency cost with respect to research activities: since knowledge production is characterized by creativity and serendipity, it is difficult for the firm to monitor the effort and competence of its workers, who may be induced to behave opportunistically. And since the distribution of creativity is very skewed (Patrucco, 2006) mistakes in the identification of the most creative workers and failure to implement the appropriate incentive structures in order to motivate them have major negative consequences on the output and average cost of research activities (Antonelli, 2008). Complex coordination mechanisms based on the setup of qualified interactions among different organizations can facilitate knowledge production by reducing agency costs thanks to the construction of a context characterized by trust and reciprocity, allowing the mutual appropriation of knowledge externalities and the sharing of research costs, and allowing access to external complementary knowledge (Antonelli, 2008).

Finally, the role of uncertainty is another important element in order to understand the increasing importance of inter-organizational interactions. Besides the well known uncertainty in the outcomes of research activities – in terms of their timing, their direction, their potential to open up new avenues of research – another important source of uncertainty is related to the economic context in which firms operate. The increasing pace of organizational and technological change that firms confront, generates what Lane and Maxfield (2005) define "ontological uncertainty": a situation where economic agents uncertain as to what processes and what other agents are likely to affect the consequences of their own actions. In these conditions, agents are not only unable to formulate a probability distribution over a set of outcomes – as in the concept of non-probabilizable risk that characterizes knightian uncertainty – but may be unable to even conceive a tentative list of possible outcomes. Firms that face ontological uncertainty are strongly incentivized to pursue qualified interactions with other organizations, in order to exert some influence on the many complex processes that will ultimately affect the results of their own activities. In fact, organizations can control uncertainty by constructing long lasting inter-organizational structures (which Lane and Maxfield, 1997, call "scaffolding structures") which provide relatively stable contexts within which to engage in shorter-term interactions: inter-firm alliances, user organizations, forums, trade associations, fairs and exhibitions, standard setting organizations, and so on. Through the construction of "scaffolding structures", organizations confront ontological uncertainty by providing a meta-stable context within which inter-organizational interactions can take place, meanings can be negotiated, strategies can be devised (Lane and Maxfield, 2005).

Together, the increased uncertainty of the economic environment and the increased complexity of technological systems drive innovation processes to become more open

[7] This problem was first acknowledged by Nelson (1959), who argued that only multiproduct firms able to capture economies of scope would be inclined to invest resources in basic research with uncertain outcomes but potentially giving rise to applications in many different fields only.

and distributed, as it has been argued by several commentators (Chesbrough, 2003; Powell and Grodal, 2005).

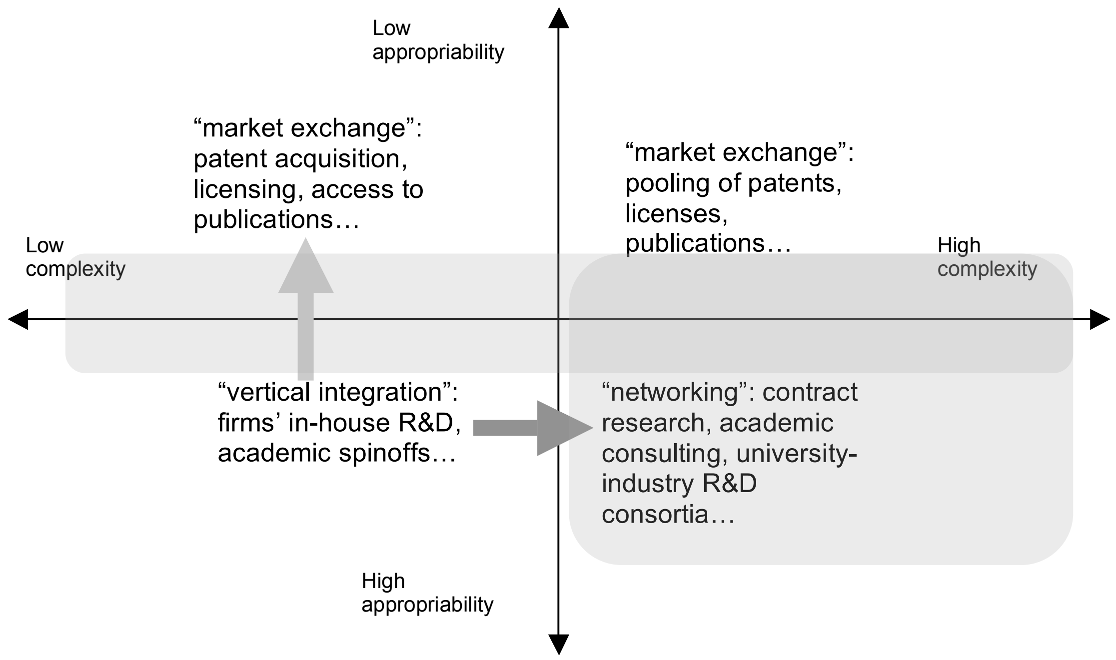
The integration of these different strands of research provides a useful theoretical framework in order to explore the structure of incentives that underpin university-industry interactions, from the perspective of the firms engaged in such interactions, of the governments that implement policies to foster universities' involvement in third stream activities, and finally from the perspective of universities themselves.

3. University-industry interactions: the firms' perspective

In this section, it is argued that the specific economic incentives underpinning firms' decisions to engage in different kinds of interactions with academia depend upon the economic properties of the knowledge that firms need in order to carry out their innovation processes and upon the context in which interactions take place.

The simple framework presented in Figure 1 relates the characteristics of knowledge to the governance forms that firms are more highly incentivized to adopt. Building upon the literature presented in the previous section, the two dimensions that can be considered as crucial in order to explain the various forms of governance for these interactions are the extent of appropriability and the extent of complexity of knowledge, shown on the horizontal and vertical axes. The boundaries between the different quadrants are not to be interpreted as strictly divisive, since the incentives underpinning different forms of governance depend on degrees of appropriability and complexity. The shaded areas highlight the situations in which the incentives for firms to engage in qualified interactions with universities are high (light grey) or very high (dark grey).

Figure 1. Knowledge properties and the governance of university-industry interactions



Knowledge appropriability is the first key dimension in order to understand the economic incentives that underpin different modes of knowledge production (Dosi et al, 2006). Appropriability can be low for several reasons: when knowledge is codified and similar to information, and property rights cannot be easily enforced, it is difficult for an organization to fully apppropriate the externalities that stem from its production; similarly, when knowledge is fungible, in the sense that it can be profitably employed in many different applications, a single organization often cannot fully appropriate all its returns. Unpredictability and serendipity in knowledge production sometimes lead to the generation of fungible forms of knowledge, and consequently they are often related to low knowledge appropriability. Basic research activities are often characterized by all these features simultaneously (high codification, difficulty to patent, serendipity and fungibility). When knowledge apppropriability is low, incentives for the private production of knowledge are also low, and knowledge production is generally publicly funded. Firms can acquire knowledge produced by the academic system through forms of market exchange such as the access to scientific publications, or, where they exist, the acquisition of patents and licenses.

On the contrary, appropriability is high when knowledge is characterized by high tacitness and stickiness, so that it is embodied in individuals and in organizational routines, as well as when knowledge is codified but property rights can be strongly enforced. Applied research and development activities generally produce more appropriable knowledge, either because they often involve a process of articulation of tacit knowledge, or because they produce knowledge that is specific to a single product or process and does not easily spill over to benefit external agents. With high appropriability, the incentives for the private production of knowledge are higher and R&D activities are often integrated within the firm. If firms decide to involve universities in the production of highly appropriable knowledge, they are likely to do so via research contracts and consulting activities, since it is reasonably easy to draft a contract according to which the knowledge produced by the university is appropriated by the firm. When universities independently produce more applied knowledge, they have become more likely to get directly involved in its commercial exploitation via the setup of academic spinoffs, thanks to the emergence of new complementary institutions such as markets for venture capital (Antonelli and Teubal, 2008).

Intermediate appropriability conditions produce higher incentives for firms and universities to engage in qualified forms of networking such as joint research consortia. In these cases, in fact, the production of knowledge requires coordinated interactions both in order to reduce information asymmetries, whose management requires monitoring and assessment, and in order to permit the absorption of knowledge spillovers by prospective users (Antonelli, 2005).

The complexity of the knowledge base upon which an organization relies is the other important dimension in order to determine the incentives for university-industry interactions. The more the knowledge base is complex, the higher the need to resort to external sources in order to produce new knowledge. The incentives for qualified interactions as a governance mode for the production and transmission of knowledge increase further. Again, for those less appropriable forms of scientific knowledge that are produced by the academic or government research systems and can be acquired through forms of market exchange (acquisition of university patents and licenses, where they exist, or access to publications), firms can pool together different sources. When knowledge is more tacit and less easily transferable, and the firm needs to access multiple sources of knowledge, networking with universities through qualified interactions (for example through research collaborations, university-industry consortia, joint ventures) becomes more attractive.

The more uncertain and serendipitous are the outcomes of research activities, and the less clear are its appropriability conditions, the more we expect the relations between universities and firms to be based upon long-term, broadly defined contracts, which may also include funded chairs and bilateral transfer of personnel, as well as the hiring of PhD graduates (Antonelli, 2008). This situation is captured, in figure 1, by the area shaded in dark grey. When knowledge is complex but highly appropriable, interactions with universities will often take the form of consulting relationships, since the high appropriability of knowledge will make it easier for the firm to draw up a contract where the externalities flowing back to the academic system or to other external agents are controlled – a situation which is captured, in figure 1, by the area shaded in light grey in the bottom right quadrant.

The incentives for firms to interact with universities are further increased when firms operate in a context characterized by ontological uncertainty, generally spurred by fast organizational and technological change. When uncertainty is high and knowledge is complex, we expect the incentives for firms to interact with universities to be the highest. In this case, pursuing qualified interactions with university institutions presents numerous advantages. Heterogeneity is high within the academic system since most academics perform research individually or in small groups whose boundaries are flexible and changing: through interactions with universities, firms can access a wide, international network of scientists with heterogeneous competences, increasing their opportunities to establish relationships with high potential to generate innovations (Lane and Maxfield, 1997; Antonelli, 2008). Learning and research opportunities are enhanced by the possibility to access new knowledge in the form of infrastructures (such as laboratories and databases) and to temporarily post researchers and scientists in academic institutions. Firms can also hedge against uncertainty by monitoring numerous innovation processes at the same time[8].

Finally, it must be remarked that interacting with universities can be cost effective from the firms' perspective, for several reasons. First, the economics of knowledge has shown that the costs of knowledge production are lower in the academic system because of the two-part structure of academic salaries (Dasgupta and David, 1994): the academics' fixed costs are covered by the payment they receive for their teaching activities, so that "the compensation schemes practiced in the academic system allow the supply side to operate on a variable cost base" (Antonelli, 2008). By interacting with universities, firms can access high quality scientific competences at a price that is often lower than that of internal competence creation. Secondly, interacting with universities may also carry lower transaction costs. Empirical studies of the cost-effectiveness of university-industry interactions compared with inter-firm interactions are scarce, although it has been shown that small firms in dynamic high tech sectors (Colombo, Grilli and Piva, 2006) are discouraged to form explorative technological inter-firm alliances by the high costs of partner search, negotiation and other administrative costs, which may turn out to be lower when the chosen partner is a university institution which possesses dedicated academic-industrial liaison offices, technology transfer facilities, legal offices and so on. Third, the scientists' affiliation

[8] Some empirical analyses confirm that monitoring scientific developments is a crucial reason for which firms engage in interactions with academia (Meyer-Kramer and Smooch, 1998).

to academia provides a signal of quality and competence, based upon the reputation acquired in the open science system (Antonelli, 2008): thanks to the strong complementarity between the quality of teaching and the quality of scientific competence, the university has incentive to hire scientists who have been able to build up a consistent reputation for scientific ability by means of publications. The presence of an independent system that certifies the competence of academic researchers lowers the firms' search costs for high quality competences and reduces the agency problems inherent in the collaboration with knowledge workers whose skills are difficult to assess.

This framework suggests that the observed quantitative increase in the exchange of knowledge through market mechanisms (patent acquisition and licensing) and in qualified interactions between universities and firms, can be explained on the basis of different mechanisms. On the one hand, the economic actors' increasing reliance on (quasi) spot market transaction for knowledge can be explained by the increasingly codified and abstract nature of the knowledge upon which innovations draw (Arora and Gambardella, 1994) and it is facilitated by the implementation of proper institutional set-ups and devices, such as the construction and use of contractual modes of technological communication (Guilhon, 2001). The increasing codification of knowledge, which leads to increased exchange of knowledge through "market transactions", is indicated by the light grey arrow in figure 1. On the other hand, as it has been discussed, the increase in qualified interactions among universities and firms is fostered by the increasingly complex nature of both scientific and technological knowledge and by the increasingly uncertain economic context in which firms operate. The increased complexity of knowledge leading to increased reliance on networking with external organizations and particularly with universities is indicated by the dark grey arrow in figure 1.

4. University-industry interactions: the government's perspective

In the last two decades, numerous governments have introduced incentives for universities to engage in third stream activities. This is often premised on the expectation that university–industry interactions can increase the rate of innovation in the economy (Spencer, 2001). The role of innovation as a source of economic growth has become an established tenet in economic theory since the development, starting from the mid-1980s, of "new growth theory" models, in which growth-driving technological change is modeled primarily as a result of the accumulation of human capital (Lucas, 1988), of knowledge spillovers in the economy (Romer, 1990) or of the introduction of successive innovations for which patent protection creates temporary monopolies (Grossman and Helpman, 1994). This approach provides theoretical grounds to justify the economic interpretation of universities as promoters of economic growth, both through their education activities (since universities contribute to increasing the stock of human capital) and through their research activities (since they generate public knowledge that spills over to the economic system).

Underlying these economic models is a view of knowledge as an economic good that enters as an input in industrial processes. The knowledge created by universities is supplied to the economic system, either indirectly, in the form of university graduates who enter the labour market, or, more directly, in the form of research output that is transformed by firms into commercially exploitable innovations. The linear model of innovation (Godin, 2006), according to which the development of an innovation is seen as a process made up of sequential stages, temporally and conceptually distinct, characterized by uni-directional causal relationships, is still pervasive in this conception. This view justifies the creation of incentives for universities to facilitate the transfer of knowledge to the economic system: in fact, even though the linear model has been superseded by a number of rich, interactive models, policy-makers in most countries "have clung to the hope of opening up a pipeline from university research to industrial practice" (Laursen and Salter, 2004).

By reconstructing the evolution of the economic understanding of knowledge, it is possible to better understand the evolution in the structures of incentives that governments have put in place for universities to engage in third stream activities, and in the economic rationales that underpin them.

Table 1 below summarizes the various steps in evolution of the theoretical interpretation of knowledge and knowledge production activities, and relates each step to the corresponding normative implications in terms of the mechanisms that guarantee the production of socially efficient amounts of knowledge and those that permit knowledge exchange.

Table 1. Evolution in the theoretical understanding of knowledge and inormative implications

Economic interpretation of knowledge	Economic properties of knowledge	Features of knowledge production	Mechanisms guaranteeing sufficient production of knowledge	Mechanisms permitting knowledge exchange
Public good	Presence of knowledge spillovers; non appropriability; not excludability	Incentives to private production are low; knowledge production is assigned to the government and academic research systems	Public funding of research in the government and academic research systems	Free dissemination on the part of the government and academic research systems
Quasi-private good	High appropriability and excludability, limited spillovers	High incentives to private production: knowledge production is vertically integrated within firms	Enforcement of the patent system, which fosters the emergence of efficient markets for knowledge	Market exchange mediated by prices
Complex, only partially appropriable good	Intermediate appropriability due to tacitness, stickiness; production requires the recombination of multiple sources	Path-dependent, localized, cumulative, collective; knowledge production takes place within coordinated interactions among organizations	Possibility to engage in qualified interactions with external knowledge holders	Possibility to engage in qualified interactions with external knowledge holders

The view of knowledge as information, enjoying the properties of a durable public good, was prevalent throughout the 1960s and 1970s. The more knowledge is similar to information, the more intense are the market failures associated with its production, and the more necessary is direct public intervention to ensure that knowledge is produced in socially optimal quantities. Both the government and the academic research systems combine public funding of knowledge production with free dissemination of research outcomes. This view has paved the way to the build-up of the infrastructure for the public funding of science (Antonelli, 2005), which has, in most countries, greatly expanded between the 1960s and the 1980s.

The argument that the enforcement of property rights is capable to effectively foster the emergence of efficient markets for knowledge - which has gained widespread acceptance since the 1980s - justifies the introduction of incentives aimed at promoting increased patenting on the part of universities, which has taken place throughout the 1980s and 1990s. The commercialization of university research encoded in patents is supposed to facilitate the transfer of knowledge through market mechanisms based on the encounter between the knowledge offered by the academic system and the knowledge demanded by firms. The existence of university patents provides firms with information about university research, thus facilitating the transfer of knowledge from academia to industry, signals the universities' competences and provides universities with an additional source of income.

Finally, the interpretation of knowledge as partly tacit, sticky, cumulative, collective, has furthered the view that the transfer of knowledge requires purposeful interaction among economic agents and hence provides a rationale for the introduction of incentives for universities to engage in direct interactions with industry. When knowledge is partly tacit, only partially appropriable and situated in organizational routines and individual skills, the patent system, and the related price mechanism, cannot fully convey information about the knowledge's content and economic value, and hence it is not able to create efficient markets for knowledge. The need for direct communication in order to foster technology transfer provides an economic argument to justify the creation of incentives for universities to engage in direct interactions with third parties, and particularly to interact with industry in the context of qualified networking relationships[9].

The engagement in third stream activities on the part of universities is, according to this rationale, supposed to benefit primarily firms, which more effectively "receive" knowledge from the academic system, while at the same time universities are seen as better fulfilling their public mission and to benefit from these activities primarily in financial terms.

However, as we argue in the next section, universities can also benefit from interactions with external organizations in order to solve dynamic coordination issues within the academic system related to the production, and not just to the exchange, of knowledge. This argument rests on the conception of knowledge production as a complex, collective, localized, path dependent process that takes place in a context of increasingly rapid technological and organizational change.

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[9] Empirical research shows that even the use of public knowledge often requires informal interactions to accompany it (Cohen et al, 2002).

5. University-industry interactions: the universities' perspective

Besides the problem of how to achieve an efficient match between demand and supply of knowledge when market mechanisms fail – assuming that knowledge has already been produced and simply needs to be disseminated - the focus on the path dependent and localized nature of knowledge highlights another important issue related to knowledge production: how can the academic system produce knowledge in a way that is most likely to sustain the fast rate of innovation that characterizes the contemporary economy.

Since knowledge production is a collective activity distributed among many heterogeneous agents, whose interactions are necessary in order to produce new knowledge, agents need to be able to dynamically coordinate their activities in order to produce knowledge that can more effectively be transformed into commercially exploitable products and services. To sustain rapid rates of innovation, feedback mechanisms must be established so that organizations that engages in knowledge production can quickly receive signals concerning what are the most promising directions of research, what kind of knowledge offers the best potential in terms of applicability, and where useful complementary sources of knowledge may be found in order to produce new knowledge.

Systems where agents are better able to achieve dynamic coordination are likely to experience faster rates of generation of new technological knowledge and hence faster rates of introduction of technological innovations (Antonelli, 2005): in fact, "by means of dynamic coordination, missing links among key complementary modules of knowledge can be built, effective alignment of agents towards a common design able to enhance the potential complementarities among the learning agents can be practiced (Richardson, 1998; Amendola and Gaffard, 1988)" (Antonelli, 2005). In turn, for these feedback mechanisms to operate, communication networks must be in place that ensure rapid exchange of information among different kinds of organizations. These communication networks need to be meta-stable in order to sustain innovation processes that unfold over longer temporal scales than that of individual interactions (Lane and Maxfield, 2005). The presence of structured and fairly stable communication networks is therefore fundamental in order to allow both the efficient production and the exchange of knowledge to take place.

Qualified interactions provide the means to both establish communication networks, and to stabilize them – thanks to the establishment of "scaffolding structures" (organizations, for example specific offices within the universities or at the central ministerial level, or specific policy programmes) capable of supporting these networks over time – and therefore to increase coordination in the economic system.

The two problems of matching demand and supply of already existing knowledge and of carrying out knowledge producing activities in ways that are most likely to generate innovations, characterize both the education and the research activities of universities. Dynamic coordination within the academic system - with respect to the identification of the most promising lines of research and of the most promising combinations of competences to be provided to graduates – is not achieved automatically through the open science system. It has in fact been noted that the open science system suffers from three main weaknesses with respect to the organization of research and education activities (Antonelli, 2008): first, it does not provide a way to determine the correct amount of public resources to be assigned to the academic system; second, it does not identify the correct amount of public resources to be allocated across academic disciplines and scientific fields; third, it provides poor guidance in order to allocate a given amount of public funds in a given discipline among different academic institutions. It is possible to argue, therefore, that universities' third stream activities involving interactions with external stakeholders can produce positive effects with respect to the coordination of the two traditional academic activities of teaching and research, by allowing the establishment of communication networks that sustain positive feedback processes between academia and industry.

Table 2 below summarizes the benefits that universities derive from the interactions with external stakeholders, and particularly firms.

Table 2. The benefits of mutual interaction between universities and firms

	Benefits of interactions between universities and firms with respect to academic activities:	
	Research	Education
Objective: to facilitate the encounter between demand and supply of knowledge and competences	1) Interactions facilitate knowledge transfer from universities to firms	3) Interactions facilitate the provision of competences that match those demanded by firms
Objective: to facilitate the feedback processes needed to sustain a rapid rate of innovation	2) Interactions promote coordination between scientific and technological knowledge by facilitating the rapid identification of directions of scientific research with promising applications	4) Interactions promotes coordination among disciplines within the academic system in the direction of better supplying the competences needed by the economic system

Each of the quadrants of the table above is discussed, in turn.

1) With respect to research activities, it has already been discussed how, when knowledge is characterized by tacitness, stickiness, complexity, qualified interactions among universities and third parties permit the effective transfer of knowledge even in situations where the match of demand and supply of knowledge is not ensured by simple market transactions.

2) Interactions can also play a very important coordinating role in the identification of promising directions for academic research. In the traditional organization of the open science system, the task of identifying the most promising directions for research is left to academics themselves. Funds for research activities are distributed directly to individual researchers or to research teams, who are relatively free to determine the content of their research activities and are only subject to the criteria of relevance determined by the scientific community. However, in recent years, the funding agencies' increasing reliance on contract funding has increased their ability to steer research priorities. The direction of scientific research is therefore influenced both by the academics' own interests and by the funding agencies' concerns (Braun, 1998).

The new economics of science approach has highlighted how this system presents some internal coordination problems (Dasgupta and David, 1994). The reward system based on competition for priority may encourage rival teams of researchers 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 (Dasgupta and David, 1994).

Furthermore, the open science system has recently come under pressure from society's need to feed ever increasing rates of innovation, which demand closer interaction between universities and firms, in order to match the signals coming from both so as to increase the opportunities for the generation of new knowledge that finds commercial applications. With a fast rate of technological and organizational innovation, the "ivory tower" model – in which the university is expected to perform the function of issuing "knowledge signals" without paying any attention either to their actual reception on the business side, or to the knowledge signals emitted from the business community - is no longer sustainable (Antonelli, Patrucco and Rossi, 2008). Instead, closer interactions between industrial and academic research can generate positive feedbacks through the provision of signals about the needs and opportunities of both parties, necessary in order to ensure that academic research proceeds in directions that are likely to generate knowledge that is useful to firms and that can, in turn, more effectively foster the firms' innovation processes.

First, such interactions can support the process of codification of the firm's empirical knowledge into more generalizable methods and procedures, which increase the applicability of this knowledge to other organizations and to other contexts. Secondly, more indirectly, access to the firms' technological knowledge can provide universities with information about promising areas of scientific exploration. That science often builds upon technology has long been acknowledged by historians and sociologists of science, not only because science needs appropriate technological instruments in order to carry out its investigations (Rosenberg, 1994; McKenzie and Wajcman, 1999), but also because technological progress indicates which directions of scientific research yield the highest potential payoff (Rosenberg 1982; Stokes, 1997). Technology is, in itself, a body of empirical knowledge, of techniques, methods and designs: this body of knowledge not only has often allowed technological innovations to be developed even when people are lacking the necessary scientific knowledge (Rosenberg, 1982; Mokyr, 1990), but also examples can be easily found of applied research that has led to the discovery of new natural phenomena (Nelson and Rosenberg, 1996).

3) With respect to education, the main problem for the academic system is to ensure a match between the competences it produces and those demanded by the economic system. The maladaptation between these systems can be can be a major source of inefficiency, leading to the production of academic graduates whose competences do not match the firms' needs; graduates find it difficult to find employment, and firms find it difficult to recruit the competences that sustain their production and innovation processes.

Traditionally, the choice of which disciplines to teach and in what proportions has been entirely left to the academic system, which has not developed particularly efficient internal coordination mechanisms. In a pure open science system, tenured chairs – which remunerate teaching activities - should be allocated to the best scientists, evaluated via the peer-review system, with no prior identification of their disciplines or locations. Consequently, the amount of resources that should be transferred to the academic system should be based exclusively on the number of scientists that reach some absolute levels of scientific excellence (Antonelli, 2008).

In practice, in order to determine the amount of overall public resources to be allocated to each discipline and to each institution, governments in different countries operate on the basis of rules of thumb, the outcome of path-dependent processes driven by political decisions and historical contingencies, and mediated by the role of academic institutions and disciplinary affiliations.

Until the early 1980s, in most countries, the dominant mechanism for the allocation of education funds was historical expenditures, with incremental resources made available for the development of new activities (OECD, 1990). The choice of what disciplines to offer was generally left to consensus dynamics within each university institution. This generated inefficiencies. In fact, the relationship between the central government (or funding agency) and the university institutions suffers from the typical problems of the principal-agent relationship. Academic institutions may have specific internal incentives to direct the public funding towards certain fields that do not necessarily respond to the need of external stakeholders: there is a strong risk that hierarchical control, within the academic system, leads to the misallocation of funds, away from promising new fields in favour of tradition and established academic corporations (Antonelli, 2008).

Over time, incremental allocations have increasingly been replaced by formula funding. Funds for education are now increasingly allocated on the basis of the demand for education expressed by the students (that is, proportionally to the number of enrolments), in line with the emphasis on creating competitive conditions for university institutions. Resource allocation on the basis of student demand introduces incentives for universities to maximize enrolments in the short term by focusing on those disciplines for which demand is greater, in order to swell the number of enrolled students and thus increase government transfers. Although demand for higher education is ultimately sensitive to the labour market's needs for specific competences, in the absence of perfect information such adjustments are only partial and may require a very long time – longer than the time scale at which changes in the competences required, induced by technological progress, take place. Student demand for courses is based upon subjective evaluations and incomplete information: personal preferences for disciplines, uninformed assessments of the likelihood that a degree will guarantee a job with a certain income, as well as reputation effects at the level of schools and institutions[10].

Therefore, greater interactions between universities and external organizations, and particularly the creation of "scaffolding structures" to channel communication between these various stakeholders, can be beneficial, since they can provide potential students with more information about the competences that are demanded by firms, thus creating a more informed demand.

4) The problem of harmonizing the competences needed by the economic system with the demand for education expressed by potential students and the supply of education offered by the academic system is exacerbated by increasingly rapid technological and organizational change: this generates radical uncertainty in what competences will be needed even in a few years' time, and this further increases the need to

[10] Because of this, institutions are incentivized to invest in often costly forms of signaling of educational quality, which actually have little to do with quality itself; for a discussion see Rotschild and White, 1991.

implement feedback mechanisms between the academic and the industrial systems.

The problem is similar to that confronted by the system of incentives that govern scientific knowledge production in a world characterized by increasing innovation rates and hence increasing uncertainty, where the "ivory tower" model of university research is increasingly being challenged by new collaborative modes of research and by new systems of rules underpinning it, which better respond to the need to match signals from the business and the academic communities. Similarly, for universities to produce graduates in an "isolated" way, only responding to short-term demand pressures and without paying attention to the signals coming from external stakeholders, is no longer suitable in order to sustain the economy's needs. Adjusting the offer of education purely on the basis of the relatively slow dynamics of student demand leaves room for misalignment and the creation of wide competence gaps.

Establishing stronger feedback processes between potential students who express the demand for higher education, academia, and other stakeholders that demand or are informed about the competences that sustain the economic system (not just firms but also technology centres, national and local policymakers, any other organization that presides over innovation opportunities) requires the implementation of meta-stable communication networks, supported by appropriate scaffolding structures, for the mutual understanding of educational priorities.

6. Concluding remarks

The tools of the economics of knowledge and the conceptualization of knowledge as a collective, complex, path dependent and idiosyncratic provide a framework that allows us to understand the economic benefits that firms and universities derive from their mutual interaction as well as the economic rationale that underpins the government's promotion of public incentives to stimulate such interactions.

The implications of this interpretative framework are in accordance with numerous claims made by the theoretical and empirical literature on university-industry interactions.

The increasing economic importance of knowledge-intensive activities in the so-called "knowledge-based economy" (Smith, 2000) exacerbates the agency problems that characterize knowledge production within vertically integrated firms, and this should lead to an increased reliance either on the acquisition of knowledge from the academic system via market transactions, or on forms of qualified interactions with academic scientists and academic research teams, depending on the proprietary features of the knowledge involved. Both trends are in fact taking place.

This framework can also explain the empirically observed tendency for firms to increasingly interact with university institutions rather than with individual scientists (Coombs and Georghiou, 2002). As knowledge becomes more complex and requires the integration of complementary sources, some codified and non-appropriable, some tacit and more appropriable, interactions with university research teams become more attractive than interactions with individual scientists because they offer the possibility to access a wider range of competences at a reasonable cost. This trend may also be due to the fact that as projects become increasingly complex, the equipment required for science is costlier and beyond the reach of companies and of individual scientists involved in consulting relationships, while universities often reach sufficient economies of scale to purchase large-scale equipment.

More generally, the arguments developed so far support the observed transition towards more distributed forms of knowledge production, as captured by several conceptual models like "knowledge mode 2" (Gibbons et al, 1994), "entrepreneurial science" and "triple helix" (Etzkowitz and Leydesdorff, 2000). The framework presented suggests that the broad shift in the organization of knowledge production – from an "old" model where scientific knowledge production activities in academia and in industry were organized according to two distinct and very different set-ups (Dasgupta and David, 1994), to a "new" model, where research is a socially distributed process, taking place in diverse locations, involving wider connections and collaborations across scientific fields, industrial sectors, countries and organizations (Mowery et al., 2004; Siegel, 2006) including universities and firms – can be explained in terms of the combined tendency towards increasing uncertainty in the economic environment and increasing complexity in the knowledge base needed to innovate. The more uncertain the environment in which firms operate and the more complex their knowledge bases - where these two dimensions are not independent, as they are both affected by the rate of technological and organizational change present in the system - the more advantageous it is for firms to network with universities in order to pursue their innovation activities, which results in more open and distributed innovation processes.

Interactions between the academic system and external stakeholders, can also perform an important function of increasing coordination within the academic system, with respect to both research and education activities. In fact, interactions not only facilitate the match between supply and demand of knowledge and of competences, but they also allow the alignment of academic activities with the signals emitted by external stakeholders, promoting the identification of promising lines of enquiry and of economically relevant competences, allowing universities to re-orient their education and research activities accordingly. Interactions promote the rapid adaptation between the signals coming from the economic system (in terms of competences required and of the promising commercial applications of new knowledge), and the signals coming from the academic system (in terms of the potential offered by the knowledge that is produced).

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