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The Business Governance of Localized Knowledge: An Information Economics Approach for the Economics of Knowledge

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ABSTRACT Information economics provides important tools to articulate an economics analysis of the governance mechanisms for the generation and exploitation of localized technological knowledge. A variety of hybrid forms of knowledge governance ranging from coordinated transactions and constructed interactions to quasi-hierarchies can be found between the two unrealistic extremes of pure markets and pure organizations. The notion of localized technological knowledge as a highly heterogeneous dynamic process characterized by varying levels of appropriability, tacitness, unpredictability and indivisibility, which take the forms of complementarity and modularity, cumulability, compositeness, fungibility, helps to grasp the logic behind the variety of knowledge governance mechanisms at work. The analysis of transaction, agency and communication costs provides basic guidance to elaborate an integrated framework able to understand the matching between types of knowledge and modes and mechanisms of knowledge governance both in generation and exploitation.

KEY WORDS: Localized knowledge, information economics, knowledge asymmetries, knowledge transaction costs, knowledge agency costs, nested transactions, knowledge governance mechanisms

1. Introduction

The distinction introduced by Joseph Stiglitz between information economics and economics of knowledge provides basic guidance to implement the economics of knowledge (Stiglitz, 2000, 2002).[1] The typical fields of investigation of information

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[1] As Stiglitz notes: "The observations just made about the ways in which information and knowledge differ from the conventional commodities are general: they apply both to new knowledge, about new products or processes, as well as to information, say about the characteristics of a particular investment opportunity. They have developed in the last 50 years two distinct branches of the subject—the economics of innovation and invention, focusing on what is often called knowledge, and the economics of information. Both have important implications for thinking about economic behavior" (Stiglitz, 2000: 1449–1450).

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economics, namely, the analysis of the characteristics of the economic system from the viewpoint of the quantity, quality, symmetry among agents, distribution, access and transparency of information and communication and their effects on the conduct of agents are most important to understanding how the generation, dissemination and use of knowledge is organized in the economic system.

In this context coordinated transactions, quasi-hierarchies and constructed interactions emerge as the key mechanisms of knowledge governance that feed a variety of hybrid forms of governance. Knowledge transactions in quasi-markets are implemented and enforced by a myriad of coordination mechanisms that try and reduce the inefficiencies of pure market transactions. Knowledge interactions, as distinct from transactions, play a key role in this context and yet they are not spontaneous, but the product of intentional action directed to make knowledge communication possible. Knowledge coordination within hierarchical organizations is implemented by means of quasi-market mechanisms, often based upon non-exclusivity in employment contracts.

The new understanding about technological knowledge as a localized, collective and heterogeneous process calls for a specific effort to identify and frame into an integrated approach the broad variety of knowledge governance mechanisms that contribute the coordination in the production and usage of knowledge. The notion of localized technological knowledge provides the basic elements to elaborate an integrated framework, able to articulate a single logic underneath such a variety of modes of organizing the generation and dissemination of new technological knowledge. The new approach to technological knowledge, as a localized process, stresses the dynamic complementarity among a variety of agents participating in the generation of knowledge as a collective activity: such an intertwined procedural action of a myriad of heterogeneous agents requires substantial levels of coordination in order to succeed (Antonelli, 2001).

According to the varying combinations of contextual conditions that characterize each agent participating in the process, the system of interactions and the supply of scientific opportunities, technological knowledge is seen as an emergent property of the complex and dynamic system where agents are embedded. As such it acquires a strong idiosyncratic and heterogeneous character, specific to the circumstances that have characterized its generation and usage. Consequently and consistently, technological knowledge is localized in the cognitive space of agents and in the technological space that defines the proximity between techniques, in the geographical space that shapes the interactions among agents, in the industrial space that characterizes the transactions among firms, in the organizational space that shapes the learning processes internal to each firm, in the institutional space that defines the relations among firms and between firms and the scientific community, in the space of product characteristics that qualifies the choices of consumers and their learning procedures.

As soon as knowledge is no longer viewed as a homogeneous product, generated elsewhere, but rather as an intricate and complex web of heterogeneous and endogenous activities, the issue of knowledge governance becomes central. Many key questions emerge: how firms can manage all the transactions and interactions about knowledge, why knowledge is the object of such a variety of interactions and transactions, what is the relationship among such a variety of governance mechanisms.

The application of the basic tools of the economics of information, and specifically the analysis of transaction costs, agency theory, asymmetric information, communication and

networking costs to the economics of knowledge makes it possible to elaborate and operationalize the debates between the Arrovian notion of knowledge as a public good deemed to under supply (Arrow, 1962), knowledge as a quasi-proprietary good that can be exchanged in markets for knowledge (Jones, 1998; Arora *et al.*, 2001) or generate equilibrium levels of free spillovers (Romer, 1990, 1994). This approach makes it possible to articulate the analysis of both the limitations and the conditions for which knowledge can be generated, exchanged and traded among individuals within an organization and among firms and organizations, across the full range of intertwined product and factor markets, by means of a variety of governance modes based upon three basic mechanisms: quasi-hierarchies, coordinated transactions and constructed interactions (Stiglitz, 2000).

Business knowledge governance is the set of institutions, corporate strategies, types of transactions and forms of interactions that characterize and shape the organization of knowledge production, exchange and usage in the business sector. The empirical literature in the economics of knowledge has identified a variety of forms of knowledge governance based upon hybrid forms of coordinated transactions, constructed interactions and quasi-hierarchies, ranging from long-term contracts to quasi-vertical integration, from epistemic communities' technological districts, from patent thicketing to venture capital. New evidence about the close interdependence between the different modes of knowledge governance has grown. Technological knowledge is the object of a variety of forms of interactions and transactions in different contexts and different and yet related markets from the markets for products using new knowledge, to the markets for property rights, from barter relations to trust-based interactions where reciprocity matters, to dedicated financial markets.

Along these lines a single framework that is able to make explicit the chain of complementarities and alternatives that push firms to rely on such an articulated mix of governance mechanisms and governance modes can be articulated. The aim of this paper is to provide an integrated framework that is able to show that the variety of different modes of knowledge governance matches the different characteristics of knowledge and its different forms.

The rest of this paper elaborates such a framework. Section 2 explores the scope for the application of information economics to the economics of knowledge and provides the basic tools. Section 3 explores the variety of hybrid forms of knowledge governance and articulates the matching between types of knowledge and forms of governance. The conclusions summarize the main results and put them in perspective.

2. An Information Economics Analysis for the Economics of Knowledge

2.1. The Heterogeneity of Knowledge

Recent advances in the economics of knowledge have made it possible to articulate the traditional analysis of its main characteristics and to identify a wider range of types of knowledge. Knowledge is now viewed as a heterogeneous bundle that can be qualified with respect to its levels of tacitness, indivisibility and appropriability (Antonelli, 2005b). Let us consider these features in detail.

Knowledge tacitness. Different levels of knowledge tacitness can be identified: knowledge can be highly tacit or sticky when it is fully embodied in persons and organizations and cannot be transmitted or communicated to third parties. Part of the knowledge can be

articulated when dedicated efforts have been made to identify the basic elements and to express them in a basic system of codes. Finally knowledge can be codified when it has been fully translated in a consistent code and an appropriate language to express it has been found (Cowan and Foray, 1997; Cowan *et al*., 2000; Cooke, 2002). Some levels of tacitness, however, characterize even codified knowledge. A fully codified knowledge that can be easily transmitted and communicated does not exist. Relevant absorption and assimilation activities are necessary even for codified knowledge to be transferred among individuals and organizations (Cohen and Levinthal, 1990). The notion of cognitive distance among agents plays a key role in this context: the degree of commonality among agents, in terms of shared codes and languages, interacts with the levels of knowledge tacitness (Nooteboom, 2000).

Knowledge indivisibility. The analysis of the notion of knowledge indivisibility has led to the identification of different forms according to the structure of the relationship among the basic knowledge modules. A weak indivisibility can be identified when each knowledge module is more self-contained, as opposed to strong indivisibility when high levels of interdependence characterize modules. In turn the notions of knowledge cumulability, knowledge fungibility and knowledge compositeness have been identified with respect to the functional form of the relationship among knowledge modules. Knowledge cumulability is found when different vintages of knowledge are necessary in order for new knowledge to be both acquired and enriched. Knowledge is fungible when a basic module of knowledge finds an array of possible applications in a wide range of scientific fields and products. Knowledge is composite, when it is itself the result of the synthesis of many different elementary knowledge modules (Laestadius, 1998; Antonelli, 2001).

Knowledge complementarity. The notion of knowledge complementarity can be identified when attention is focused upon the agents involved in the generation and use of new technological knowledge. In the localized technological knowledge approach in fact the generation of technological knowledge is viewed as the result of emerging complementarity of a myriad of learning agents, each possessing a bit of knowledge. The successful generation of new knowledge for each agent is conditional on the access conditions to external knowledge. No agent can command the full variety of knowledge modules that are necessary to generate new knowledge. At each point in time agents organize their knowledge exploration strategies in order to increase their chances to access the pools of external knowledge. Agents build communication channels and elaborate interaction strategies that are finalized to increase the chance to acquire external knowledge. Accordingly, learning agents try and focus the direction of their research activities so as to enhance the compatibility, interactivity and hence complementarity between accessible external knowledge and internal knowledge. The amount and the characteristics of new technological knowledge being generated are shaped by the conditions into which the basic complementarity between internal and external knowledge takes place and is articulated.

Knowledge appropriability. Although it is difficult for inventors to fully appropriate the stream of economic advantages stemming from the generation of new knowledge, a variety of institutional and market conditions do have an impact on knowledge appropriability. Moreover, the actual appropriability of knowledge differs with respect to the characteristics of knowledge, whether it is tacit or codified, cumulative, fungible or composite. Different

levels of appropriability can be identified. Finally, the strategic conduct of agents needs to be considered. Agents try and increase the appropriability of the knowledge they have contributed to generate so as to increase the valorization of their proprietary knowledge.

2.2. Information Economics at Work

Knowledge, as an activity, is characterized by high levels of uncertainty. It is very difficult to anticipate the outcome of a research process, its duration, its actual economic value and even its specific content. Serendipity plays a crucial role. Knowledge as an economic good is characterized by several well-known limitations. The organization of the division of creative labor within and among firms is consequently very difficult. In this context, it is clear that agents differ greatly in the capability of both generating, using and understanding technological knowledge: knowledge asymmetries are intrinsic. Information about knowledge is not only asymmetric but also intrinsically limited: opportunistic behavior and bounded rationality are not exceptions but rules. In such a context the organization of the generation and use of knowledge is afflicted by a variety of economic problems such as transaction costs, agency costs, networking and communication costs. Appropriate governance mechanisms, however, have gradually emerged and make it possible to coordinate some levels of division of labor and exchange. A wide gulf between the two extreme cases of knowledge as a public good and knowledge as a quasi-proprietary good exists. For the same reasons a variety of hybrid forms of knowledge governance based upon coordinated transactions and quasi-hierarchies can be found in between the two extremes of pure market transaction and pure hierarchical command. Here the characteristics of knowledge matter and the application of the basic tools of information economics provides major opportunities to grasp the rationale of knowledge governance mechanisms within the business sector.

From the governance viewpoint it is most relevant to know whether knowledge is mainly tacit, codified or articulable and what are its appropriability conditions together with such characteristics, stemming from knowledge indivisibility, as cumulability, compositeness, fungibility have a major role in assessing the appropriate governance mechanisms and modes for their specific effects on knowledge transaction, coordination and interaction costs (Antonelli, 2005b). Let us apply the basic tools of information economics to the economics of knowledge in detail.

Knowledge transactions and communication costs can be identified and defined in terms of the costs of all the activities that are necessary to exchange bits of knowledge among independent parties. Two important distinctions must be introduced here. The first is between knowledge transaction costs and knowledge networking costs. Let us consider first knowledge transaction costs: it is useful to make a distinction between knowledge transaction costs on the demand side and knowledge transaction costs on the supply side (Argyres, 1995; Oxley, 1999; Cooke, 2002).

Static knowledge transaction costs. Knowledge transaction costs are found both on the demand and the supply side. Knowledge transaction costs on the supply side define all the costs that agents bear to use the markets for knowledge as a product per se. Knowledge transaction costs on the supply side consist primarily of all the activities that are necessary to make sure that, while attempting to exploit proprietary knowledge, it does not leak out

depriving the legitimate holder of part of, if not the whole revenue. Such knowledge transaction costs can also be quantified by the sum of the costs of the activities that are carried out to prevent disclosure and to secure the possession of proprietary knowledge plus the missing portions of revenue stemming from unintentional disclosure and the following leakage. Knowledge asymmetries here are most relevant as they provide the basis for opportunistic behavior: the understanding about the economic value of new modules of knowledge differs greatly among agents, according to their competence and specific conditions (Oerlemans and Meeus, 2001).

Next to the problems determined by imperfect appropriability, the costs of using the markets for knowledge include more traditional activities such as marketing, advertising, technical assistance and in general all the activities that are necessary to identify perspective customers and to strike an appropriate contract with them. The provision of technical assistance to the users of the technological knowledge is at the same time a cause of considerable costs and an effective mechanism to prevent uncontrolled leakage and the opportunistic behavior of users. Technical assistance is the base on which to implement pricing strategies that take into account the effective amount of economic benefits stemming from the downstream use of the knowledge.

Knowledge transaction costs on the demand side define all the costs associated with the exploration activities in the markets for disembodied knowledge such as search, screening, processing and contracting. Knowledge exploration strategies take into account knowledge transaction costs on the demand side in the context of the choice between ''make'' internal knowledge or ''buy'' external knowledge. As it is well known, the assessment of the actual quality of the knowledge can be difficult when the vendor bears the risks of opportunistic behavior and dangerous disclosure. Hence the perspective buyer bears the risks of buying a ''lemon'' (Akerlof, 1970). A close interaction takes place between knowledge transaction costs on the demand side and knowledge transaction costs on the supply side.

Dynamic knowledge transaction costs. A relevant distinction is found between static knowledge transaction costs and dynamic knowledge transaction costs. The latter are defined by the instantaneous costs of using the market to trade knowledge at each point in time, with no appreciation of the stream of long-term consequences engendered by the use of the markets. Knowledge asymmetries are most relevant when the prospects for future developments matter. Dynamic transaction and coordination costs are defined in terms of the expected costs of the governance of the stock of knowledge with respect to the stream of generation of new knowledge. Inclusion now yields the opportunity to appropriate the eventual benefits stemming from the accumulation of knowledge in terms of higher opportunities for the introduction of additional units of knowledge. Exclusion and transaction instead yield new costs in terms of the missing opportunities to benefit from the cumulative learning processes associated with the production process itself (Langlois, 1992).

Dynamic knowledge transaction costs are relevant both on the demand and the supply side. On the demand side, search and screening costs include the resources to evaluate the scope for incremental advance on the supply side; dynamic knowledge transaction costs arise mainly because of the high risks of opportunistic behavior of the customers with respect to derivative knowledge. When derivative knowledge matters, the vendor of the knowledge bears the risks of non-appropriation of the results of the scope of implementation

of the knowledge, which has been sold. Uncontrolled appropriation of the stream of rents associated to use of the stock of proprietary knowledge, by means of small incremental research costs, can take place with evident damages for the vendor. The working of the markets for knowledge is greatly favored by the extent to which patents and copyrights can be enforced in the marketplace and licensing is an effective tool to trade specific items of knowledge and competence. The enforcement of the markets for patents is a primary condition for the reduction of knowledge transaction costs and hence the creation of markets for knowledge. The role of the judiciary system in this context is extremely important.

Nested transactions. Information economics has little explored the intricate realm of nested transactions. As a matter of fact many transactions in a single market do take place because they are nested with transactions in other related markets. Transactions in upstream markets can take place, even with high transaction costs if and when transaction costs in downstream markets are much lower. This is also true when the relationship between markets and related transaction costs takes place horizontally and diagonally between markets that share some basic inputs or some customers or some providers. Such nested transactions need to be explored when a variety of forms of indivisibility and direct interdependence among products takes place either in the markets for inputs or in the markets for output. Joint production of different goods and related economies of scope are often found. This is also the case for a variety of cases of joint consumption: when the use of a product requires or facilitates the use of other products. Finally nested transactions can take place when indirect network externalities apply: when the number of users of either a product or a production factor affects the conditions of production and use of other products.

When a direct relationship takes place between the levels of transaction costs in the first market and the levels of transaction costs in the second market, *coeteris paribus* the levels of production costs and the demand conditions, the analysis of the market transaction cannot be applied to each single market but to the complete set of interrelated markets. Two specific cases can be identified: (a) interdependent transactions and (b) economies of scope in transactions. Interdependent transactions can be considered as externalities in transactions, when transaction costs in a market have effects on transaction costs in other, related markets. The notion of economies of scope in transaction, instead, can be identified when, the costs of transactions for a bundle of products are lower than the costs of transaction for each, single product.

Nested transactions, both in the form of interdependent transactions and economies of scope in transactions, are most relevant in the economics of knowledge for the high levels of knowledge indivisibility. The same knowledge module can apply to a variety of products and embodied in a variety of activities that, because of that, become strongly interdependent. Agents need to assess the full set of transactions and can accept to use markets with high transaction costs if and when a clear and direct compensation can be found in other related markets.

Knowledge signaling costs. Information about knowledge is especially confused. The mapping of the modules of knowledge in the economic and scientific space is difficult as much as the identification of the competence of agents possessing modules of complementary knowledge. Both the agents involved in the generation of new knowledge

and in its use have a great incentive to rely on systematic signaling about their competence and their needs, respectively. Perspective suppliers of new knowledge have a clear interest in disseminating information about their capabilities in order to attract the interest of perspective buyers. Perspective users need to disseminate information about the specific details of the complementary modules of knowledge that are necessary in order to attract potential suppliers. Knowledge signaling helps the emergence of the markets for knowledge. Yet it has clear drawbacks. On the supply side it risks increasing the non-appropriability of knowledge favoring uncontrolled leakage. On the demand side it risks revealing to rivals sensitive information about the missing internal competences and the research projects that are being implemented with negative implications in a strategic setting. Knowledge signaling can take different forms. Scientific publications can be regarded as a form of knowledge signaling by researchers, both working in the academic system and in corporations. The increasing number of scientific publications authored by scientists working in corporations can be regarded as a form of knowledge signaling directly solicited by the firm. Patents play a major role in this context as they can be considered both a form of knowledge appropriation and a form of "protected" signaling of the competence of assignees.

Networking and communication costs. The application of information economics analysis to understanding the governance of localized knowledge makes further progress possible. The important notion of communication costs and specifically knowledge networking costs can be introduced here. Knowledge does not spill freely and automatically in the atmosphere: dedicated efforts are necessary to create the institutional context into which external knowledge can be acquired and to reduce its uncontrolled leakage. The capability of agents both to retain some proprietary control and to communicate and hence to access external technological knowledge depends on the fabric of institutional relations and shared codes of understanding which help to reduce information asymmetries and the scope for opportunistic behavior and to building a context into which reciprocity, constructed trust and generative relationship can be implemented.

The economics of communication, an emerging branch of the economics of information, is very necessary in order to grasp the working of knowledge externalities and technological transfer. Knowledge networking is necessary when knowledge is dispersed and fragmented, retained by a myriad of heterogeneous agents, and yet characterized by high levels of indivisibility with important potential benefits in terms of externalities stemming from its integration and recombination. Yet knowledge communication is not automatic, neither is it obvious: dedicated reception efforts are necessary together with appropriate emission of relevant signals. The identification and appropriation of relevant codes, protocols and communication channels and specific languages require substantial efforts. Knowledge communication is the result of much intentional activity designed to create a context conducive to combine variety and complementarity. Systematic networking is necessary to establish knowledge communication flows. The network structure of the system plays a key role in shaping the flows of knowledge communication and hence the availability of external knowledge. Specific, dedicated networking activities are necessary in order to manage the flows of knowledge that are not internal to each firm and yet cannot be reduced to arm's length transactions. Networking activities make knowledge interactions, as distinct from knowledge transactions, possible.

Networking activities are a specific—indispensable—ingredient of the basic governance of knowledge (Antonelli, 2001, 2003).

Firms often rely on networking with other independent parties, to increase the proprietary control of their knowledge, to acquire external knowledge and to better exploit it. External knowledge can be acquired by taking advantage of the spillovers from academic activities, and from localization in the proximity of other firms. Qualified user–producers interactions are the source of new knowledge both for upstream suppliers and downstream customers. Knowledge dissemination is better controlled within networks of interactions based upon constructed and repeated interactions, qualified by contractual relations (Antonelli and Quèrè, 2002).

The notion of nested networking interactions is parallel to the notion of nested transactions. Once again, because of high levels of intrinsic knowledge indivisibility, a variety of interactions in different and yet related contexts can take place. In these circumstances the analysis should embrace the full set of related contexts and assess both the levels on interaction costs in each of them and for the full set. A specific case of nested networking interactions and transactions emerge. Here interactions take place because of the effects in terms of transactions in related markets. Such related markets could not work without the set of interactions in the related market. Networking in a market can even help create a market for a related product. Or the other way around transactions in a given market help relying on interactions in the related set (Patrucco, 2003, 2008 forthcoming).

Principal–agent problems. When attention is focused on the activities that lead to new knowledge, as opposed to knowledge as a good, a new distinctive characteristic emerges: its unpredictability. High levels of uncertainty characterize the generation of knowledge: serendipity and creativity play a crucial role. The generation of new knowledge is characterized by substantial unpredictability about many different facets: its results, its timing, its content and its scope of application, hence its economic value. Unpredictability affects especially the generation of new knowledge with high levels of codification and scientific content. In this context it is very difficult to organize and manage employment relations in such a context. Principals have major problems in assessing the actual levels of creativity and effort of their agents and to value their output. The costs of hierarchical coordination, articulated in agency and organization costs limit severely the size and the span of knowledge-intensive activities conducted within the boundaries of a single unit (Arrow, 1974). Agency costs limit the use of hierarchical command of the activities that are necessary to generate and use technological knowledge within the boundaries of the firm for two classes of reasons. Knowledge asymmetries play a major role within organizations as well. Because of the key role of serendipity and creativity in the generation of new knowledge it is difficult for principals to control the actual content of the operations that lead to the generation of a given amount of standardized knowledge. Agents can try and take opportunistic advantages of the basic information asymmetries with respect to principals about: (a) the perspective value of the knowledge produced and (b) the actual effort and work that has been necessary to use to generate it. Agency costs in the generation of knowledge within complex organizations are consequently very high also because of the limitations in anticipating the outcome of a research in progress not only in terms of rates, but also and mainly in terms of directions. The outcome of a given research project can be relevant but in fields of application that differ from the expected ones. The traditional

organization of labor in knowledge-intensive activities characterized by high levels of craftsmanship and self-employment with strong professional content is clearly explained by the high levels of agency costs in monitoring efforts, outputs and applications in the generation of knowledge (Holmstrom, 1989; Garicano, 2000).

Internal organization costs as well limit the number of complementary activities that can be internalized by each firm and hence the amount of knowledge that can be generated, implemented and exploited internally. Unit organization costs are elastic not only to the size of activities but also and mainly to the variety of activities that need to be internalized. The larger the rate of increase, with respect to the number of activities, of unit organization costs the larger the number of complementary activities that cannot be retained within the boundaries of the firm. Because of hierarchical coordination costs, incumbents miss important opportunities. Large corporations are unable to implement all the opportunities they contribute to create. Coordination costs in fact apply both the specific activities that are required to generate new knowledge and to the production processes that are necessary in order to use and exploit the knowledge generated (Arrow, 1974).

Innovations in organizations and institutions. New institutional arrangements, both with respect to new forms of contracts and new types of intellectual property rights, emerge. Procedural contracts, where the parties agree upon procedural rather than content obligations, emerge with positive effects both upon coordination among partners in research ventures, once the latter have been established, and transaction costs in the building phase of new consortia and clubs. Procedural contracts make it possible to articulate the behavioral obligations of the partners about the sequence of operations and their timing, even when their content cannot be fully specified. From this viewpoint procedural contracts are an important institutional innovation that help the better definition and hence the management of incomplete contracts with clear effects on knowledge governance, typically afflicted by serendipity, bounded rationality and limited knowledge about the full set of future events (see Brousseau and Fares, 2000; Brousseau and Glachant, 2002). The emergence of new specialized intermediaries such as venture capitalists able to perform essential functions such as knowledge screening, assessment, evaluation, to bundle new knowledge together with managerial skills and equity into new companies that can be eventually traded in the form of knowledge-intensive property rights in new specialized financial markets play a crucial role in this context (Avnimelech and Teubal, 2004; Antonelli and Teubal, 2006). New forms of quasi-hierarchical command have been explored and implemented with the introduction of non-exclusivity in employment contracts within research organizations and the exposure of internal units to increasing levels of competitive selection in the provision of knowledge inputs by external sources. Institutional innovations are being introduced in the field of intellectual property rights such as the introduction of the General Public License, where the erosion of the exclusivity of proprietary and patented knowledge is balanced by the obligation of users to notify their use to the assignee, to make explicit reference to prior knowledge and to make it available to third parties, that are paving the way to new hybrid forms of intellectual property rights influenced by original applications of the liability rule (see Samuelson *et al*., 1994; Lessig, 1999; Reichman, 2000).

Table 1 summarizes the main results of the application of information economics to the economics of knowledge. Knowledge transaction, agency, coordination and networking costs are set to vary according to the characteristics and forms of knowledge.

Table 1. Characteristics of knowledge and the conditions of governance

	Tacit/sticky	Articulable	Codified/public
Cumulative	Knowledge asymmetries	Low networking costs	Unpredictability
	Dynamic transaction costs	Proximity	Agency costs
	Agency and organization costs	Trust	Low transaction and networking costs
	Transaction costs on the supply side	Reciprocity	Hostages
		Procedural contracts	
Composite	Knowledge asymmetries	Low networking costs	Unpredictability
	Exploration costs	Nested interactions and economies of scope in transactions	Agency costs
	Transaction costs on the demand side	Procedural contracts	Low transaction and networking costs
	Diseconomies of scope in coordination		Intermediaries
			Hostages
			Content contracts
Fungible	Knowledge asymmetries	Low networking costs	Unpredictability
	Exploration costs	Reputation	Agency costs
	High agency costs	Nested interactions and externabilities in transactions	Low transaction and networking costs
	Transaction costs on the supply side	Procedural contracts	Content contracts
	Dynamic transaction costs		Hostages
	Diseconomies of scope in coordination		Intermediaries
			Nested transactions
Modular divisibility	Knowledge asymmetries	Low networking costs	Unpredictability
	High transaction costs	Cognitive distance	Agency costs
	High agency costs	Nested interactions	Low transaction and networking costs
	Nested transactions	Complementary competencies	Nested transactions

When knowledge is mainly tacit, transaction costs in the marketplace are very high. It is difficult to assess its economic value: its tradability is hampered by major information and knowledge asymmetries between producers and users. The latter are not able to use it without the close assistance of the former. Without direct control the producers risk losing the command of the economic rents stemming from its use. Intellectual property rights cannot be used to enforce appropriability without consistent preliminary codification efforts. Opportunistic behavior is easy when no proprietary control can be exerted both within and among organizations. The hierarchical coordination of knowledge producers with downstream activities that embody technological knowledge is an effective way to extract

economic value. As such hierarchy is a remedy to the limitations of knowledge as an economic good per se and a tool to achieve, indirectly, its tradability and hence division of labor among knowledge producers. Agency costs and coordination costs, however, limit its internal exploitation and generation. Agency costs are relevant within organizations for the risk of opportunistic behavior of employees who can try and exploit directly the advantages of the knowledge embedded in their own brain: tacit knowledge with high levels of modular divisibility can be easily exploited on a personal basis. In this case the chances of principals appropriating the rents stemming from the research they have funded are low. Quasi-hierarchical forms of internal coordination can be successfully applied in this context. This is less true when knowledge indivisibility is high and knowledge is embedded in larger organizations and its implementation requires groups of experts with diverse competences. Coordination costs arise fast with the variety of activities retained within the borders of the firm. This is especially relevant when knowledge is either composite or fungible. In the first case transaction costs are found on the supply side, while in the latter on the demand side. When technological knowledge exhibits high levels of cumulability, dynamic transaction costs matter because of inter-temporal complementarity among different vintages of knowledge: vendors risk missing the opportunity for major future improvements, customers may be unable to master the flow of sequential improvements because of a lack of embedded competence. When knowledge is composite and fungible, coordination costs exhibit fast rates of increase with the variety of activities and competences. Coordination costs increase when knowledge is composite for it is necessary to manage the many different fields from which knowledge modules are drawn and synthesized. Coordination costs increase when knowledge is fungible because there is a strong incentive to diversify into the different fields of application of the same module of fungible knowledge.

Networking costs are lower when knowledge is articulated and a basic rationale can be elaborated so as to manage the interactions among parties that rely on each other for the access to external knowledge. Hybrid forms of governance emerge as appropriate mechanisms. Transactions are implemented and associated to complementary organizational devices. Trust and reciprocity help networking activities when the value of the knowledge modules is not yet fully assessed and articulated. Physical proximity among agents helps reduce the scope for opportunistic behavior for the higher levels of monitoring and repeated interactions. Procedural contracts among the parties can be articulated so as to make explicit the sequence of actions and commitments even with low levels of definition of the actual content. Contracts are incomplete with respect to the content, but specified with respect to the obligations of the parties through the process of knowledge generation and exploitation. Low levels of cognitive distance among the parties involved in the interaction help the creation of epistemic communities based on shared knowledge. Reputation plays a major role to ease both transactions and interactions. The analysis of nested networking and transaction costs becomes relevant here.

Finally, when knowledge is more codified transaction costs are still relevant and yet lower. Pure markets would failure. By means of coordinated transactions, however, the agents involved are better able to elaborate contractual relations which specify the content obligations of the parties involved: contracts are ‘‘less’’ incomplete with respect to the terms of exchange. Intellectual property rights can be assigned and content contracts can be articulated. Hostages can be exchanged so as to increase the reliability of the parties involved. Lower transaction costs often match high coordination and agency costs with clear

incentives for firms to rely on the markets for knowledge both to purchase and to sell it. The selection of the appropriate kind of markets becomes a major issue. Nested transaction costs play a major role in this context.

Technological knowledge is intrinsically heterogeneous: it is a basket of different activities and different processes characterized by significant variety. According to the types of technological knowledge and the related levels of knowledge transaction, communication, networking and coordination costs, firms select the modes of governance that make it possible: (a) the effective generation of knowledge by combining at cheaper conditions the external and internal sources of knowledge[2] and (b) the best forms of knowledge exploitation. Rarely the mechanisms identified are exclusive: as a matter of fact, firms rely on articulated mixes of governance mechanisms, according to the characteristics of their portfolios of knowledge activities.

The following Section 3 applies the analytical framework elaborated so far to the ever-increasing variety of knowledge governance mechanisms. Tables 2 and 3 summarize the analysis filling Table 1 with the matching between the types of knowledge and the wide array of forms of knowledge governance identified by the literature of the economics of knowledge, with respect to governance mechanisms on the generation and exploitation side, respectively (March, 1991).

3. Types of Knowledge and Governance Mechanisms

3.1. The Quasi-Hierarchical Command of Tacit Knowledge

Tacit knowledge is the result of learning processes and cannot be easily converted into information. Moreover, it cannot be separated from the individuals that have accumulated the relevant experience. In this case, internal coordination within the boundaries of the firm is more appropriate. Knowledge asymmetries are most relevant: with low levels of knowledge appropriability and hence high risks of opportunism and dissipation of the rents associated with knowledge, knowledge transaction costs are very high and firms cannot rely on the marketplace to valorize their intangible outputs. Because of high levels of uncertainty in the generation and even in the exploitation of tacit knowledge, however, agency costs are very high. Forms of quasi-hierarchical coordination can be successfully applied.

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[2] Along these lines a knowledge production function and a cost equation can be identified. Internal learning and research and development, external codified knowledge, and external tacit knowledge, respectively, enter a knowledge production function as inputs. Their costs, that is, the costs of internal research and learning activities, the total costs of external codified knowledge, including knowledge transaction costs, and the costs of external tacit knowledge, including knowledge networking costs, enter a cost equation. Maximization procedures make it possible for firms to select the ''best'' mix of inputs. This analysis has many important implications about the role of the local context into which firms are embedded in assessing the quantitative evidence about R&D expenditures and output in terms of rates of generation of new knowledge. It is clear, for instance, that when and where external knowledge is cheap, both because of low purchasing costs in the markets for knowledge, and low knowledge transaction and networking costs, firms will rely less on internal learning and research activities. In the opposite case, when and where the access conditions to external knowledge are less easy, firms will rely more on internal research and learning activities. When external knowledge is available at low costs, clearly, firms can generate more knowledge at lower costs. This analysis provides a clue to understanding the puzzling evidence about the low levels of formal research activities of firms localized in fertile and dynamic technological districts (see Patrucco, 2008, forthcoming).

Table 2. Governance mechanisms for knowledge generation and types of knowledge

	Mechanisms		
Modes	Quasi-hierarchies for tacit and sticky knowledge	Constructed interactions for articulable knowledge	Coordinated transactions for codified knowledge
Cumulative	Learning	KIBS	Patent thicketing
	Intramuros R&D	Procedural contracts	Content contracts
	Open science	Constructed trust within vertical clubs	Vertical clubs
	Academic consultants	Technological districts	Academic outsourcing
		Academic outsourcing	Epistemic communities
			Open source
Composite	Learning	Procedural contracts	Academic outsourcing
	Upstream integration	KIBS as hubs	Content contracts
	Intramuros R&D	University–corporation liaison centers	Technological clubs
	Open science	Multi-industrial and metropolitan technological districts	Standardization committees
	Academic consultants		Open source
	Technological platforms		Acquisition of high-tech small firms
	Joint ventures		KIBS
			Markets for patents
			Markets for licenses
Fungible	Learning	Technological platforms	Content contracts
	Intramuros R&D	Procedural contracts	Academic outsourcing
	Downstream integration	Academic outsourcing	Cross-licenses
	Open science	Inter-industrial joint ventures	KIBS
	Academic consultants	KIBS	Open source
	KIBS	Centered networks	Acquisition of high-tech small firms
	Joint ventures	Reputation	Markets for patents and licenses
Modular divisibility	Scientific entrepreneurship	M&A	Quasi-markets for licenses and markets for goods

University. The academic system is an effective institution for the governance of the generation and dissemination of new knowledge characterized by high levels of tacitness. Scientific knowledge in fact, even when it takes the form of a highly codified expression, has high levels of tacitness and requires high levels of competence to be generated, transmitted and communicated. As Dasgupta and David (1987, 1994) have shown open science works when an academic institution provides the necessary monetary and hierarchical rewards to scientists, according to their qualification and their reputation. The reputation of scientists is built upon publications scrutinized by peer review. In open science the production and dissemination of new knowledge signals the levels of competence and the skills of the

Table 3. Governance mechanisms for knowledge exploitation and types of knowledge

	Mechanisms		
Forms	Quasi-hierarchical command of tacit and sticky knowledge	Constructed interactions for articulable knowledge	Coordinated transactions for codified knowledge
Cumulative	Vertical integration	KIBS	Patent thicketing
	Centered platforms	Procedural contracts	Quasi-markets for licenses with technical assistance
	In-house outsourcing	Sponsored spin-off	Long-term content contracts
	Joint ventures		
Composite	Upstream diversification	KIBS as hubs	Patent thicketing
	Open platforms	Procedural contracts	Quasi-markets for patents and licenses
	Joint ventures	Centered networks	Content contracts
Fungible	Downstream diversification	Inter-industrial joint ventures	Quasi-markets for patents and licenses
	Open platforms	Procedural contracts	Market cascades with vertical linkages
	Joint ventures	Sponsored spin-off	Cross-licenses
	In-house outsourcing	KIBS	Open source and liability regime
		Growth poles	Content contracts
		Reputation	
Modular divisibility	Scientific entrepreneurship	Venture capitalism	Quasi-markets for licenses and markets for goods
		IPO	

scientist and hence disseminates new knowledge. Because of its effects in terms of reputation and hence ultimately inclusion in the academic system, however, the pursuit of publication is at the same time, an incentive. This mechanism works properly as long as the costs borne by the system to fund the academic system are compensated by the externalities generated by the academic system. The application of principal–agent viewpoint provides a complementary interpretation for the understanding of the working of the academic system. From this perspective the non-exclusivity that characterizes the employment contract within universities, and the freedom to enter the markets for professional services traditionally recognized to academics, combined with the joint production of education and knowledge play a crucial role. The university can now be regarded as a unique form of quasi-hierarchical organization where academics are free to choose their activities and to publish the results of their research. Publications signal their competence and are not only a means to build reputations. The publication is part of a dynamic process where the scientist has a direct incentive to publish as a way to attract resources in external professional markets (Spence, 1973; Antonelli, 2006). From this viewpoint the need for public funds is much less relevant. In the extreme case, the academic system comes closer to a special form of professional order: membership in the academic system provides the basic qualifying conditions to operate in the markets for high quality knowledge-intensive professional services.

Research and development. Knowledge generation is conducted internally by means of research activities conducted mainly within research laboratories located nearby production plants in order to enhance the interaction with learning processes. Academic consultants are often used in this context to access external knowledge: academics are hired as private consultants and are directly integrated into the internal production of knowledge. The allocation of resources to fund new research activities and the identification of perspective users of new knowledge generated is managed internally by means of internal exchanges among affiliates and operative units. The management of the internal markets for technological knowledge and its matching with competent and dedicated competencies in the allocation of financial assets is more and more a key element in understanding the working of multinational corporations and large holdings when tacit knowledge matters. Intramuros research and development laboratories, however, are more and more exposed to new forms of competitive pressure as their products are exposed to the comparative assessment of external sources such as academic laboratories and other knowledge-intensive business services providers. In so doing, new forms of quasi-hierarchical command of the internal production of knowledge are being implemented.

Scientific entrepreneurship. The creation of new firms, by new entrepreneurs, with an academic background, is often the direct result of the exploitation of tacit knowledge, which, as such cannot be valorized by other governance modes. Scientific entrepreneurs are inventors, occasionally of academic origin, which cannot rely on the markets for disembodied knowledge and prefer to exploit the rents associated with their knowledge by means of the production and sale of the products that embody, either as a product or a process innovation, the new knowledge (Etzkowitz, 2002). Entry in new markets is often the consequence of serendipity in knowledge creation. Incumbents enter into new product markets in order to exploit new technological knowledge that has not been generated intentionally. Here the choice between to sell or to use applies. The creation of new firms and diversification and downstream vertical integration of incumbents can now be seen as a governance mechanism specifically implemented in order to increase the appropriability of new knowledge. The firm will choose to make and hence to include within the boundaries of the portfolio of activities, the modules, which use the knowledge as an intermediary input, when, the tradability and appropriability conditions are low.

Corporate growth. The embodiment of technological knowledge into new products and their eventual sale in the marketplace becomes necessary in order to exploit effectively new technological knowledge. Internalization of knowledge exploitation and creation is necessary when knowledge appropriability is low. Such internalization takes place at different levels: within the filiere of activities that use the same module of knowledge the firm selects the stages where integration is necessary and may rely on either networking or even the marketplace for others. Nested analysis of the bundle of activities comes into place.

Broad, seemingly unrelated, diversification is often the result of exploitation of fungible knowledge. With given knowledge transaction costs firms, able to introduce technological knowledge with high levels of fungibility, are likely to be larger and diversified into the variety of product markets where the same knowledge module can be successfully applied. Strong increasing returns take place in the usage of the same stock of technological knowledge and can counterbalance the increase in average coordination and manufacturing costs. Knowledge fungibility has a direct bearing on the choice of internalization. When the

generation of new knowledge in operating downstream modules is directly influenced by the competence and the knowledge acquired in operating the module upstream, the firm has an incentive to make rather than to sell. Conversely, from the viewpoint of knowledge generation strategies, when knowledge is composite and knowledge transaction costs are high, the firm has an incentive to integrate vertically in upstream activities. Vertical flows of knowledge, from the peripheral units to the center, contribute to the continual growth of corporations.

The distinction between knowledge fungibility and knowledge compositeness helps understanding the strategies of external growth of incumbents both with respect to strategies of knowledge exploration and knowledge exploitation. When knowledge is composite and has low levels of tradability, external growth by means of takeovers, mergers and acquisitions, is a powerful tool to internalize essential knowledge components that are embedded in the firms that are acquired. Conversely, when proprietary knowledge has both high levels of fungibility and low levels of tradability, external growth becomes an effective strategy of knowledge exploitation. The differences between the two strategies, in terms of their effects on the performance of firms, are sharp. When the external growth is the result of a strategy of knowledge exploitation, its direct effects concern primarily the economic performances. The external growth makes possible the application of superior knowledge to preexisting activities and has an effect in terms of an increase in profitability and market share. When the external growth is the result of a strategy of internalization of external knowledge, instead, its direct effect consists primarily in the increase in the output of knowledge and generally in the command of technological knowledge. Eventual effects in terms of economic performances also take place albeit with some lags. Multinational growth often takes place when the scope of both profitable application and sourcing of new knowledge is global and high levels of knowledge transaction costs afflict the international markets for knowledge. Global and yet internal markets for knowledge substitute and often complement knowledge transactions on international markets (Fai and von Tunzelmann, 2001).

Technological platforms. Technological platforms are emerging forms of quasi-hierarchical command of tacit knowledge. Technological platforms in fact can be considered as an intermediate form of vertical integration where, however, the elements of the platform are independent companies that cooperate within a hierarchical architecture but are not fully coordinated *ex ante* by the center. The units enjoy some degree of autonomy and their inclusion in the platform is often assessed *ex post*. The creation of shared technological platforms is especially appropriate for the generation of technological knowledge that exhibits high levels of compositeness and cumulability and coordination costs are too high for a single company to control the full process. Large firms able to command the basic technology and to provide *ex ante* goals provide the rest of the system with the selective opportunity to contribute technological platforms where other specialized firms can integrate their own distinctive competencies.

An array of industries based on complex systems, such as energy production, railway, airplane engineering systems, rely more and more on the centralized coordination of a variety of specialized, independent suppliers organized in a single frame. The platform is managed and designed by the firm, which retains the command of the basic knowledge and is able to play the role of hub company. In turn a hierarchy of such systems is often

articulated. The hierarchy is based upon the levels of responsibility in the definition of the objectives and goals of the collective undertaking and in taking the risks for the final results.

The automotive industry relies more and more on the notion and the methodology of the technological platform as an effective tool to stimulate the division of innovative labor and to coordinate the complementarity and consistency of the innovative activities of a myriad of firms. The hub company defines the basic goals of the project and invites other firms to contribute the objectives, in a context of delegated flexibility. Each firm specializes in a narrow niche that contributes the broad array of competences and skills required to introduce a new car. The introduction of a new car requires the command of high levels of systemic compositeness which spans from product to process innovations and each is the result of hundreds of interdependent components. Technological platforms make it possible for hub companies to organize the creative contribution of a variety of firms by means of the structured access to the general design of the new product. In this context it is clear that the implementation of an array of standards, including interface standards makes it easier for the management of the flows of goods within the network of firms. The hub company plays a key role as the designer of both the new technology and of the architecture of standardized interfaces. The financial industry provides clear evidence about the key role of technological platforms as a way to generate and exploit technological knowledge (Consoli, 2005a, b).

When the dynamics of technological knowledge and the frequency of market change increase, technological platforms are exposed to the limitations of rigidity. In such circumstances instead of *ex post* outsourcing of rigid components that have been already designed by the hub company, technological platforms often evolve into interactive co-design processes where specialized suppliers enter into a co-engineering process where each new component is designed jointly by the specialized producer and the hub company into a flexible and yet organized system of distributed competence.

Technological platforms are an effective tool to exploit fungible technological knowledge, as well. The general quality of the services provided by the platforms is enriched by the collective endeavor with positive externalities for all the parties involved. The mechanism of network externalities is fully exploited by means of the selective entry of competent players into a single integrated framework centrally organized and managed by the platform-builder. The hub company, able to command fungible technological knowledge can exploit its technological advance and retain the control of incremental value generated by the enrichment of the variety of services and products made available by a common platform. The evidence of the creation of such technological platforms in advanced mobile telecommunications has gradually diffused into other sectors.

In-house outsourcing. In-house outsourcing emerges as a new way to govern complementary modules of knowledge that must be eventually recombined into a composite final product, and it is built on the combination of under-the-same-roof outsourcing, interdependent outsourcing and continual re-contracting. According to the different levels of compositeness of knowledge modules and knowledge activities, different and ad hoc organizational and contractual solutions can be implemented in order to lower transaction costs and exploit effectively core competencies and operations, that is, competencies and operations that can yield major returns. In other words, in-house outsourcing allows efficiency in the recombination of different modules of knowledge into a composite final bundle (i.e. a new product), and at the same time supports knowledge

fungibility in that the single modules that are the outcomes of interdependent and yet autonomous activities can enter the innovation production function of prospective buyers external to the firm and even competitors (Bonazzi and Antonelli, 2003).

Joint ventures. Joint ventures among firms that are competent in complementary bits of knowledge appear as appropriate governance mechanisms for the generation of new knowledge. Joint ventures are especially useful when technological knowledge is composite and each founding partner commands a different type of knowledge. For the same token joint ventures are a reliable form of exploitation of new knowledge, especially when the latter is fungible. The joint venture can be the result of the combination of complementary assets owned by company A with fungible technological knowledge possessed by company B. In this case company B, unable to exploit internally the new knowledge because of diseconomies of scope and coordination, can rely upon a form of indirect command. So far joint ventures can be considered a form of quasi-hierarchy effective both in the generation and in the exploitation of new knowledge. The joint venture in fact is owned by both companies and yet enjoys substantial levels of autonomy.

3.2. Coordinated Transactions for Codified Knowledge

Codified knowledge consists of a body of consistent and explicit information that can be transmitted and applied, although substantial levels of competence and experience are necessary in order to understand and make use of it. Codified knowledge is often found in fields where technological opportunities are slowing down and the levels of knowledge cumulability are lower. When technological knowledge can be better appropriated by the innovator, either because of its high levels of natural appropriability, or because the regime of intellectual property rights is highly effective and easily enforced, firms may prefer to sell directly the technological knowledge as a good per se in the markets for knowledge, or to buy it to generate new knowledge. Even when knowledge is fully codified and systematic efforts of articulation have been made, however, the intentional assistance of the original holder is necessary for its use. The markets for technological knowledge become an effective mechanism both to exploit and acquire knowledge only if implemented with dedicated forms of coordination. Arm's length markets perform poorly and are substituted by quasi-markets.

When such markets for knowledge are available, the selection of knowledge activities that firms retain within their boundaries is much wider. The exploration for external sources of knowledge and knowledge outsourcing becomes common practice. Firms can rely on external providers for specific bits of complementary knowledge. Knowledge outsourcing on the demand side matches the supply of specialized knowledge-intensive business service firms. Universities and other public research centers can complement their top-down research activities finalized to the production of scientific knowledge with the provision of elements of technological knowledge to business firms. The exploitation of the knowledge generated as well can take a variety of forms: firms can use it to produce a new product or sell it as a product per se.

Academic outsourcing. Outsourcing of research activities to qualified academic laboratories becomes common practice. Firms perform less and less the research activities with a high scientific content within their own laboratories and rely upon the

competence of universities. This is especially relevant when technological knowledge is codified and composite: in this case firms should command a wide array of scientific fields with little chances to achieve high levels of specialization and competence in each. The systematic access to the wide range of competence provided by universities in fact makes it possible to increase the chances for effective recombination and eventual generation of new knowledge at much lower costs. Universities can be selected according to their reputation and competence and a variety of contingent contracts can be activated with highly specialized laboratories. When technological knowledge exhibits lower levels of codification, the relations between universities and firms are typically based upon long-term broad contracts within framework programs that cover many different contracts and include funded chairs and bilateral transfer of personnel, as well as the systematic hiring of students who have finished a doctoral program. The more structured the fabric of contractual relations the lower the risks of leakage and premature disclosure by scientists seeking visibility and extended reputation. Firms try and exert a strong control on the results of the research activities by means of intellectual property rights and specific contracts based upon timing and priority in dissemination. The academic ethos based upon open science is put at risk (Geuna, 1999).[3]

Trade in patents and licenses. A strong intellectual property right regime clearly favors the reduction of knowledge transaction costs. The role of the judiciary system with respect to the enforcement conditions of the contracts for disembodied technological knowledge is also most relevant (Anand and Tarun, 2000; Kingston, 2001). With lower levels of knowledge transaction costs and high internal coordination costs, firms are induced to consider the marketplace both to exploit their knowledge and to explore for external sources of knowledge. Trade in licenses and patents however can take place only within the context of tight relations between vendors and customers. The former wants to control the actual use of their proprietary knowledge. The latter need the technical and managerial assistance of the innovators. Once more transactions do not take place alone, but implemented by strong contractual agreements.

Recent statistical work by OECD and other national statistical institutes has made available an interesting and reliable body of data about international transactions in disembodied technological knowledge. The technological balance of payments is built upon the records about international technological transactions in terms of technology payments and technology receipts among a large number of advanced countries. The evidence provided by the statistics of the technological balance of payments suggests that international markets for disembodied technology are growing very fast. Actually, through the 1990s international transactions in technological knowledge have been growing faster than domestic expenditures in R&D activities. Data show that the technology payments

[3] Knowledge generated by academic departments within the context of specific contracts with firms risks becoming proprietary with clear reductions of its dissemination. At the same time however, according to much economics of information, the working of competition in a market characterized by radical knowledge asymmetries provides an important counterbalancing effect when the role of signaling is appreciated. Academic departments in fact have a strong incentive to signal to perspective customers the quality of the research in progress and to disseminate information about the scientific scores. Academic publication, no longer viewed as the distinctive mission of publicly funded researchers, is now pursued by academic departments as a signal to attract new potential customers for their services.

represent a significant share of total expenses in R&D activities in most countries. Technology payments have an order of magnitude very close to that of the research activities funded by the business sector in the main OECD countries.[4]

Knowledge-intensive business services. The trade of disembodied knowledge in the marketplace is favored by specialized business service firms which act as intermediaries. Specialized intermediaries act as go-between firms respectively searching for complementary bits of knowledge and/or possible fields of application of the technology already generated in order to test its actual fungibility. Specialized business services can help the parties to establish the actual direct relationship when they act as assistant to the exchanges and help the transactions to be performed. In this case knowledge intermediaries specialize in reducing the amount of search costs and provide basic assistance in assessing the reputation and reliability of the parties. They can also act as full intermediaries: they buy the licenses and they sell them to third parties. Knowledge-intensive business services emerge as effective intermediaries to trade knowledge, especially when fungibility is high. Specialized intermediaries play a major role as knowledge converters: they accumulate generic knowledge and specialize in the delivery of a variety of specific and contextual applications (Antonelli, 1999; Spulber, 1999).

When knowledge is composite, knowledge-intensive business services able to concentrate different knowledge modules and activate different knowledge communication flows from a variety of sources become actual system integrators and as such are able to command the relevant recombination processes so as to play a key role as central hubs of the knowledge generation process. In this way knowledge-intensive business services become the center of the innovation process. Tight contractual relations qualify the transactions between knowledge-intensive business services and their customers: both parties want to keep a clear control on the knowledge being exchanged and on their conditions of usage and access.

Market cascades. The notion of market cascades plays an important role in this context. The notion of nested transactions helps clarifying this point. Firms can combine different strategies for knowledge exploitation and knowledge outsourcing because they act in different and yet related markets. Firms can choose in fact the layers and the stages of the chain value leading to final products into which either to sell or to buy knowledge. Firms can sell their knowledge as a license in upstream markets and yet manufacture the products that embody such knowledge and sell them in the downstream markets as well. Conversely firms can select the downstream markets for services, associated to a given knowledge

[4] Traditional R&D-intensive countries, such as the UK, Germany and USA exhibit a clear trend towards an increasing use of external knowledge. The ratio of technology payments (TP) to the research and development activities performed by the business sector (BERD) has been steadily increasing through the 1980s and 1990s in Germany from less than 15 to 34 percent at the end of the century. In the UK it spans from less than 15 percent in the early 1980s to 22 percent in 1999. In the same time interval in the USA it has increased from 1 to almost 5 percent. France remains stable at around a 15 percent ratio. Countries with lower levels of BERD/GDP intensity, such as Belgium show an increasing trend fetching 125 percent in 1999 from the 72 percent levels of 1981. Italy remains around 30 percent levels for all the periods considered. Canada, in the vicinity of 25 percent in 1981, shrinks to 16 percent in 1999. Countries like Spain are instead reducing their dependence upon external knowledge: the ratio of TP to BERD shrinks from a ratio of 150–160 percent towards the 50 percent levels. Finally Japan, once a strong importer of foreign technology reduces the ratio of TP to BERD from 7 percent in 1981 to 4 percent in 1999 (Antonelli *et al.*, 2003).

module, and abandon the upstream product markets. Such decisions, about the layer into which to enter the marketplace depend upon the levels of knowledge compositeness, cumulability and fungibility. With high levels of fungibility the firm can easily combine selected sales in upstream markets with downstream operation. With high levels of cumulability firms have a strong incentive to exploit directly the layers into which not only higher markups, but higher rates of incremental learning as well, are possible.

The telecommunications industry provides large evidence on such dynamics. A broad digital knowledge base makes it possible for firms to select a variety of layers, from transmission to switching and distribution, in a wide range of product markets including broadband or cellular technology, television and fixed telephony (Antonelli, 2001; Krafft, 2003). The case of numerical control provides the full range of cases. The technology of numerical control can be sold as a patent or a license. It can be sold embodied in software, in the numerical control itself or finally it can be embodied in a machine tool with numerical control. The machine tool in turn can be sold as such or it can be used as a capital good in the production of cars and trucks. The engineering industries and specifically the packaging and textile machinery industry provide similar evidence. Each of these industries differs widely in terms of transaction costs on the supply side.

On the demand side, it is clear that the purchase of external knowledge with high levels of complementarity with the internal knowledge base is especially attractive. This is the case also when knowledge is composite. In turn, the notion of market cascades applies: firms can select whether to buy patents, licenses, knowledge-intensive business services, and an array of knowledge-intensive products that belong to the same filiere and the selected stage of the production process either as capital goods or intermediary goods incorporating high levels of technological knowledge. Transaction costs for the knowledge input here need to be assessed in each of the markets and valued at the overall level.

Market transactions of knowledge are often characterized by the systematic use of long-term contracts and structured interactions among the parties involved. This is especially the case when knowledge cumulability is high. In such case knowledge transactions in fact include post-assistance and the help of knowledge producers to knowledge users not only to increase the chance of more effective technology transfer but also to increase the chances of the vendor retaining some control upon the flows of incremental knowledge that is likely to be generated by the users.

The markets for the property rights of knowledge-intensive firms provide an additional layer of the market cascade that makes possible arm's length knowledge transactions. As a matter of fact, financial markets provide an alternative and a remedy to knowledge transaction costs. When knowledge cannot be sold as a disembodied commodity, or internal coordination and monitoring costs limit the opportunities for its embodiment into new products, the property rights on that knowledge can be traded. This is a viable solution when technological knowledge is sticky: financial transactions are better suited than knowledge transactions. Financial markets, in this case, provide effective governance mechanisms both for knowledge exploitation and knowledge exploration strategies.

Financial markets. Venture capitalism emerges as a useful and distinctive tool to support the birth and growth of new knowledge-intensive firms because it is able to combine the selective allocation of financial funds with the provision of competence and rare business skills. The goal of the creation of the new company, here, is not, like in scientific

entrepreneurship, the foundation of a new firm and its eventual growth, but rather its listing on the stock market. Venture capitalism is an effective governance mode especially when knowledge is sticky. Knowledge stickiness is found when it is difficult to separate the knowledge not only from the human capital but also mainly from the routines and procedures of the organization where learning activities have been taking place and the knowledge has been generated and articulated. In this case an issue of indivisibility emerges.

According to the localized knowledge approach, venture capitalism is a distinctive and effective governance tool, exactly because it makes it possible to combine several elements: (1) the assessment of the possible interfaces between scientific and technological knowledge, (2) the articulation of technological knowledge, (3) the selection of new ventures, and most important (4) the assistance to newcomers in terms of managerial competence and actual knowledge about the appropriate organization, marketing and production based upon the new technological knowledge. A bundle of transactions and interactions are integrated into venture capitalism as a governance mechanism: the provision of managerial and technical assistance is as important as the provision of financial funds. Funding indeed plays a role, but quite marginal with respect to the previous role. The basic difference between venture capitalism and banks resides exactly in the role of the knowledge communication flows among the parties involved. Banks able to provide effective managerial assistance to new firms are performing the typical function of venture capitalists. From this viewpoint the combined emergence of venture capitalism and dedicated financial markets specialized in transactions of knowledge-intensive property rights, such as the Nasdaq, is providing a new, effective form of knowledge governance.

The role of bundling aimed at minimizing transaction costs plays a major role in grasping the working of knowledge governance mechanisms. Here the notion of economies of scope in transaction costs fits the evidence: the creation of a bundle of products makes it possible to save on transaction costs. The bundling of products and services into new high-tech start-ups moreover makes it possible to combine two distinct demand schedules: the demand for financial products expressed by asset managers and financial institutions dealing with the investment of financial resources and the demand for knowledge expressed by firms. The combination of these two demand schedules has a strong positive effect in terms of the provision of funds to the production of knowledge, its distribution within the system and its selection. The interaction between the competence of different categories of financial operators in fact contributes to the increase of information transparency within the system.

Financial markets, and more generally the markets for knowledge-intensive property rights, provide an opportunity for a market for knowledge to emerge. Venture capitalism can be regarded as a major institutional innovation. The incorporation of the knowledge-intensive organization into a new company, either as a start-up or as a spin-off, and its sale in a dedicated financial market becomes a viable solution to trade knowledge with clear positive effects both on the demand and the supply side. The sale of knowledge embodied in knowledge-intensive property rights becomes a viable solution for new firms specializing in the production of knowledge, as well as for firms that cannot exploit directly the new knowledge because of steep organization cost curves. Conversely mergers and acquisitions are more and more, especially when the object is a high-tech IPO, a viable

solution to integrate new reliable modules of knowledge into a broader corporate structure.[5]

Mergers and acquisitions of new small high-tech firms become an effective tool to increase both the acquisition and hence the effective dissemination of technological knowledge into the economic system. In information and communication technologies the CISCO model has emerged as a reference: CISCO has pioneered the acquisition of high-tech start-ups as the primary if not exclusive tool to acquire new technological knowledge (Chesbrough, 2003). The evidence provided by small biotech firms is especially convincing here. New small firms assisted by venture capitalism and often created by academic spin-offs have introduced all the major innovations in biotechnology. Eventually however the large established corporations, traditional incumbents in the pharmaceutical industry, have acquired most of them. Incumbents here had all the advantages of global marketing and production capabilities, high levels of visibility and reputation in the markets for final products. Incumbents however were far less successful than smaller and younger high-tech firms. Here technological knowledge is embodied in the corporate structure and could be appropriated by means of the organization of routine-based firms (Gompers and Lerner, 1999).

Financial markets perform an important role in the governance of knowledge not only as an effective tool for the provision of financial resources to new technological undertakings. Financial markets make it possible to implement and valorize the working of knowledge complementarities. Financial markets make it possible to manage a flow of mergers, initial public offerings and acquisitions by means of which firms are able to change their boundaries. The effects of knowledge fungibility and compositeness can be better managed by means of the continual selection of the units and activities that it seems appropriate to coordinate internally, within the boundaries of the bureaucratic organization, and the units and activities with which knowledge transactions can take place in the markets (Avnimelech and Teubal, 2004; Antonelli and Teubal, 2006).

3.3. Constructed Interactions for Articulable Knowledge

Articulable knowledge consists of a mix of tacit and codified knowledge and it can be considered a step in a process of codification. As such it exhibits intermediate conditions of appropriability. In such conditions knowledge spillovers are possible but require substantial efforts to be absorbed by perspective users. Firms may select external coordination strategies based upon networking to implement both the development of a research project with the acquisition of relevant external knowledge and its commercial exploitation. Technological communication can take place however only if the parties are able to manage the strong information asymmetries. For this reason the exchanges of articulable knowledge take place by means of constructed interactions within technological clubs and coalitions. Here knowledge networking activities are required and include high levels of monitoring and assessment of the actual conduct of the partners in the club. When technological knowledge is articulable, the contractual interaction among partners within technological clubs can be better implemented because of the reduction in information asymmetries

[5] As a consequence, R&D statistics are less reliable as an indicator of the effective amount of resources invested in the generation of new knowledge by firms.

among parties and the higher levels of observability of the actual efforts and related contributions of each member. Trust combined with cognitive and geographical proximity can help the division of labor and complement corporate hierarchies. The exchange of articulable scientific and technological knowledge is also practiced within research communities based upon repeated interactions and closed reciprocity in communication. The incentives to the creation of informal and yet intentional interaction procedures, often implemented by co-localization within technological districts, are very strong in this case.

Long-term cooperation contracts. Knowledge interactions and networking based upon long-term bilateral contracts make it possible to valorize knowledge indivisibility and hence to access, generate and exploit technological knowledge that cannot be either coordinated internally or traded in the marketplace. External coordination among a small number of firms is formed around long-term cooperation contracts that specify the conditions of access and usage of the eventual findings. Knowledge contracted cooperation differs from knowledge transactions. The latter take place when actual exchanges take place and two parties agree to sell and buy respectively a piece of knowledge. Knowledge networking based upon contracts make it possible for structured, cooperative interactions based upon flows of knowledge communication among parties with strong elements of coordination and duration in time. Knowledge cooperations based upon contracts provide a barrier to the explosion of free-riding and opportunistic behavior. Knowledge networking however is not a ''free lunch'' but requires dedicated activities and receptivity-enhancing networking behaviors. Networking consists in the systematic and organized sharing of codes of conduct among independent firms, which agree explicitly upon knowledge interactions qualified in terms of trust, reciprocity and repetition and based upon contracts and to access the competence and the expertise of the other party in a context qualified by a clear identification of the parties (Menard, 2000; Cassier and Foray, 2002).

Technological clubs. A specific form of knowledge cooperation can be identified when more than two or three firms cooperate. Technological alliances and research coalitions are formed with the specific task to create and manage collective research pools. Such relations can be symmetrical when each partner owns a complementary bit of original knowledge and asymmetrical when the value and the relevance of the proprietary knowledge possessed by each party differs. The assessment of the actual worth of the knowledge controlled by each party of course is the first problematic issue to be solved. Each firm will try and secure the benefits stemming from its own specific bit of knowledge and will try and minimize the risks of leakage or uncontrolled dissemination, even within the club. The implementation of specific control rights is a typical solution. By means of a clear definition of the control rights of each partner into the club and the allocation of dedicated markets, defined in product and geographical terms, and timing of access to the sequential results, partners can solve the problems of information asymmetry and the risks of opportunistic behavior (Lerner and Merges, 1998; Brousseau and Glachant, 2002).

The distinction between procedural and content contracts is relevant here. Procedural contracts are incomplete contracts designed to specify the modality of the interaction while content contracts focus the characteristics of the actual transaction. It is in fact possible to implement and eventually to enforce specific procedural contracts about the process of participation and timing of assignment of property rights, temporary and partial exclusivity, time lags and partial and discriminated domains of privilege to subsets of contributors,

selected according to the amount of inputs and to the actual results. The reputation of the fellows in the club plays an important role in building technological clubs as it increases trust: the higher the reputation of the members the higher is the stability in cooperation (Attalah, 2003).

The characteristics of knowledge matter to shed some light on the kinds of technological clubs. When knowledge cumulability matters, vertical clubs are often found aligned along user–producer relationships. Horizontal clubs are instead more effective when knowledge is composite. Vertical technological clubs often complement the sale of patents and licenses and are based upon the close inspection of the activities of the customers and users of the patents. The relationship between the vendors and the customers takes place within long-term contracts, which include the assistance and the active cooperation of the two parties. The major goal here is not only the reduction of transaction costs stemming from the prospects for future knowledge but also the coordination of the learning opportunities stemming from eventual and shared implementation of the original knowledge. The vendors participate both in the appropriation and the participation in the creation of the derivative knowledge stemming from its implementation and incremental accumulation (Johnson, 2002). Generative relationships are very effective within vertical technological clubs when new knowledge is generated within the context of user–producer interactions (Von Hippel, 1988). Vertical technological clubs differ from horizontal ones. In the latter all parties are involved in a shared research activity where each member contributes its own competence and nobody claims the role of knowledge originator (Foray and Steinmueller, 2003).

Sponsored spin-off. Firms more and more practice sponsored spin-off as a tool to valorize second-best technological opportunities. When coordination costs and specifically agency costs in the generation of new knowledge are too high and technological knowledge is sticky, the creation of a new enterprise by the team of researchers and experts with the help and assistance of the former employer is a viable solution. The sponsored spin-off is assisted by the parent company in terms of technical assistance, provision of funds and especially long-term purchasing contracts for the output. In turn the sponsored spin-off remains under the formal and informal control of the parent company in terms of incremental knowledge generated and definition of the standards and characteristics of the products. Sponsored spin-off is also a way to reduce agency costs and yet to increase the division of labor and the specialization. The parent company may even rely for the production of a component or a dedicated input, formerly manufactured internally, to the new company (Patrucco, 2005).

Patent thicketing. Cross-licensing and patent thicketing are useful governance mechanisms when technological knowledge is composite and appropriability conditions exist. The chances to go ahead depend on the command of a variety of different bits of technological knowledge. The costs of internal coordination of the activities that are necessary for the accumulation and implementation of the full range of kinds of knowledge become quickly prohibitive. The distinctive specialization and capabilities of each firm cover only a minor portion of the full range of complementarities. In these circumstances firms may find it profitable to create a pool of knowledge resources by means of cross-licensing. The access of each firm to the proprietary knowledge of the others depends upon the amount of proprietary knowledge each firm is able to contribute. Cross-licensing is an

effective mechanism of governance especially when the range of applications of the knowledge generated is itself wide and barriers to mobility limit the competition among firms. Each firm can benefit from the knowledge generated in distinct product markets. Cross-barriers to entry in national markets and transportation costs may favor such agreements (Reitzig, 2004).

Standardization committees. When knowledge is both codified and composite, standardization committees are useful governance mechanisms. Standardization committees help the valorization of the complementarities of knowledge modules possessed by different firms. Standards emerge in this case as the result of the intentional participation of firms into a process of collective implementation of a common knowledge base and are especially effective in managing its applications into specific technological results that exhibit high levels of interoperability and compatibility (Antonelli, 1999).

Networking within geographic and technological clusters. Knowledge interactions based upon geographical and technological proximity differ from contractual networking and are distinct and specific with respect to knowledge transactions. Proximity substitutes for contracts for many reasons. First, proximity reduces the scope for opportunistic behavior because of the exposure to repeated interactions and also reduces the costs of communication. Second, proximity favors the sharing of language and communication protocols. Thirdly, proximity favors the connectivity of labor markets and hence the circulation of tacit knowledge embodied in the skills of personnel. Fourthly, proximity favors the informal barter of know-how both in user–producer relationships and even among competitors relying on tacit codes of reciprocity and repetition because of the frequency of mutual interactions. High levels of reputation for local trust and an effective tradition of mutuality in knowledge interactions qualify the attraction of regions for firms seeking to benefit from the advantages stemming from knowledge indivisibility (Feldman, 1999).

Nested networking and transactions are most important to understand the working of knowledge dissemination and generation within geographic clusters. Here the behavior of firms in labor markets and the conduct in the many markets for intermediary inputs, including professional services, are strongly intertwined. Transaction and networking costs need to be assessed in the full range of activities where direct interdependence among firms takes place. Reciprocity and assessment take place across many markets that are closely related both by proximity and by knowledge indivisibility. Spillovers do not flow freely in the atmosphere, but can be absorbed only when communication protocols have been established (Cohen and Levinthal, 1990). Constructed interactions are necessary to absorb knowledge spillovers for the high levels of knowledge communication costs.

The distinction between knowledge cumulability, fungibility and compositeness makes it possible to identify four distinct mechanisms at work within geographical clustering:

(I) When fungibility applies, coordination costs prevent firms, typically large corporations, from taking advantage of all possible applications of their proprietary knowledge. Firms are induced to select the technologies they want to develop internally and may allow the leakage of marginal technological knowledge. Interstitial opportunities for smaller firms are created. Small firms grow around the driving engines provided by large corporations. The flows of technological communication are vertical as they are centered upon a central beam that provides

the role of a switching system. Here the analysis of Francois Perroux on the ''poles de croissance'' and the driving role of large corporations applies (Perroux, 1964).

(II) When complementarity among diverse and dispersed bits of knowledge matters and takes the form of knowledge cumulability instead, the spatial agglomeration of small firms that are active within the same filiere and command complementary bits of knowledge may favor the collective generation of new technologies. Here there is no beam and the flow of technological knowledge is typically horizontal and it is based upon reciprocal access. Sectoral technological districts specialized in a narrow range of products, typically characterized by high levels of sequential complementarity emerge as effective nodes that favor knowledge communication and hence the generation of new technological knowledge by firms that rely upon external knowledge (Patrucco, 2003).

(III) When technological knowledge is composite, the variety and heterogeneity of the competence of firms becomes the key issue. The complementarity among a broad array of technological fields is key to favor the recombination and eventual generation of new knowledge. Multi-industrial technological districts, with a strong urban character and effective access to high quality academic infrastructures become an effective mechanism of governance (Jacobs, 1969).

(IV) Finally, within technological districts, vertical knowledge interactions between users and producers—along the industrial filieres that link industries specializing in final products to upstream industries specialized in advanced intermediary inputs and capital goods—play a key role. Such interactions stimulate and qualify the feedbacks between the demand for new, advanced technologies and their supply. Close relations between vendors and customers make easier the mutual understanding and bilateral flows of knowledge that can be better articulated with huge positive effects in terms of rates of introduction of innovations (Von Hippel, 1988; Antonelli and Barbiellini Amidei, 2006).

These four models differ sharply as they are based upon different characteristics of technological knowledge and grasp completely different modes of interaction among firms. In the first case, diseconomies of scope and coordination costs for large corporations are the key factors that lead, often by means of sponsored spin-off, to the creation of technological interstices. Growth poles are clearly a mechanism for the exploitation of technological knowledge. In the second case proximity favors strategies of social generation of a given module of technological knowledge. Higher levels of total factor productivity increase can be directly expected from the localized exploitation of knowledge fungibility. In the third case instead, proximity favors the implementation of strategies of explorations in a variety of technological modules. Broad exploration eventually leads to higher rates of generation of new knowledge and as a consequence to faster rates of introduction of innovation and ultimately to higher levels of productivity growth. When knowledge is composite, the variety of the knowledge modules available within a geographical cluster becomes a relevant issue. The larger such variety, in fact, the higher the chances that the recombination process is able to yield the generation of a new technological knowledge that is composite. Here the distinction between inter-industrial and intra-industrial knowledge externalities is important. When knowledge is composite, the clustering of a wide variety of firms, active in different industries and with a different

knowledge base, is far more conducive to the generation of new knowledge, than mono-industrial clusters, specialized in a narrow range of activities. Urban districts typically provide such multi-industrial opportunities. Finally, the fourth case differs for the key role of vertical inter-industrial complementarities between firms and industries that belong to the same filiere: actually in most cases the filiere itself is the result of a localized process of constructed interactions that enable increasing levels of division of labor and specialization.

Reputation within epistemic and professional communities. Epistemic communities play an important role when the division of knowledge labor is based upon knowledge interactions, as distinct and specific with respect to knowledge transactions and knowledge contracts, qualified by a clear membership into a well-defined professional community. The generation of new knowledge and its free dissemination within epistemic communities is based upon the rewards stemming from the correlated production of professional reputation. Here the notion of nested interactions and transactions is most important and provides a major clue to assessing the much debated evidence.

Members of professional communities are ready to contribute to the collective production of new knowledge provided not only that they can access the knowledge generated by others, but also and primarily that they can capitalize on the professional rewards based upon reputation that is associated with the social visibility and recognition of the contributions to the common endeavor. Agents are clearly able to assess jointly the costs stemming from possible opportunistic behavior in one set of interactions and the advantages stemming from transactions in the related markets for professional services. This analysis makes it possible to understand an important aspect of the working of open science in general and of one of its specific applications as open source.

Open source. A relevant application of the basic model, elaborated in open science and based upon professional reputation, has been spreading in the software industry where knowledge is characterized by strong elements of cumulability and fungibility. The open source software can be considered the best case of an open technological platform. In the open source experience the source code of the GNU/Linux computer operating system has been made available to the public. Incremental enrichment of the basic code is then provided by the spontaneous contributions of a myriad of actors selected by an informal organization of gatekeepers. Richard Stallman and Eben Moglen have elaborated the notion of General Public License (GPL) as the basic governance tool. According to the GPL each player can access the source code, can modify it and distribute the results of his/her work to third parties at no cost, provided that three important conditions are respected: (a) the original assignee is notified by the new user and registered, (b) an explicit reference to prior proprietary—albeit non-exclusive—knowledge is made in the new knowledge, and (c) all the advances introduced are in turn made public and available to third parties.[6] The

[6] It is worthy and analytically rewarding to spell the origin of the acronym FLOSS (Free Libero Open Source System) currently used to define the system according to which users have access to the General Public License provided they agree to make available the results of their interventions. The insertion of the Latin word Libero in Italian or Libre in French is made necessary by the lack of specificity of the English language, unable to articulate the distinction between freedom of speech and freedom of charge. The FLOSS is clearly based upon the first but does not imply the second. Users have in fact a barter obligation to make available to others the results of their access to the open source.

introduction of the GPL has been most effective as a tool to secure the systematic codification of the new software produced and the implementation of its complementarity and accessibility to third parties. Spontaneous entry in the GNU/Linux platform is induced by the free access to the code source and by the increasing size of the library of applications made available by previous users. Each additional project however is not planned in advance and it is rather the result of the idiosyncratic activity of each user. In turn, each user is expected to make the results of his/her activity accessible to third parties by means of the GPL.

In the generation of this kind of software knowledge, learning as a joint product of current activity plays a key role. New enriched codes are the result of exploration activities and specific dedicated activities being carried out as a part of the professional activity of new users. The social recognition of their contributions plays an important role in this community as an indicator of professional expertise and contributes to the creation of professional reputation. In turn for each agent the exploitation of the reputation conveyed by the granting of the GPL takes place easily in the supply of an array of software services ranging from maintenance to specific customized applications and localized implementation.

The successful working of the GPL seems to be based upon the strong notion of complementarity: complementarity between the elaboration of new applications and the implementation of the source code and complementarity between reputation and exploitation, at the agent level. At the system level it is clear that the GPL works as an affective signaling mechanism that makes public and easily accessible all the implementations to the source code. In a free software system the identification of all progress would be undermined and the working of the open knowledge platform would be hampered by major and recurrent information asymmetries.

From this viewpoint the GPL can be considered as a first step in the departure from the property rule and a first application of the liability rule in the governance of knowledge. According to the GPL agreement in fact the patent is assigned to the inventor who is informed but cannot prevent the use of his proprietary knowledge by third parties. The latter, however, are obliged to register, and to recognize, by means of explicit references, the contribution of the prior and proprietary knowledge patented and to provide the results to third parties. These obligations, together with the automatic granting of the authorization to the user after notification, can be considered a form of application of the liability rule. This is especially clear if the crucial role of the citations is appreciated as a main factor in implementing the social recognition and professional reputation of the first inventor and hence in increasing the rents he can extract in the markets for professional services (see Samuelson *et al*., 1994; Reichman, 2000).

The open source software seems to work successfully owing to the strong role of complementarity between learning and working on the one hand and between social recognition and professional reputation, with the attached effects in terms of fees and wages for the contributors on the other hand. In such circumstances agents are willing to contribute freely the social endeavor because of the lateral effects in terms of increased visibility and earnings (Lerner and Tirole, 2002). In the working of epistemic communities the complementarity between the generic knowledge embedded in the source code and the specific and idiosyncratic knowledge upon which applications can be introduced plays a major role. The appropriability of the specific knowledge upon which each application to a

narrow and highly contextual case is based is high. Applicators can command a large share of the rewards stemming from the applications. Applicators hence have a clear incentive to share the basic knowledge embedded in the source code and to implement collectively the code which becomes the common pool from which each applicator will eventually draw in order to apply the general principles to specific cases (Dalle *et al.*, 2003, 2004).

Epistemic communities appear to be especially effective when the common undertaking has no specific and explicit *ex ante* tasks. In the open source case in fact the path of knowledge generation advances by means of the proliferation of incremental applications that build upon cumulability and compositeness, but without an explicit direction and final destination. On the opposite, free contribution to the common undertaking can take place because each agent contributes the specific results of his/her own activity, after it has been conceived and subsequently used according to the specific and idiosyncratic needs of that undertaking. Complementarity here is an *ex post* outcome, rather than a planned, *ex ante*, condition for the upgrading of the knowledge path. As such the working of epistemic communities is characterized by substantial unpredictability both in terms of the rates and the direction of the collective activity (Von Hippel and Von Krogh, 2003).

4. Conclusions

This work has provided an information economics analysis for the economics of knowledge and explored systematically the effects of knowledge characteristics upon the assessment of the design, the characteristics and the performances of the institutions and processes that shape the governance of the generation and distribution of technological knowledge. Economics of information provides important tools to understand the details of knowledge governance mechanisms. Neither pure markets nor pure hierarchies can provide the necessary levels of coordination and division of labor. An array of knowledge governance mechanisms, ranging from coordinated transactions and constructed interactions to quasi-hierarchies, however, has progressively emerged according to the characteristics of knowledge and the costs of using markets and organizations. Both the forms and the characteristics of knowledge have a direct bearing on the costs related to knowledge transactions, knowledge interactions and the internal coordination of knowledge generation and hence on knowledge governance mechanisms and knowledge governance modes.

The application of the basic tools of information economics to the economics of knowledge provides an interpretative frame able to appreciate the variety of constraints and incentives of the different governance mechanisms, which shape the generation of technological knowledge in a market economy. This approach has made it possible to appreciate the constraints raised by organizational factors such as coordination, networking and transaction costs in shaping the process of accumulation and generation of new knowledge and to articulate a single analytical framework that seems able to integrate the broad variety of modes of governance that a wide empirical literature in the economics of knowledge has identified. At the same time the approach, elaborated so far, has made it possible to highlight the key role of nested transactions and interactions and the need to go beyond the analysis of single transactions when indivisibility matters. Both economies of scope and externalities in transaction matter. This notion is most relevant in the analysis of knowledge governance but seems to have a wider scope of application.

In this context, the dynamic coordination among such a myriad of agents, which keep changing their technologies, their knowledge, their competences, that is, their location in the multidimensional spaces into which they are located, and their knowledge exploration and exploitation strategies, becomes the key issue. In the specific context of the economics of localized knowledge, dynamic coordination is especially relevant to reduce the costs of ''multiple inventions'' that is the waste of resources invested in the generation of the same knowledge by different agents unaware of the parallel efforts of others. Only when such a dynamic coordination takes place, can external knowledge be timely and consistently available and actually complementary with internal learning and research strategies. Increasing returns in the generation of knowledge depend, of course, on the solution of the many facets of the knowledge trade-off but depend primarily upon the levels of dynamic coordination a system is able to express. Knowledge is the key emergent property of the complex system dynamics only when dynamic coordination is successfully implemented.

Business knowledge governance is not a sufficient condition for dynamic efficiency to be assured in the knowledge markets. When increasing returns matter, such as in the case of knowledge complementarity, cumulability, fungibility and compositeness and the price mechanism is unable to convey all the relevant information, the markets are unable to set the right incentives and hence move in the right direction. In the present institutional context, knowledge governance mechanisms in place are not able to provide all the necessary coordination between the variety of agents that participate in the collective process of generation of new knowledge. The basic trade-offs between appropriation and dissemination, concentration and distribution, incentives to produce and incentives to use, variety and complementarity remain to be solved. Technological knowledge is such an imperfect good that spontaneous market coordination cannot provide the necessary consistency between private and public optima. Public policy interventions specifically designed to increase dynamic coordination by means of the defense of the working of knowledge commons and the increase in the informational efficiency of knowledge governance are necessary.

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References

Akerlof, G. A. (1970) The market for lemons: quality uncertainty and the market mechanism, *Quarterly Journal of Economics*, 84, pp. 488–500.

Anand, N. B. and Tarun, K. (2000) The structure of licensing contracts, *Journal of Industrial Economics*, 48, pp. 103–135.

Antonelli, C. (1999) *The Microdynamics of Technological Change* (London: Routledge).

Antonelli, C. (2001) *The Microeconomics of Technological Systems* (Oxford: Oxford University Press).

Antonelli, C. (2003) Knowledge complementarity and fungeability: implications for regional strategy, *Regional Studies*, 39, pp. 595–606.

Antonelli, C. (2005b) Models of knowledge and systems of governance, *Journal of Institutional Economics*, 1, pp. 51–73.

Antonelli, C. (2006) The economics of university: a knowledge governance approach, Laboratorio di economia dell'innovazione WP 1/2006.

Antonelli, C. and Barbiellini Amidei, F. (2006) Technological change and industrial growth: the Italian evidence, Working Paper of the Ufficio Ricerche Storiche of the Bank of Italy.

Antonelli, C. and Quèrè, M. (2002) The governance of interactive learning within innovation systems, *Urban Studies*, 39, pp. 1051–1063.

Antonelli, C. and Teubal, M. (2006) Venture capitalism as a mechanism for knowledge governance, Laboratorio di economia dell'innovazione WP 2/2006.

Antonelli, C., Marchionatti, R. and Usai, S. (2003) Productivity and external knowledge: the Italian case, *Rivista Internazionale di Scienze Economiche e Commerciali*, 50, pp. 69–90.

Argyres, N. S. (1995) Technology strategy governance structure and interdivisional coordination, *Journal of Economic Behavior and Organization*, 28, pp. 337–358.

Arora, A., Fosfuri, A. and Gambardella, A. (2001) *Markets for Technology* (Cambridge, MA: MIT Press).

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*, pp. 609–625 (Princeton, NJ: Princeton University Press for NBER).

Arrow, K. J. (1974) *The Limits of Organization* (New York: W. W. Norton).

Attalah, G. (2003) Information sharing and the stability of cooperation in research joint ventures, *Economics of Innovation and New Technology*, 12, pp. 531–555.

Avnimelech, G. and Teubal, M. (2004) Venture capital start-up co-evolution and the emergence and development of Israel's new high tech cluster, *Economics of Innovation and New Technology*, 13, pp. 33–60.

Bonazzi, G. and Antonelli, C. (2003) To make or to sell? The case of in-house outsourcing at FIAT Auto, *Organization Studies*, 24, pp. 575–594.

Brousseau, E. and Fares, M. (2000) Incomplete contracts and governance structures: are incomplete contract theory and new institutional economics substitutes or complements, in: C. Menard (Ed.), *Institutions Contracts and Organizations. Perspectives from New Institutional Economics* (Cheltenham: Edward Elgar).

Brousseau, E. and Glachant, J. M. (Eds) (2002) *The Economics of Contracts* (Cambridge: Cambridge University Press).

Cassier, M. and Foray, D. (2002) Public knowledge, private property and the economics of high-tech consortia, *Economics of Innovation and New Technology*, 11, pp. 123–132.

Chesbrough, H. (2003) *Open Innovation. The New Imperative for Creating and Profiting from Technology* (Boston: Harvard Business School Press).

Cohen, W. M. and Levinthal, D. A. (1989) Innovation and learning: the two faces of R&D, *Economic Journal*, 99, pp. 569–596.

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

Consoli, D. (2005a) Technological cooperation and product substitution in UK retail banking: the case of consumer services, *Information Economics and Policy*, 17, pp. 199–216.

Consoli, D. (2005b) The dynamics of technological change in UK retail banking services: an evolutionary perspective, *Research Policy*, 34, pp. 461–480.

Cooke, P. (2002) *Knowledge Economies* (London: Routledge).

Cowan, R. and Foray, D. (1997) The economics of codification and the diffusion of knowledge, *Industrial and Corporate Change*, 6, pp. 595–622.

Cowan, R., David, P. A. and Foray, D. (2000) The explicit economics of knowledge codification and tacitness, *Industrial and Corporate Change*, 9, pp. 211–253.

Dalle, J. M. and David, P. A. (2003) The allocation of software development resources in open source production mode, SIEPR Discussion Paper No. 02-27.

Dalle, J. M., David, P. A., Ghosh, A. R. and Steinmueller, W. E. (2004) Advancing economic research on the free and open source software mode of production, SIEPR Discussion Paper No. 04-03.

Dasgupta, P. and David, P. A. (1987) Information disclosure and the economics of science and technology, in: G. Feiwel (Ed.), *Arrow and the Ascent of Modern Economic Theory* (London: Macmillan).

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

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

Fai, F. and von Tunzelmann, N. (2001) Scale and scope in technology: large firms 1930/1990, *Economics of Innovation and New Technology*, 10, pp. 255–288.

Feldman, M. P. (1999) The new economics of innovation spillovers and agglomeration: a review of empirical studies, *Economics of Innovation and New Technology*, 8, pp. 5–26.

Foray, D. and Steinmueller, W. E. (2003) On the economics of R&D and technological cooperation: insights and results from the project "COLLINE", *Economics of Innovation and New Technology*, 12, pp. 77–92.

Garicano, L. (2000) Hierarchies and the organization of knowledge in production, *Journal of Political Economy*, 108, pp. 874–904.

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

Gompers, P. and Lerner, J. (1999) *The Venture Capital Cycle* (Cambridge, MA: MIT Press).

Holmstrom, B. (1989) Agency costs and innovation, *Journal of Economic Behavior and Organization*, 12, pp. 305–327.

Jacobs, J. (1969) *The Economy of Cities* (London: Jonathan Cape).

Johnson, D. K. (2002) "Learning-by-licensing": R&D and technology licensing in Brazilian invention, *Economics of Innovation and New Technology*, 11, pp. 163–177.

Jones, C. I. (1998) *Introduction to the Economics of Growth* (New York: W. W. Norton).

Kingston, W. (2001) Innovation needs patents reforms, *Research Policy*, 30, pp. 403–423.

Krafft, J. (2003) Vertical structure of the industry and competition: an analysis of the evolution of the infocommunicaton industry, *Telecommunications Policy*, 27, pp. 625–649.

Laestadius, S. (1998) Technology level, knowledge formation and industrial competence in paper manufacturing, in: G. Eliasson *et al.* (Eds), *Microfoundations of Economic Growth*, pp. 212–226 (Ann Arbor: University of Michigan Press).

Langlois, R. N. (1992) Transaction-cost economics in real time, *Industrial and Corporate Change*, 1, pp. 99–127.

Lerner, J. and Merges, R. P. (1998) The control of technology alliances: an empirical analysis of the biotechnology industry, *Journal of Industrial Economics*, 46, pp. 125–156.

Lerner, J. and Tirole, J. (2002) Some simple economics of open source, *Journal of Industrial Economics*, 52, pp. 197–234.

Lessig, L. (1999) *Code and Other Laws of Cyberspace* (New York: Basic Books).

March, J. (1991) Exploration and exploitation in organizational learning, *Organization Science*, 2, pp. 71–87.

Menard, C. (Ed.) (2000) *Institutions Contracts and Organizations. Perspectives from New Institutional Economics* (Cheltenham: Edward Elgar).

Nooteboom, B. (2002) Learning and innovation in organizations and economics (Oxford: Oxford University Press).

Oerlemans, L. A. G. and Meeus, M. T. M. (2001) R&D cooperation in a transaction costs perspective, *Review of Industrial Organization*, 18, pp. 77–90.

Oxley, J. E. (1999) Institutional environment and the mechanisms of governance: the impact of intellectual property protection on the structure of inter-firm alliances, *Journal of Economic Behavior and Organization*, 38, pp. 283–309.

Patrucco, P. P. (2003) Institutional variety, networking and knowledge exchange: communication and innovation in the case of the Brianza technological district, *Regional Studies*, 37, pp. 159–172.

Patrucco, P. P. (2005a) The emergence of technology systems: knowledge production and distribution in the case of the Emilian plastics district, *Cambridge Journal of Economics*, 29, pp. 37–56.

Patrucco, P. P. (2008) Collective knowledge production, costs and the dynamics of technological systems, *Economics of Innovation and New Technology* 17, forthcoming.

Perroux, F. (1964) *L'economie du XX siecle* (Paris: Presses Universitaires de France).

Reichman, J. (2000) ''Of green tulips and legal kudzu'': repackaging rights in subpatentable invention, *Vanderbilt Law Review*, 53, pp. 17–43, Reprinted in Dreyfuss, R. & Zimmerman, D. (Eds) (2001) *Expanding the Boundaries of Intellectual Property*, pp. 23–54 (Oxford: Oxford University Press).

Reitzig, M. (2004) The private value of ''thickets'' and ''fences'', *Economics of Innovation and New Technology*, 13, pp. 457–476.

Romer, P. M. (1990) Endogeneous technological change, *Journal of Political Economy*, 98, pp. 71–102.

Romer, P. M. (1994) The origins of endogenous growth, *Journal of Economic Perspectives*, 8, pp. 3–22.

Samuelson, P., Davis, R., Kapor, M. D. and Reichman, J. H. (1994) A manifesto conceming the legal protection of computer programs, *Columbia Law Review*, 94, pp. 2308–2365.

Spence, M. (1973) Job market signaling, *Quarterly Journal of Economics*, 77, pp. 355–379.

Spulber, D. (1999) *Market Microstructures: Intermediaries and the Theory of the Firm* (Cambridge: Cambridge University Press).

Stiglitz, J. (2000) The contributions of the economics of information to twentieth century economics, *Quarterly Journal of Economics*, 115, pp. 1441–1478.

Stiglitz, J. E. (2002) Information and the change in the paradigm in economics, *American Economic Review*, 92, pp. 460–502.

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

Von Hippel, E. and Von Krogh, G. (2003) Open source software and the ''Private-Collective'' innovation model: issues for organization science, *Organization Science*, 14, pp. 209–223.