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THE GOVERNANCE OF TECHNOLOGICAL KNOWLEDGE: STRATEGIES, PROCESSES AND PUBLIC POLICIES

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THE GOVERNANCE OF TECHNOLOGICAL KNOWLEDGE: STRATEGIES, PROCESSES AND PUBLIC POLICIES[1]

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1. INTRODUCTION

In the last fifty years the economic role of knowledge has emerged and progressively gained the central place in the arena of the economic debate. Knowledge is indeed the primary resource into all human activity. Its identification as an economic good however has requested a long time and enduring efforts. Yet it takes different forms, is the result of different processes, it exhibits its powerful effects in a wide variety of contexts and it is highly sensitive to a number of key conditions. The identification of its different forms and characteristics and their systemic assessment into a single frame is the primary task of economics of knowledge as a discipline and competence, within the broader context of economics.

The economics of knowledge has gradually emerged as a discipline in a context characterized by a sharp evolution of the analysis and of the basic foundations. Such an evolution has made it possible to increase substantially our understanding of the economic characteristics of the generation and use of knowledge in the economics systems.

The distinction introduced by Joseph Stiglitz between information economics and economics of knowledge provides basic guidance (Stiglitz, 2000). The tools elaborated by information 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 their effects on the

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conduct of agents can be applied to understanding how the generation, dissemination and use of knowledge is organized in the economic system.

This work provides an analysis of the changing foundations of the economics of knowledge and of their effects upon the assessment of the design, the characteristics and the performances of the institutions and processes that shape the generation and distribution of technological knowledge.

Major changes have occurred in the economic understanding of knowledge in the second part of the XX century. Knowledge has been first regarded as a typical public good that markets and profit-seeking agents could not produce in the appropriate quantities and with the appropriate characteristics. These theoretical ingredients paved the way to the build-up of the infrastructure for the public provision of knowledge. Consensus on the analysis of the public good characters of knowledge has been first contrasted and eventually substituted by the new argument about the quasi-private nature of technological knowledge. The identification of the central role of external knowledge in the production of new knowledge marks the second step. The 'discovery' of the knowledge trade-off stressed the key role of its dissemination and the limitations of the intellectual property rights. Eventually a more balanced view based upon a deeper analysis of the generation and distribution of knowledge as a localized process has been elaborated. The appreciation of the different forms and characteristics of knowledge makes it possible a closer analysis of the role of knowledge interactions and transactions as aspects of a broader governance problem. This evolution can have important consequences on the analysis, the implementation and the institutional design of the production and distribution of knowledge.

2. KNOWLEDGE AS A PUBLIC GOOD

The seminal contributions of Kenneth Arrow marked for a long time the economics of knowledge. The arrovian frame shaped the debate about the economic organization for the supply of knowledge and provided the theoretical foundations for the build up of the public knowledge commons.

In the arrovian approach technological knowledge was seen as a public good for the high levels of indivisibility, non-excludability, non-tradability and hence non-appropriability. In this context markets fail to provide the necessary coordination and the case for undersupply takes place. Markets are not able to provide the appropriate levels of knowledge because of the lack of incentives, and the opportunities for implementing the division of labor and hence achieving adequate levels of specialization.

The public provision of technological knowledge, and especially scientific knowledge has been long regarded as the basic remedy to under-provision. This led to the actual build-up and the systematic implementation of public knowledge commons. The legacy of patronage, such as Universities and Academy of Sciences received new endorsement and support (Arrow, 1962; Nelson, 1959).

The key role of the public knowledge commons, based upon the public funding of universities and other public research centers was also consistent with the top-down view about the generation of technological knowledge. In the linear approach in fact technological knowledge was the eventual result of the application of new scientific discoveries. In the linear model a clear division of labor could be articulated between the role of universities and corporations. Universities and public research center were better equipped to perform scientific research. The eventual application of scientific discoveries for the actual generation of technological knowledge and the introduction of technological innovations was instead assigned to corporations.

The provision of public subsidies to firms undertaking research and development activities was regarded as a necessary condition to remedy the low appropriability conditions and hence the lack of incentives. Public procurement is the third basic tool to increase the production of knowledge. The demand for weapons especially becomes a major instrument to focus resources and identify research direction and objectives with a broader and general scope for derivative technological applications at the system level and relevant from the viewpoint of the general production of new scientific and technological knowledge. The natural leakage of technological knowledge from the military sector - often within the same corporations - feeds the levels of technological opportunity for the rest of the system. The spillover from the high-tech military activities provides unique opportunities for the introduction of product and process innovations in all the other sectors of the economy.

The arrovian approach easily integrated into the schumpeterian legacy according to which the large corporation with substantial market power was the appropriate institution to accelerate the rate of introduction of technological change. Because of the low levels of natural appropriability financial markets perform poorly in providing the necessary amount of external funds to firms undertaking research activities. Financial markets and specifically banks are most likely to ration the credit to innovation both because of radical uncertainty and low appropriability (Stiglitz and Weiss, 1981). Even when a research project finally generates a new bit of knowledge, the risks that the inventor, and hence the banker who provided the funds, is able to reap the benefits are put at stake by non-appropriability. Non-appropriability leads to non-fundability. Only large incumbents in product markets characterized by barriers to entry, could fund internally research and development activities, with their own money. Ex-ante monopolistic market power based upon barriers to entry in existing product markets would provide extraprofits and hence secure the financial resources to fund research and development expenditures and, most importantly, reduce the risks of uncontrolled leakage and imitation. Competitors have yet to enter and entry is barred by substantial cost disadvantages. Appropriability is provided by barriers to entry rather than by barriers to imitation. The large corporation is also considered the appropriate tool to increase the rate of introduction of innovations as it provides internal markets for financial resources and competence: because of low appropriability regimes, arms' length transactions in external markets cannot be used to coordinate neither the allocation of financial resources into research activities and their selection nor the necessary division of scientific and technological labor.

The foundations of the well-known schumpeterian trade-off between static and dynamic efficiency are laid down in this context. Monopoly reduces static efficiency, but makes it possible, via extraprofits and increased ex-post appropriability based on barriers to entry and hence imitation, the dynamic efficiency engendered by the increased amount of knowledge generated and hence the augmented flow of innovations.

Monopolistic market power based upon proprietary technological knowledge and the technological innovations stemming from its implementation was deemed to be temporary. Hence the welfare losses generated by the divergence between marginal and average costs were assumed to be short lived. Temporary monopolistic market power moreover could provide sufficient incentives to innovators to undertake risky activities finalized to the introduction of innovations. The short-term duration of monopolistic power provided an automatic solution to the schumpeterian trade-off between dynamic and static efficiency.

The creation of intellectual property rights was regarded as the complementary institutional set-up, parallel to the public provision of scientific knowledge and the benign neglect to monopolistic market power. Patents and copyrights, if properly implemented, could reduce non-excludability and non-appropriability. In a proper institutional design, intellectual property rights may also favour tradability and hence lead to higher levels of specialization and division of labor in the technological applications of new scientific discoveries, made possible by the public support. Intellectual property rights can help increasing the incentives to the production of incremental technological knowledge, but only in a broader context shaped by the role of the State (Kingston, 2001).

At this time in fact intellectual property rights are not considered as the major tool to improve the static and dynamic efficiency of the economic system in the production of knowledge. Patents are mainly viewed as an instrument designed to increase the incentives of firms to introduce minor technological innovations. Public subsidies, public direct participation in the production and demand for knowledge are regarded as the basic instruments to push the introduction of radical technological innovations (Machlup and Penrose, 1950; Alchian and Demsetz, 1973).

3. KNOWLEDGE AS A PROPRIETARY GOOD

The first major shift in the economics of knowledge takes place when the notion of knowledge as a public good is challenged and knowledge is regarded as a quasi-private good with higher levels of natural appropriability and exclusivity and hence tradability (Nelson and Winter, 1982).

Technological knowledge is now viewed as the result of a bottom-up process of learning, which takes place mainly within the borders of firms. Technological knowledge is based upon tacit knowledge accumulated by means of learning process. Here the work of Polanyi becomes a basic reference. The distinction between tacit and codified knowledge provides in fact the foundation to the new approach to technological knowledge (Nelson and Winter, 1982).

Tacit knowledge is the result of learning processes, it is not easy to articulate it and made explicit. Much empirical analysis has explored the role of learning in the accumulation of competence and the eventual generation of new knowledge. Interesting distinctions have emerged between learning by doing and learning by using. Imitation is hampered by major information and adaptation costs, appropriability is de-facto secured by high levels of stickiness in routines and procedures: the not-invented-here syndrome is much more effective than assumed in the public good tradition (Mansfield, Schwartz, Wagner, 1981; Harabi, 1995).

The theory of the firm is deeply affected by the new approach. Within the evolutionary approach, the resource-based theory of the firm has consolidated around the assumption that the generation of technological knowledge is the distinctive feature of the firm. The accumulation of competence, technological and organizational knowledge and the eventual introduction of technological and organizational innovations is now considered the essential role of the firm. The firm does not coincide with the production function and cannot be reduced to a production function. From this viewpoint the firm precedes the production function: the technology is in fact the result of the accumulation of knowledge and its application to a specific economic activity (Penrose, 1959; Foss, 1997).

The resource-based theory of the firm has grown as a development and an application of the economics of learning. The enquiry about the dynamics and the characteristics of learning processes, such as learning by doing and learning by using, and their relevance in explaining technological change has led to the identification of the firm as the primary locus of the generation and valorization of knowledge immediately relevant for the economic action, at least in market economies (Loasby, 1999).

The resource-based theory of the firm focuses the attention on the characteristics of the process of accumulation of competence, the generation of technological knowledge and the introduction of technological and organizational innovations, not only as key factors to understanding the firm, but also as the relevant characteristics in the general production of technological knowledge. In this context the firm is the primary , if not the single, actor in the production of knowledge for the whole economic system. The firm is viewed as the privileged locus where technological and organizational knowledge is generated by means of the integration of learning processes and formal research and development activities. The firm is considered in this approach primarily as a depository and a generator of competence and eventually knowledge (Foss, 1997; Nooteboom, 2000).

Large firms are regarded as the key actors in the generation of knowledge. The size of firms is considered to be a key condition to generate successfully new knowledge. Increasing returns are considered to play an important role with major threshold effects. Below a given size the effective performance of research activities and the implementation of learning processes would not be considered possible. The focus on the role of large corporations of this approach is clearly consistent with the schumpeterian legacy based upon ‘Capitalism, Socialism and Democracy’ (1942), itself far away from the schumpeterian legacy drawn from ‘The Theory of Economic Development’ (1911/1936). The contrast between schumpeterian legacies was eventually well articulated by Christopher Freeman (Freeman, Clark and Soete, 1982).

Because technological knowledge is now viewed as the sticky joint product of internal learning, it cannot spill freely in the air. Relevant absorption costs for potential users should be taken into account and qualified interactions between producers and users of new knowledge are necessary for technological knowledge to be actually transferred from one organization to another. The explicit and intentional assistance of original knowledge holders to perspective users is relevant, if not necessary.

More recently much empirical evidence and theoretical research have shown that appropriability is de-facto much higher than assumed. Knowledge is contextual and specific to the original conditions of accumulation and generation: as such natural appropriability conditions are far better than assumed. Imitation costs seem high as well as the costs of receptivity and re-engineering necessary to make use of non-proprietary knowledge. The costs of the non-invented-here-syndrome are appreciated. The assistance of original knowledge holders to perspective users is relevant, if not necessary. The notion of non-appropriability has been the object of systematic redefinition and new understanding (Levin, Klevorick, Nelson, Winter, 1987).

The new growth theory built upon the new appreciation of de-facto appropriability arguing that the economic effects of knowledge can be substantially appropriated, at least to such an extent that firms can fund correct levels of research and development expenditures. According to much new theorizing, the characteristics of knowledge are no longer regarded as conducive to market failure (Romer, 1990 and 1994; Aghion and Tirole, 1994).

In this context, intellectual property rights play an important role to create the institutional conditions to secure appropriability and hence to increase the levels of incentives to fund research activities by firms. Intellectual property rights, if properly designed, may also favour tradability and hence lead to higher levels of specialization and division of labour. Intellectual property rights can help not only to increasing the incentives to the production of scientific and technological knowledge, but also its tradability and hence the efficiency of the generation process (Geroski, 1995; Arora, Fosfuri and Gambardella, 2001).

This new approach paved the way to significant steps towards the privatization of public knowledge commons. The public provision of subsidies to firms undertaking research and development activities and the direct role of the State in the production of knowledge comes under a closer scrutiny. The role of University as the single provider of externalities to the economic system is questioned (Henderson, Jaffe and Trajtenberg, 1998).

A closer look to the working of the public commons and the actual need to put under scrutiny the productivity of the resources invested in the public knowledge commons, both at the system and the single units level, is advocated (Jaffe and Lerner, 2001). The new enclosures substitute the knowledge commons. Public research centers and Universities were solicited to patent their discoveries and often forced to enter the markets for the technological outsourcing of large corporations. The conditions for the effective appropriation of knowledge are enforced both at the firm level and in public organizations: the mobility of human capital is more and more regarded as a sensitive issue (May, 2000; Mowery, Nelson, Sampat, Ziedonis, 2001).

The new theory provided theoretical support to a new understanding upon the role of public research. As a consequence, a wave of privatizations has been taking place: Universities have been pushed to enter the markets for knowledge and knowledge outsourcing. Academic patenting and scientific entrepreneurship have been praised as new effective tools to stimulate the distribution of knowledge and to increase the incentives to its production. Much analysis has been carried out on the regional aspects of the interplay between the research system and the business community: geographical distance has proved a relevant factor in this context. (Feldman, 1993, 1994 and 1999; Audretsch and Stephan, 1996; Audretsch and Feldman, 1996; Geuna, 1999)

At the same time, the role of intellectual property rights is reconsidered. Intellectual property rights can complement and integrate the appropriability of technological knowledge, so that actual markets for knowledge, now much closer to traditional economic goods, can be developed. Intellectual property rights are now regarded as a complementary condition to increase the tradability and consequently to achieve the standard conditions for equilibrium supply of knowledge in the economic system. The extension of patent protection to new forms of knowledge such as software, algorithms and genetic entities finds here its foundations (Merges and Nelson, 1994; Sakahibara and Bransletter, 2001).

In this context the role of financial markets as an important component of the mechanism design for the governance of technological knowledge is appreciated. Special attention is paid to the opportunities provided by financial market as an insititution for the exchange of property rights of new innovative companies. The role of IPO (Initial Public Offerings) as a way to convey financial resources into new ventures and at the same time to assess and select the choices of venture capital receives much attention. Venture capital in fact can work only if financial markets are ready to offer an opportunity to dispose of the shares of new companies after incorporation and eventual market success (Lerner, 1995; Kortum and Lerner, 2000). This evolution of financial markets marks a major shift with respect to the traditional emphasis on the limits of financial markets. In the previous approach the stock exchange did not play a role and only credit was considered. Bankers were supposed to be reluctant in providing credit to risky ventures based on research activities and innovation. The case for credit rationing emerged as a major problem to fund innovation activities (Stiglitz and Weiss, 1981). In turn targeted credit rationing in financial markets stressed the role of internal financial markets and extraprofits to fund internally research activities that bankers cold not properly fund because of the lack of instruments able to generate and assess the necessary information on the risks and the eventual pay-off of investments in research activities (Saint Paul, 1992).

Scientific entrepreneurship grows into a fully fledged scientific capitalism as the new viable mechanism to incentivate, generate and disseminate technological knowledge in economic systems. Scientific capitalism is based upon scientific entrepreneurship, effective intellectual property rights systems, academic patenting, venture capitalism, initial public offering and financial institutions, including dedicated stock exchange systems (Nasdaq) where the new ventures can be assessed and possibly recombined with existing companies, by means of mergers and acquisitions. Technological knowledge can flow within the economic system embedded in new companies.

But, once again, the trade-off between static and dynamic efficiency emerges.

4. THE DISCOVERY OF THE KNOWLEDGE TRADE-OFF

The second major swing takes place when a closer analysis of knowledge appropriability made it possible to understand, next to its negative effects in terms of missing incentives and hence undersupply, the positive effects of technological spillover and the key role of technological externalities (Nelson, 1987; Griliches, 1992; David, 1993).

The new approach is based upon the discovery of external knowledge as an essential intermediary input in the production process of new knowledge The discovery of external knowledge, available not only by means of transactions in the markets for knowledge, but also by means of technological interactions, marks a new important step in the debate. External knowledge is an important input in the production process of new knowledge. This major progress is made when the special character of knowledge as a non-exaustible good that is at the same time an output and an input into the production of other knowledge is grasped and retained at the core of the analysis. Here the derivation from the arrovian notions of the non-excludability and non-divisibility of knowledge is clear.

Static efficiency provided by the articulated mechanism design of the so-called 'scientific capitalism' is now confronted with the negative effects in terms of dynamic efficiency by the excess control and exclusivity of knowledge as a quasi-private good. The dissemination of knowledge is put at risk by its very stickiness, by the proprietary character of much technological knowledge, the dwindling role of public knowledge commons and by the strong intellectual property rights regimes that have been enforced. Poor dissemination and exclusivity put at risk the access to external knowledge for each agent and hence the working of cumulablity and complementarity. This reduces the future flow of additional units of new knowledge.

An important contribution to understanding the role of external knowledge is provided by an extension and implementation of the approach based upon learning processes. The competence and experience that is necessary to innovate is acquired not only in the repeated usage of a given set of capital goods and intermediary products and in the production of well identified products. Also the experience accumulated in marketing and interacting with a well defined set of consumers and competitors in a limited range of products, is necessary in order to generate new knowledge and eventually introduce new products. Interactions with actual customers are a primary source of tacit knowledge about their tastes and needs (Lundvall, 1985). No successful product innovation can be effectively and successfully introduced without some dedicated competence about the market place. The distance, in the product space, from the products being traditionally delivered to the market place, can be considered a strong factor of increasing innovation costs and decreasing efficiency in the generation of innovations. Proximity in product space matters as the prime source of information about the tastes of customers and their potential interests. Proximity in the product space matters as well as about the capabilities of competitors and their strategic attitude. The introduction of product innovations in market niches that are far away from the source of the experience of each firm is put at risk by the lack of specific competence and relevant, additional costs should be recognized (Von Hippel, 1988).

The retrieval of the Austrian tradition, as articulated by Hayek about the dispersion of knowledge as a key charactistic of economic systems, even in static conditions where technological change is not considered, contributes this line of analysis. Technological knowledge is now viewed as dispersed and fragmented into a variety of specific and idiosyncratic applications and contexts. This view contrasts sharply the centralized and top-down understanding of knowledge built around the arrovian tradition (Hayek, 1945).

The core of the new analysis is now centered upon the exploration and identification of the conditions into which external knowledge, as an essential input in the production of new knowledge and new technologies, is effectively disseminated in the economic system. This line of enquiry contributes the founding of the systems of innovation approach, where the production of knowledge is viewed as the result of both knowledge transactions and the cooperative interactions, mainly rooted in regional space, of agents undertaking complementary research activities.

The focus is now more and more centered upon the analysis of the mechanisms of governance of the broad array of knowledge interactions among agents, including coordinated division of labor and market transactions, and their effects in terms of generation of and dissemination of new knowledge.

Regional economic contributes significantly the new approach highlighting effectively the role of geographic space in the distribution and circulation of knowledge and at the same time regional analysis is deeply affected by the new understanding of knowledge as a way to understand the role of geographic space (Feldman and Audretsch, 1999; Feldman and Massard, 2002; Antonelli, 2001 and 2003a).

The forms of technological knowledge are now seen as a major factor in assessing the chances of distribution and circulation. Tacit knowledge is clearly sticky and embedded into the organizations and possibly the individuals that have accumulated the relevant experience. Codified knowledge is better communicated and absorbed. Eventually however tacit knowledge can be articulated and finally it translates into its codified form. Only when knowledge is fully codified and systematic effort of articulation have been made, it can be diffused without the intentional assistance of the original holder (David, 1993; Cowan and Foray, 1997; Cowan, David and Foray, 2000; Ancori, Bureth and Cohendet, 2000).

The role of communication and transmission of knowledge is more and more appreciated. Communication theory is applied successfully to the analysis of knowledge communication processes. The density of communication channels and their duration are considered as relevant structural elements of an economic system. The role of business interactions are appreciated from the viewpoint of their communication role. Prices, of course, are no longer viewed as the single vectors of all relevant information for economic decision making. Next to prices in fact, vital information are transferred and contribute the generation of knowledge by each economic agent.

The key distinction between receptivity and absortive capabilities as distinct from the strength and intensity of the message receive due attention. The structure of economic systems from the view point of the knowledge communication flows receives much attention: the structure of the communication channels is analyzed and the organization of communication flows within the networks of relations appreciated (Cohen and Levinthal, 1989 and 1990).

Systems differ with respect to the speed and capillarity of the flows of knowledge communication. In turn the rate of generation of new knowledge and introduction of new technologies is clearly influenced by the permeability of the system. Percolation analysis is borrowed from physics and introduced in the economics of knowledge as a tool to appreciate the distinctive role of receptivity and connectivity in communication processes (Antonelli, 1999).

The role of small firms is now recognized and the contribution of large corporations reconsidered. The evidence especially in new information and communication technologies confirm that small firms and especially new ventures had played a central role in the introduction of key radical innovations. Proximity of small firms to large research laboratories, and academic centers was now regarded as the vital condition (Audretsch, 1995; Audretsch and Feldman, 1996; Audretsch and Stephan, 1996)

The advantages of the intellectual property right regime, in terms of increased incentives to the market provision of technological knowledge are now balanced by the costs in terms of delayed usage and incremental enrichment. The vertical and horizontal effects of indivisibility display their powerful effects in terms of cumulability. Indivisibility of knowledge translates into the basic cumulative complementarity among bits of knowledge. Complementarity and cumulability in turn imply that new bits of knowledge can be better introduced building upon other bits already acquired, both in the same specific context and in other adjacent ones. The access exclusion from the knowledge already acquired reduces the prospect for new acquisitions and in any event has a strong social cost in terms of duplication expenses (O' Donoghue, 2001).

The costs of exclusion associated to intellectual property rights, as a consequence, should be taken into account. Monopolistic control of relevant bits of knowledge, provided both ex-ante and ex-post by patents and barriers to entry in the products markets respectively, can prevent not only its uncontrolled leakage and hence its dissemination but also further recombination, at least for a relevant stretch of time

(Arrow, 1969; Dasgupta and David, 1987 and 1994; David, 1993; Shavell and Ypersele, 2001).

Here in the economics of technological knowledge the issues of externalities on the demand side become relevant and evident. The generation of technological knowledge is now considered to be characterized by technical and pecuniary externalities. The notion of user-interdependence makes its foray into the scene when agents value the levels of usage of other agents of certain goods. As far as scientific and technological knowledge is concerned, interdependence among users, hence on the demand side, is very strong. The actual chances of generating a new relevant bit of knowledge for each agent depend upon the levels of accumulation of skills and competence, education and access to information of the other agents in the community.

The amount of external technological knowledge, available in a given context, industrial, technological or regional, becomes an important endowment, as well as the conditions of access to it and the characteristics of the relational set-up. The issues of the distribution of knowledge become central in the debate and the notion of an actual knowledge trade-off is articulated. Uncontrolled leakage and low appropriability regimes reduce incentives, but may not necessarily lead to under-provision. Low appropriability engenders technological externalities and spillovers that are the prime factor in increasing the efficiency of generation of new knowledge, at the system level: the growth of efficiency can compensate for lower inputs (Griliches, 1992).

Intellectual property rights are now questioned as it seems evident that too strong a regime of protection may have positive effects in terms of increased incentives to the generation of knowledge, but has clearly negative effects in terms of delayed and slower circulation and distribution of the new knowledge available (Mazzoleni and Nelson, 1998). The duration of exclusive property rights assigned by patents and the conditions for their renewal, become a central issue for the possible negative drawbacks in slowing the rate of generation of new knowledge, especially when general purpose knowledge with a wide scope of applications is concerned (Scotchmer, 2001; Shankerman and Scotchmer, 2001).

The breadth of patents is also questioned: when the breadth is large the protection is not specific and the negative effects in terms of foreclosure can easily exceed the advantages in terms of increased incentives. A narrow definition of the scope of application of intellectual property rights is thus recommended (Klemperer, 1990; Merges and Nelson, 1994; Hopenhayn and Mitchell, 2001),

The introduction of a prize system has been advocated in this context as a possible alternative to patents. Prizes are seen as the proper incentive to the generation of technological knowledge because they combine the reward to innovators with informational advantages of patents in signaling the new relevant knowledge, which becomes available, but they do not impede the circulation of the new knowledge. The limitations of the prize system however are easily found on the screening and assignment procedure whereby committees of scientists and technologists might easily assign the rewards to the wrong piece of technological knowledge. An issue of bureaucratic coordination failure based upon bounded rationality clearly emerges (Wright, 1983; Shavell and Ypersele, 2001).

5. LOCALIZED TECHNOLOGICAL KNOWLEDGE

A new step is made with the full appreciation of the localized character of technological knowledge. In this approach technological knowledge is made possible by the continual efforts of accumulation of competence and technological knowledge based upon localized learning processes and the eventual introduction of innovations by agents rooted in a well defined set of scientific, technical, geographic, economic and commercial circumstances[2] (Atkinson and Stiglitz, 1969; David, 1975 and 1985; Stiglitz, 1987; Antonelli, 1995, 1999, 2001, 2003).

Technological knowledge is primarily the result of the valorization and implementation of underlying learning processes, in doing as well as in using and in interacting, that are localized in the specific context of action of each economic agent. The capability and the competence acquired by means of learning processes are heavily localized in a limited technical space for many reasons. Agents are characterized by bounded rationality and yet are able to learn. The mix of bounded rationality cum learning capabilities makes sure that the generation of technological knowledge is possible only in the proximity of the specific learning context. Proximity matters also in regional and technological space with respect to other learning agents as it makes it possible to take advantage of communication flows among complementary innovations and innovative activities and hence of contextual spillovers. Proximity in the product space matters because of the key role of learning to interact with customers and rivals and consumers switching costs.

[2] In this approach technological change is the endogenous outcome of the creative reaction, to the mismatch between expectations and actual facts, of myopic firms that are not bounded to quantity-price adjustments, but are able to change also their technology in a limited technical space defined by the pervasive role of irreversibility of fixed production factors and the effects of bounded rationality and learning processes. As a consequence at each point in time the market place is kept in disequilibrium between one possible equilibrium and many alternative ones introduced in a continual variety of efforts and attempts by heterogeneous and creative agents surprised by the mismatch between expectations and actual product and factor markets. The introduction of technological changes is an endless process because each innovation modifies the context anticipated by each other agent and hence induces other innovations. The process is path dependent because at each point in time irreversibility constraints the decision making of actors and yet their creative reaction can engender solutions that cannot be fully anticipated from their past. The assumptions about the irreversibility, of at least some inputs, and the key role of learning qualify the process as non-ergodic: historic time matters. The assumptions about failure induced technological change based upon reactivity, creativity and endogenous innovative capability mark the distinction between a past-dependent process and path dependent one: each innovation cannot be fully predicted from the past of the innovator.

Firms are viewed as biological agents, who are not limited to adjusting prices to quantities and vice versa. They are also able to learn and change their technology, as well as their strategies. A strong complementarity is assumed between learning, as a knowledge input, and other internal knowledge inputs such as R&D laboratories, within each firm. Moreover firms can generate new knowledge and hence eventually introduce new technologies, only when and if they are able to take advantage of external knowledge. No firm can rely exclusively on its own internal knowledge, either tacit or codified, whether it is the result of learning processes or formal research and development activities. In so doing the localized knowledge approach recognizes the role of Universities and other research centers as suppliers of strategic inputs into the production of knowledge (Antonelli, 1999, 2001, and 2003).

The relationship between external and internal knowledge becomes a key issue. Neither can firms generate new knowledge relying only on external or internal knowledge as the single input. With appropriate ratios internal knowledge and external knowledge enter into a multiplicative production function. Both below and above the threshold of the appropriate combination of the complementary inputs the firm cannot achieve the maximum output. According to the acquisitions of the localized approach, the representative firm cannot be not seen as the single actor in the process of generation of new knowledge. The variety of firms and learning institutions play a key role in understanding the essential features of the generation and circulation of knowledge when it is viewed as a collective good, with varying degrees of appropriability, dispersed and fragmented in the economic system, the result of both top down and bottom up processes, where learning by doing, learning by using and learning by interacting with suppliers, customers and rivals play an essential role.

Knowledge is now, more and more, viewed as collective good. The notion of collective good differs sharply both with respect to the arrovian tradition of knowledge as a public good and the approach to knowledge as a quasi-private good. Collective goods in fact are characterized not only by partial appropriability and shared property rights[3] but also by the role of the intentional effort, participation and contribution of each agent. Collective knowledge in other words is a shared activity that can implemented only by interactive agents that belong to a community of action and understanding. Collective knowledge pays attention to the elements of indivisibility and complementarity among the bits of knowledge possessed by each agent that characterize both the generation and the dissemination of knowledge in the system and value the contribution of external knowledge into the production of new knowledge. In this approach the role of technological communication among learning agents is stressed as a major factor affecting the actual capability of each agent to implement its internal knowledge. The communication of bits of knowledge in other words is not considered as obvious and spontaneous, but on the opposite, it is viewed

[3] And hence, limited spillovers and externalities such as in the notion of knowledge a quasi-private good introduced by Romer (1994 and 1996).

as the result of intentional efforts both in terms of connectivity and receptivity (Antonelli, 2001).

Localized technological knowledge can be understood as a collective activity characterized by the complementarity both between external and internal knowledge and the stock of existing knowledge and the flows of new knowledge. The implications of the indivisibility are reconsidered. The differences in the key role of the indivisibility of knowledge in its own generation, from the role of indivisibility in the usage of new knowledge are appreciated. Knowledge indivisibility is defined in terms of diachronic and synchronic complementarity of bits of knowledge. Diachronic complementarity leads to cumulability. Here the Newtonian understanding of the production of science as 'standing on giants' shoulders identifies a key attribute of knowledge production: the cumulative complementarity between different vintages of knowledge (Scotchmer, 1991, 1996, 2001).

When attention is focused on synchronic complementarity, the traditional notion of knowledge indivisibility is articulated here in the more specific notion of knowledge complexity. The chances to generate new knowledge are conditional on the identification and integration of the diverse and disperse bits of complementary knowledge that are inputs into the knowledge production process. The understanding of the notion of ‘modularity’ contributes this field of investigation. The map of knowledge can be organized in terms of modules. Each module is associated by weak and strong ties of complementarity to others, according to the specific direction of the research process (Gibbons, Limoges, Nowotny, Schwarzman, Scott and Trow, 1994; Loasby, 1999; Nooteboom, 2000; Brusoni and Prencipe, 2001).

When complexity matters, recombination plays a key role in the generation of new knowledge. New knowledge is generated mainly by means of the recombination of both pre-existing and parallel units of knowledge. Technological knowledge varies with respect to the role of knowledge complexity. In some industries the technological knowledge necessary to introduce technological innovations and to run the current business effectively is characterized by high levels of complexity. The sources of the knowledge currently used are diverse and yet need to be all kept under control. The automobile industry is a clear example of an industry with high levels of technological complexity. The effective production of competitive cars requires the command of an impressive range of different technologies including mechanical engineering, electronics, chemistry, electrical engineering, plastics technology, informatics, telecommunications and robotics. The introduction of new technologies in the automobile industry requires the full understanding of the compatibilities and complementarities of each and between each of these technologies.

New information and communication technologies themselves are the result of the complementarity among a wide variety of scientific fields including electronics, telecommunications, space technology, physics, chemistry, plastics and rubber. The new information and communication technological system is the result of the sequential introduction of a variety of complementary and interdependent technological innovations.

General systemic technologies emerge when a variety of specific bits of knowledge are drawn together and organized and combined in a new system of understanding. New information and communication technologies provide to-day a clear example of a new technological system which emerges on the basis of the identification and valorization of both synchronic and diachronic complementarities among units of knowledge possessed by a myriad of actors and as such dispersed and fragmented. New technological systems emerge around new organizing principles, which make it possible to recombine different bits of knowledge and integrate them into a new single framework. This understanding leads to the notion of resource pooling. The chances to generate new knowledge are conditional on the capability to draw together bits of knowledge that are actually diverse and yet complementary (Bresnahan and Traitenberg, 1995; Lypsey, Bekar and Carlaw, 1998).

When attention is concentrated upon the use of new technological knowledge, a second and quite distinct specification of the notion of indivisibility emerges: fungeability. Fungeability defines the downstream complementarity of any bit of knowledge. Some elements of technological knowledge may apply to a narrow and specific range of activities, either new products or new processes. Other bits of new knowledge can have important applications to a great array of new products and processes. Fungeability is defined and measured by the scope of application of a new bit of knowledge.

New information and communication technologies, like previous general purpose technologies, are characterized also by this second relevant aspect. New information and communication technologies in fact have also high levels of fungeability as they apply to a great variety of products and processes. No product and process can be manufactured without the substantial application of new information and communication technologies or without substantial effects of the application of new information and communication technologies (Antonelli, 1992).

Biotechnology provides clear evidence about the pervasive role of knowledge fungeability and yet low levels of knowledge complexity. Biotechnologies apply to a wide range of industries and activities including pharmaceuticals, food and beverages, pesticides and agricultural chemical products at large. Advances in biotechnology stem from a rather limited range of scientific fields and technological competencies. A large part of the XX century has been characterized by the high levels of fungeability of mechanical engineering in internal combustion technologies. The same core of technological knowledge and competence has been sequentially applied to the production of a wide range of products including cars, trucks, buses, armoured vehicles, agricultural machinery, construction machinery, ships and planes.

Complexity feeds the generation of new technological knowledge. New fungeable technological knowledge in turn feeds new recombinations and hence new steps forward. This dynamics has all the characteristics of a self-reinforcing process. Such a process in turn is wider and faster the larger is the fungeability of each bit of new knowledge.

In sum, the localized knowledge approach has made it possible major progress, consisting in the identification of a broad array of the characteristics and the forms of knowledge. Technological knowledge can be tacit, codified and articulable. Technological knowledge can be easily appropriated, or it can be a public good. Technological knowledge can also be a collective good when the intentional action and participation of agents is requested in order to acquire and implement it. Finally technological knowledge is characterized by varying degrees of: fungeability, defined by the scope of possible applications of a given unit of knowledge as measured by the variety of possible uses and applications of a given unit of knowledge that can be replicated with little incremental and variable costs, b) complexity, defined by the variety of complementary unit of knowledge that it is necessary to generate a new element of knowledge by means of recombination, c) cumulability, defined by the vertical and diachronic complementarity between the stock of existing knowledge and the flow of new knowledge, d) stickiness, defined in terms of embeddeness of knowledge in human capital and routines and finally e) tradability, defined by the extent to which knowledge can be traded as a disembodied good in the market place.

6. THE GOVERNANCE OF LOCALIZED KNOWLEDGE

The extension of the governance approach elaborated by Oliver Williamson to the analysis of knowledge generation and circulation seems a fertile area of investigation, especially when it applies to variety rather than to quantity. The characteristics of knowledge and the details of its generation and dissemination process can be appreciated from the view point of the economics of governance especially when the basic ingredients of the resource based theoory of the firm are taken into account and properly integrated into a single interpretative frame (Coase, 1937; Williamson, 1975, 1985, 1996; Penrose, 1959; Foss, 1997)).

Technological knowledge can be generated within economic systems by means of a variety of governance mechanisms: by means of actual knowledge transactions, especially if implemented by appropriate intellectual property rights regimes and specialized intermediaries, internalized within corporations by means of the coordination provided by hierarchical bureaucracy and finally, within networks based upon transactions implemented and integrated by means of qualified interaction systems. Following the resource-based theory of the firm, the corporation is a resource pool designed and managed so as to implement the opportunities for the accumulation of both new technological and organizational knowledge. The rates of technological and organizational learning influence each other in shaping the dynamics of the firm, the evolving composition of the collection of activities that are retained within its borders and ultimately its growth (Chandler, Hagstrom, and Solvell, 1999; Teece, 2000; Antonelli, 2004a)[4].

This range of choices in terms of governance and the borders of the corporation, as a learning agent, can be analyzed and understood with respect to the characteristics of the processes of knowledge generation and usage. Different governance mechanisms and governance choices emerge according to the characteristics of technological knowledge and to the related levels of knowledge transaction costs. The integration of the transaction costs approach with the resource based theory of the firm shows that firms select inclusion and exclusion not only with respect to the static assessment of coordination, transaction and production costs for a given product and a given item of technological knowledge, but also and mainly with respect to the technological opportunities that are associated with the future learning processes (Antonelli, 2001; Antonelli and Quèrè, 2002; Antonelli, 2003 and 2003a).

The distinctive notions of knowledge transactions and interactions costs can be identified and defined in terms of the costs of all the activities such as search, screening, processing, contracting that are necessary to exchange bits of knowledge among independent parties. An important distinction can be made between static knowledge transaction costs and dynamic knowledge transaction costs. Static transaction costs are defined by the costs of using the markets to trade knowledge at each point in time and with no understanding of the stream of long term consequences engendered by the use of the markets. Dynamic transaction and coordination costs are defined in terms of opportunity 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 yields new costs in terms of the missing opportunities to benefit from the cumulative learning processes associated with the production process itself.

Knowledge transaction costs are relevant both on the demand and the supply side. On the demand side the identification of the agents holding specific bits of knowledge and the assessment of their quality is expensive in terms of search and screening costs including the resources to evaluate the scope for incremental advance. On the supply

[4] In the resource based theory, the dynamics of the firm is shaped by the dynamic interdependence among the accumulation of localized knowledge and competence respectively in coordination, transaction and production (Chandler, 1962, 1977, 1990). The characteristics of the process of accumulation of competence, of the generation of technological knowledge and of the introduction of technological and organizational innovations, are key factors to understanding the firm. Parallel to knowledge, competence is a central ingredient. Competence is defined in terms of problem-solving capabilities and makes it possible for the firm not only to know-how, but also to know-where, to know-when, and to know what to produce, to sell, to buy. Competence and knowledge apply to the full set of activities: production activities, transaction activities and coordination activities (Nooteboom, 2000).

side, knowledge transaction costs arise mainly because of the high risks of opportunistic behavior of the customers. Uncontrolled usage of the knowledge can take place with evident damages for the vendor. Derivative knowledge also matters: the vendor of the knowledge bears the risks of non-appropriation of the results of the efforts of implementation of the knowledge, which has been sold (Scotchmer, 1996)[5].

The forms and the characteristics of knowledge have a direct bearing on knowledge transaction costs, that is the costs for using the markets for technological knowledge. Knowledge transaction costs, are affected by the characteristics of knowledge. From the governance viewpoint it is relevant to know whether knowledge is mainly tacit, codified or articulable. The appropriability conditions matter. Finally such characteristics as cumulability, complexity, fungeability and stickiness have a major role in assessing the appropriate governance mechanism for their specific effects on knowledge transaction costs. Let us analyze carefully the impact of the characteristics of knowledge on the fabric of governance mechanisms.

The forms of technological knowledge matter: whether technological knowledge is more tacit, articulable or codified has a direct bearing on the governance of knowledge production. The exchange of tacit scientific and technological knowledge seems easier within research communities based upon repeated interactions and closed reciprocity in communication. Random inclusion can take place with positive effects, provided newcomers are properly selected. The incentives to the creation of informal interaction procedures, often implemented by co-localization within technological districts, are very strong in this case[6].

The exchanges of articulable knowledge take better place within vertical technological clubs and coalitions formed between vendors and customers-users. Vertical technological clubs differ from horizontal ones where all parties are involved in a shared research activity. Vertical technological clubs 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

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[5] The costs of writing proper contracts are relevant and the variety of contingencies, which must be taken into account, is very large. 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 contract 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 both to the amount of inputs and to the actual results (Menard, 2000). A strong intellectual property right regime and favorable conditions for its actual implementation in the markets for technological knowledge clearly favor 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).

[6] Following a long standing tradition in industrial organization, the characteristics of product markets, in terms of the condition of competitivity, do matter as well in assessing the choices of the firm whether to sell or to use the knowledge generated. High barriers to entry and high levels of product differentiation favor the use of the upstream markets for licenses, as opposed to the downstream markets for products, simply because they reduce the risks of opportunistic behavior and the effects of uncontrolled leakage of the proprietary knowledge.

the active cooperation of the two parties. The reputation of the fellows in the club plays an important role in building vertical technological clubs. The major goal here is the reduction of transaction costs stemming from the prospects for future knowledge: the vendors can retain the rights to participate into the appropriation of the derivative knowledge stemming from its implementation and incremental accumulation conducted by the customers. When technological knowledge is more articulable, the contractual interaction among partners within technological clubs can be better implemented. Here knowledge transaction costs include high levels of monitoring and assessment of the actual conduct of the partners in the club.

Appropriability conditions play a key role in assessing the appropriate governance mechanism. When technological knowledge can be easily appropriated by the innovator, either because of its complexity and hence natural levels of high appropriability, or because the regime of intellectual property rights is effective and easily enforced, firms may prefer to sell directly the technological knowledge as a good per se in the markets for knowledge.

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 market place to valorize their intangible outputs. The embodiment of technological knowledge into new products and their eventual sale in the market place becomes necessary. Here the relevant governance choice for the firm is clearly between making and selling rather than between making and buying[7]. The firm will choose to make and hence to include within the borders of the portfolio of activities the modules, which use the knowledge as an intermediary input, when, the tradability and appropriability conditions are low (Teece, 1985, 2000; Antonelli, 2001 and 2004a).

Finally the specific characteristics of technological knowledge in terms of cumulability, fungeability, complexity and stickiness also play a major role in assessing the relevant mechanism of governance. When technological knowledge is characterized by high levels of cumulability, so that the generation of each new unit of knowledge relies upon the localized accumulation of technological knowledge, dynamic coordination and transaction costs emerge. The larger is the cumulability of the technological knowledge, specific to the products and the production process of a firm, and the larger are the incentives towards the internalization of the knowledge generation process. The sale of technological knowledge in fact has high costs in terms of missed opportunities for further advances. The same argument applies when

[7] Downstream vertical integration can now be seen as a governance mechanism specifically implemented in order to increase the appropriability of new knowledge. Scientific entrepreneurs are simply inventors, which cannot rely on the markets for disembodied knowledge and prefer to exploit the rents associated with their invention by means of the production and sale of the products that embody, either as a product or a process innovation, the new item of knowledge. In the same vein corporate diversification in new business lines, both vertically and horizontally related to the previous ones, can be seen as the result of the choice between selling the new bit of knowledge as a product per se or rather using it as an intermediary product to make new products and sell them (Antonelli, 2004a).

learning plays a key role in the generation of new knowledge: the full control of the production process is likely to yield important benefits in terms of increased rates of accumulation of new technological knowledge (Antonelli, 2003).

Knowledge fungeability is defined by the variety of production activities to which the same unit of knowledge can be successfully applied. With given knowledge transaction costs firms, able to introduce technological innovations with high levels of fungeability, are likely to be larger and more diversified and integrated. 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[8]. Knowledge fungeability 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. Finally when fungeability is high as well as transaction costs in the markets for technology, the firms has a strong incentive to use internally the technological knowledge by means of downstream diversification in a wide range of products. When complexity and knowledge transaction costs are high, the firm has an incentive to integrate vertically in upstream activities.

With high levels of knowledge fungeability firms may select the product markets into which they prefer to operate directly and hence use the knowledge rather than buy. With high and increasing cooperation costs however the firm will select a number of product markets into which to license the fungible knowledge. In turn here, the kind of markets matter. With high levels of product differentiation and barriers to entry and to mobility firms are more likely to use the markets for license as an effective way to valorize the knowledge assets with high levels of fungeability (Arora, Fosfuri, Gambardella, 2001).

This is true also when knowledge complexity applies and the operation of downstream modules has positive effects on the generation of new knowledge in the module upstream. Although the two modules are technically separated, high levels of indivisibility are found with respect to the generation of new technological knowledge and hence with respect to the introduction of new technologies. Knowledge transaction costs are especially relevant when technological knowledge is characterized by high levels of complexity: each new bit of knowledge is the result of the recombination of many different elements. Knowledge transaction costs in fact matter also on the demand side. Important resources can become necessary in order to search, identify and purchase the bits of external knowledge that are necessary for the generation of new knowledge. Knowledge transaction costs affect here the choice

[8] The welfare losses stemming from high knowledge transaction costs and hence high levels of vertical integration in the case of high levels of knowledge fungeability are high because the application of each bit of fungible knowledge to other activities is limited by the embodiment in a firm active in a narrow range of products.

between making all the diverse bits of knowledge or purchasing them in the markets for technological knowledge.

Joint-ventures among firms that are competent in complementary bits of knowledge appear as appropriate governance mechanisms when the parties are actively involved in the research process and are not considering the exit form the related product markets. Joint-ventures are all the more effective when the firms that join forces operate in different product markets. Within the framework of the joint-venture the interactions among parties take the form of barters implemented by common property rights. Common property rights in fact provide the reliable context into which reciprocity can take place (Caloghirou, Ioannides, Vonortas, 2003). Intellectual property rights here can perform the essential informational role of signaling, spreading the information that the knowledge corresponding to a patent exists and can be acquired (Geroski, 1995).

The understanding of the differences between knowledge complementarity and knowledge fungeability makes it possible to better specify the working of geographic agglomerations or technological districts. Two well distinct mechanisms can now be identified. When fungeability 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. When complementarity among diverse and dispersed bits of knowledge matters instead the spatial agglomeration of small firms that command complementary bits of knowledge may lead to the collective generation of new technologies. Here there is no beam and the flow of technological knowledge is more horizontal and it is based upon reciprocal access. The two models differ sharply as they are based upon two different characteristics of technological knowledge and grasp two completely different modes of interaction among firms (Antonelli, 2003b).

Knowledge stickiness is found when it is difficult to separate the knowledge, often tacit, from the human capital and the organizational routines of the unit where learning activities have been taking place and the knowledge has been generated. In this case an issue of indivisibility emerges. Financial markets and more generally the markets for property rights provide an opportunity for a firm that cannot exploit directly the new knowledge because of steep organization costs curves. The incorporation of the unit into a new corporation and its sale in the financial market becomes a viable solution. Here technological knowledge is embodied in the corporate structure (Gompers and Lerner, 1999).

Codified technological knowledge better meets the conditions for tradability especially if implemented by an appropriate intellectual property right regime and when the assistance of innovators is necessary and useful to reduce adoption and adaptation costs of perspective users The markets for technological knowledge with actual arms' length transactions are often found in this context. The design of actual content contracts, such as in the case of licenses, is possible and enforcement more reliable. Codified knowledge is often found in fields where technological opportunities are slowing down and the levels of knowledge cumulability are lower (Cowan, David and Foray, 2000).

7. POLICY IMPLICATIONS.

The great ingenuity of economics resides in the asserted coherence between profit maximization and social welfare. When markets are competitive, returns are constant and all products are economic goods, profit-seeking and profit maximizing agents, interacting in the market place exclusively by means of full fledged transactions, are able to identify the best combination and hence to generate the maximum amount of social welfare.

The production and circulation of knowledge does not match these conditions. The identification of each bit of complementary and useful knowledge as well as of the agents holding specific bits of knowledge and the assessment of their complementarity, both with respect to their present and future needs and opportunities, the correct definition of the flows of entry into new knowledge modules and the exit from declining ones, the proper combination of the incentives to invest in the generation of new knowledge, and the incentives to circulate and use external knowledge remain essential functions that governance mechanisms in place perform poorly.

The selection of the firms and agents with whom knowledge transactions and interactions can take place, the creation of technological clubs and research joint ventures as institutional organizations designed to carry on collective research within selective coalitions, the identification of the areas where to invest new resources can take place, successfully in a context where profit-maximization and maximum social welfare are jointly achieved, only if appropriate information is available on the technological competence of perspective partners and the future paths of technological change and technological knowledge are perfectly known to everybody.

When increasing returns associated with knowledge cumulability, complexity and fungeability are at play, especially within the modules that characterize technological systems, moreover, governance mechanisms at work are a necessary but not sufficient condition to achieve dynamic efficiency. With increasing returns the case for dynamic market failure emerges. Dynamic coordination moreover, even with constant returns, can be achieved only within the context of technological regimes characterized by low levels of discontinuity and surprise. The markets for future ideas appear to complicated even to be considered.

A divide takes place between the results of the maximization of profits and the conditions for the maximum social welfare. Governance mechanisms in place appear to provide a set of incentives that may or may not lead the system towards stable and fair solutions. Tradability is a necessary but not sufficient condition for dynamic efficiency to be achieved, bureaucratic coordination and networking do not assure that profit maximization coincide with social welfare. The aggregate outcomes of the governance mechanisms at the firm level are far from being attracted by a single equilibrium point.

Because of the complementarity, between internal and external knowledge, and among modules of knowledge related by weak indivisibility, especially if it is specified in terms of a multiplicative relationship, the aggregate outcome of both market transactions and interactions is unstable and sensitive to interactions and subjective decision-making. When both demand and supply schedules are influenced by externalities, multiple equilibria exist (Marmolo, 1999).

The amount of knowledge each firm can generate depends upon the amount of external knowledge available, that is upon the amount of knowledge that other firms, especially when involved in complementary research projects, have generated and cannot appropriate or are willing to exchange. An iterative dynamic process is at work with no stable attractors: both negative and positive self-reinforcing mechanisms can take place.

Inclusion needs to be coordinated and managed. Free riding can take place, although reciprocity and mutuality in interactions based upon knowledge barters, implemented by repeated and long-lasting exchanges, can help reducing the extent and the effect. Exclusion is dangerous for the risks of missing the relevant complementary input, which characterizes the generation of new technologies. Multiple equilibria and micro-macro feed-backs affect the working of bureaucratic coordination, networking interactions and transactions in the markets for technological knowledge and their outcome. The dynamic coordination of agents plays in this context a central role.

The need for economic policy seems stronger than ever. The governance of technological knowledge needs to be complemented by a public policy action able to implement institutional interventions. The governance of knowledge commons needs to be implemented at the policy level. In this approach the implementation of the institutional set up by means of actions that reduce uncertainty and create information, so as to reduce the effects of bounded rationality and information loads, seems to be a viable strategy to reduce the divide between profit maximization and social welfare.

As it is well known only future prices make it possible to solve the problems of dynamic coordination. When a vector of future prices is available for all products agents can identify the correct amount of resources to invest in each activity and the effects of the trajectories of demand and future entry and exit can be assessed. When future markets and future prices are not available, the market is unable to perform properly its basic function of dynamic coordination among the expectations and conducts of a variety of agents and hence fails to provide the indispensable consistency in the long term allocation of the resources. (Richardson, 1960).

It seems very difficult to match these requirements when technological change is considered and even more when technological knowledge is taken into account. Yet the economic organization of the decentralized production of knowledge, as an economic good, can approximate if not match the basic requirements of standard economic processes when the role of future prices and communication in the market place is proxied.

Public policy can reduce the major limits of the governance system for a more effective production and circulation of knowledge with interventions directed to increase the amount of information each agent has access to. The creation of transparency can be obtained by means of: a) credible announcements of public authorities about long terms plans; b) the creation and implementation of interface agencies; c) a reduction of exclusivity levels in the intellectual property right regimes. Let us analyze them in turn.

7.1. CREDIBLE ANNOUNCEMENTS

Credible announcements about long term selective research strategies made by the State can help the creation of correct expectations about the direction of future research and act as guiding system. The creation of social commitment about the long term strategies is the key issue here. Hence the process needs to be carefully articulated and designed so as to build upon a reliable consensus, able to generate converging expectations.

The selection of a limited number of high levels scientific goals marks the first step of the process. It implies the societal participation of the most qualified members of the scientific community. The process is designed as a way to generate confidence and reliability about the plans. The goals must be socially consistent and their relevance must be shared by a large community of practitioners and users.

The second step consists in the credible announcements of the intention of public agencies to invest, for a long and consistent period of time, sufficient resources in that direction can orient the full system. Universities can identify the fields where new talents can be directed. Public research centers can tilt their present set of competencies and expertise towards areas of closer complementarity and interdependence with the core regions of the knowledge domain. The business community can elaborate its own expectations about the future trends and hence is better able to allocate resources in the production of knowledge. Firms can elaborate consistent investments in selected directions and organize their learning strategies. Finally the flows of transactions in the markets and interactions within networks can be implemented in a context characterized by a shared view about the future direction of the knowledge generation process.

The benefits of the knowledge fall out from military expenses have been often identified and stressed. Military expenses, as a matter of fact supply the combined advantage of identifying clearly a limited number of goals, delivering credible announcements about long term commitments in well identified areas of knowledge together with huge procurement programs of well standardized products that need to be perfectly compatible and consistent (Edquist, Hommen, and Tsipouri,2000).

Procurement acts as a clear incentive and attract new competencies and skills. Credible announcements about long term commitments make the entry sustainable in the long term and increase the incentives for the allocation of new resources in the long term (Michie and Smith, 1996).

In this context long term standardization can further reduce information load and the scope for opportunistic behavior. Standards help defining the interfaces between modules of technological knowledge ad facilitate the relations among agents possessing bits of complementary knowledge. Standardization procedures however are complex. Rivalry among agents affect the outcome of standardization processes. De-facto standards are often found when ex-ante coordination among conflicting agents fails to generate fair solutions able to achieve consensus. In turn de-facto standards register the outcome of rivalry rather than directing the competitive process with social welfare objectives. The policy action can favor the ex-ante definition of compatibility and interoperability standards among and within knowledge modules so that the relations among the agents participating into the generation of knowledge, as a collective undertaking, is enhanced and favored.

The creation of long term standardization committees provided with some enforcement capabilities can provide additional information for the parties involved as well as for all those willing to join the process. Such committees may also favor the creation of interfaces and interactions within the business community and between the business community and the academic system.

The combination of societal selection of goals, public procurement, de-jure ex-ante standardization processes and credible announcements about long term projects acts as a clear signal about the increase of future prices of well defined skills and fields of knowledge. Supply should be attracted and be ready to increase: the entry of profit-seeking agents can increase the production of knowledge and favor the division of labor and their actual coordination in the market place.

The credible announcement of long lasting great initiatives and the implementation of large research projects based upon the framed and yet selective participation of a variety of agents in scientific and technological undertakings with direct economic and productive fall-outs should have the same positive effects, often experienced for military expenses and related spatial ventures, also when applied in peaceful activities.

7.2. KNOWLEDGE COMMUNICATION: INTERFACE AGENCIES

When prices are the single vectors of all relevant information, communication among agents in the market place is easy. Each agent can easily identify the demand for its own perspective products and each user can easily identify the agents able to supply the necessary products. Instantaneous market clearing makes sure that both nominal and hedonic prices are fair. When technological knowledge matters and scientific and technological information is not conveyed by the price system, more sophisticated communication systems are required. The identification of the demand and the supply are difficult.

Spontaneous knowledge communication is far below the required levels. As a matter of fact knowledge communication takes place at appropriate levels accidentally and occasionally in a few regional and institutional settings. Knowledge communication between the academic and the business community seems especially poor. Publications work poorly as effective vectors of the information about new scientific discoveries seen as possible areas of development and implementation for technological knowledge. The relationship between top-down process of deductive 'scientific' work and bottom-up generation of technological knowledge is often characterized as an 'uneasy alliance'. The direct association and participation of scientists and technologists into common ventures seems able to reduce the gaps (Feldman and Link, 2000).

The creation of public interface agencies with the mission to increase knowledge communication flows and hence to reduce the gaps between demand and supply, can increase the efficiency in the working of the knowledge governance systems. Public interface agencies can help identifying the supply buried in the stocks of knowledge, often in the public domain, in Universities and other public research centers, and stir the demand for their application. The role of public interface agencies is to push the academic community towards the market place and selected segments of the business community towards the academic one. Small firms, less than larger corporations, are not even able to search in the market place. Minimum threshold in the performance or research activities is often above the size of small companies (Swan, Newel and Robertson, 1999).

7.3. INTELLECTUAL PROPERTY RIGHTS: SIGNALING AND LICENSING

The debates about the knowledge trade-off had been concentrated upon the positive and negative effects of the creation of intellectual property rights. Little attention had been paid to the informational role of intellectual property rights. Intellectual property rights have an important role from an informational viewpoint and as such exert relevant consequences.

First, patents play a major role as signaling devices, which help the identification of the available bits of complementary knowledge and their owners so as to reduce search costs. Secrecy, the alternative to intellectual property right, to secure exclusive ownership can have dramatic effects generally in terms of networking costs and specifically in the form of technological communication costs, and hence upon the amount of knowledge complementarities which can be effectively activated (Arundel, 2001, Oxley, 1999; Teece, 2000).

The appreciation of the informational role of patents has significant implications for their characteristics. With respect to the automatic granting of intellectual property rights, as in the case of copyrights, the selective and discretionary assignment of patents seems even more appropriate. The scrutiny of an Authority is in fact most useful as a screening device which makes it possible to sort out the bits of new knowledge that are actually relevant and useful. For this very same reason patents assigned following the first-to-invent procedure seems more useful than patents assigned with the first-to-file approach: the latter procedure better qualifies the content of the patent in terms of novelty and ingenuity. Second, it seems also clear that a narrow definition of the scope of a patent is more useful, from an informational viewpoint, than a wide one. The identification and location of the relevant bits in the great map of knowledge becomes easier for each perspective user.

Second, intellectual property rights can provide not only a remedy to the public good nature of technological knowledge. They are a remedy to tight vertical integration between the generation of new technological knowledge and its application to the production of new goods or to new production processes, rather than to its undersupply.

This analysis contrasts the traditional argument according to which the market supply of technological knowledge is deemed to undersupply because of its public good nature. The public good nature of technological knowledge as a matter of fact does not necessarily leads to undersupply but rather pushes the knowledge-creating firm to use it as an intermediary input for the sequential production of economic goods. The markets for the products that are manufactured and delivered by means of the technological knowledge they embody can generate the incentives to generation of appropriate quantities of knowledge.

Effective property right systems can rather favor the creation of markets for disembodied technological knowledge where the firms can specialize in the production of knowledge as a good per se. With a weak intellectual property right regime in fact the holders of each bit of knowledge have much a stronger incentive to integrate vertically into the production of new goods and processes based upon the novel ideas and to rely upon industrial secrets as a way to reduce the informational leakage with the radical reduction of the circulation of the relevant bits of disembodied knowledge. The embodiment effect can be especially negative when the scope of application is wide and reverse engineering is complex, at least for unrelated perspective users. Intellectual property rights reduce the incentive to internalize the valorization of technological knowledge by means of downward vertical integration, they can favor the creation of markets for technological knowledge and hence favor the distribution of fungible technological knowledge to a wider range of economic activities, but they do not necessarily increase the incentive to generate new knowledge, because of the sheer appropriability

Thirdly and consequently, the assignment of intellectual property rights seems by now a necessary condition not only to increase appropriability, but also as an institutional device which can improve the viability of the markets for knowledge and facilitate the interactions among holders of bits of complementary knowledge. Patents in fact can help transactions in the markets for knowledge because they make it easier for demand and supply to meet (Arora, Gambardella and Fosfuri, 2001).

Following the resource-based theory of the firm, technological knowledge can be considered the primary output of the firm: the firm exists because it is a depository of knowledge. The choice whether to sell it or to use and make with it is especially relevant. This approach can contribute the debate on the economic organization for the supply of knowledge. The new appreciation of the role of intellectual property rights is now found in the assessment of their positive effects in terms of higher levels of specialization and division of labor. From this viewpoint the so called knowledge trade-off, that is the balanced assessment of both the positive effects of the monopolistic control of patents in terms of increased incentive to the supply of knowledge and the negative effects in terms of the reduced distribution of knowledge, needs to be reconsidered.

The systematic use of patents because helps the identification of bits of relevant knowledge for perspective users, is essential to reducing the waste of duplication and to make easier the working of cumulability in the production of new knowledge. Patents can make knowledge interactions easier, provided the exclusivity of ownership is properly tuned. The basic problems of the knowledge trade-off emerge again and yet can be tackled in a different way.

The notion of essential facility has been elaborated upon these bases. When a piece of property acquires the characteristics of an essential facility, the rights to access and interconnection cannot be exclusive. A separation between the rights of ownership and the rights of use is necessary in order for actual and workable competition to be implemented and eventually made possible (Baumol and Sydak, 1994)[9].

According to the results of much economics of knowledge, knowledge shares all the relevant characteristics of an essential facility. Knowledge is characterized by intrinsic indivisibility and yet it is dispersed and fragmented in a variety of uses and possessed by a variety of owners. Each bit of knowledge is complementary to each other along chains of weak and strong indivisibilities, which act both synchronically and diachronically. The exclusive access to each bit of knowledge can prevent others from cumulative undertakings.

The separation between ownership and usage conditions experienced in the case of the telecommunications industry can apply with success to intellectual property rights. The monopolistic rights delivered to inventors however can reduce the circulation of knowledge protected by intellectual property rights. Such effects are especially negative when knowledge complementarities apply and bits of knowledge can have important effects for the production of other knowledge in other fields of applications, often remote from those of original invention and introduction. The separation between the ownership of intellectual property and the right of exclusive

[9] As it is well known, competition in the telecommunication industry has been made possible by mandated interconnection. Mandated interconnection is a major factor of change and evolution in the definition of property rights. The ownership rights on the one hand and the rights of exclusive use on the other, traditionally associated in one single rights, have been separated and rights of use of the network have been separated from the ownership rights. Firms do and can own telecommunication networks and can claim their property on all the segments of the network, but cannot claim any longer the right to the exclusive usage. Other firms have the right to access the network and make a selective use of it. Dedicated authorities have been established since the late 1980s in most advanced countries in order to implement the right to interconnection, to regulate it and to fix the prices of interconnection (Fransman, 2002). Communication Authorities have been established to monitor the effective separation between the right of ownership and the rights of usage of telecommunication networks. Their activity here is most necessary because of the ever changing conditions of the technology and hence the ever changing conditions of the separation between ownership and usage. Second and most important, Communications Authorities have been established in order to fix ex-ante the levels of interconnection tariffs. Interconnection tariffs must reflect properly the costs of the network and must make both appropriate returns on the investments for the owners as well as viable conditions of entry to new competitors. Newcomers must be put in conditions of actual competitivity in downstream markets with respect to incumbents and other competitors in the telecommunications industry (Madden, 2003). The evolution of property rights in the telecommunications industries has been the result of the understanding of the role of complementarities and the dual effects of economies of scope and externalities on the actual costs of both incumbents and new competitors in the industry. Mandated interconnection is indeed a significant departure from a full fledged and traditional definition of property rights. A generalization can be drawn. The separation between ownership and rights of exclusive use is necessary within economic and physical systems where and when complementarities matter in order to restore and enforce the conditions for competitive markets. The evolution of the property rights regime in the telecommunications industry is directly pertinent to the case of knowledge complementarities.

use, already experienced with success in the telecommunications industry with the notion of mandated interconnection, can apply in this central and strategic area as well.

Such a reduction of the exclusivity of intellectual property rights can be realized by means of compulsory licensing and the liability rule. Compulsory licensing is more and more associated to the authorization to mergers and acquisitions by Antitrust Authorities. Mergers are authorized provided that the firms agree to grant the licenses of their patents to all perspective users. The ex-ante definition of the appropriate levels of the royalties can become a problem however.

The transition towards the liability rule in intellectual property rights can be considered a useful device to implement mandated interconnection in intellectual property rights. Liability rule consists in the right of the owner of intellectual property to claim for appropriate payments for the usage of her rights (Kingston, 2001). In this context, the right of exclusive use is no longer associated to the rights of ownership of any intellectual property. Like in telecommunications networks, ownership is recognized as well as the right of other parties to take advantage of it for their own transmission needs.

In the case of intellectual property rights the ex-ante definition of the equivalent of interconnection tariffs seems difficult on many counts. First of all research activities are characterized by high levels of risk and intrinsic uncertainty, both in terms of the chances of generating an output and with respect to the possible field of application of any such novelty, so that the allocation to each novelty of the effective costs is most difficult. Ex-ante definition of the costs of each new piece of knowledge is problematic. Much less difficult is the ex-post identification of the economic value stemming from the application of a given specific piece of new knowledge.

The reduction of the rights of exclusive use of intellectual property, the introduction of the mandated right to access intellectual property for third parties combined with the eventual enforcement of the liability rule such that the judiciary system can help securing ex-post the payment of fair levels of royalties to the effective owners can become an effective institutional innovation. Intellectual property and hence patents can play a strong role in increasing the quality of the knowledge interactions. Full visibility of intellectual ownership can help locating bits of complementary knowledge and hence reducing the costs of technological communication and networking activities at large. Especially when the parties can agree eventually upon the payments of appropriate royalties. By means of non-exclusive property rights, implemented by liability rules, knowledge interactions can come closer to market transactions and hence increase the scope for the valorization of knowledge complementarities.

8. CONCLUSION

A long process has been taking place, since the old days of knowledge as a public good. A better understanding of the dynamics of knowledge accumulation has been elaborated. Technological knowledge is a highly imperfect good. First of all it is not only an output, but also an input, an essential intermediary production factor that is relevant both in the generation of new technological knowledge and in the generation of other goods. The dynamic efficiency of each firm and of the system at large depends upon the factors affecting the distribution of knowledge and the conditions of access to existing knowledge.

The localized approach calls the attention on the economic characteristics of the knowledge in terms of levels of modularity, fungeability, cumulability, complexity, stickiness and appropriability and its forms whether tacit, articulated or codified. The analysis of the conditions for tradability is the ultimate result of all these advances.

A systemic approach to understanding the mechanisms of the institutional set up that are most conducive to foster the rate of accumulation of technological knowledge and its distribution and hence of introduction of technological innovations proves to be the appropriate analytical framework. The systemic analysis of the interdependent and complementary conditions of access and exclusion to the flows of technological interactions, transactions, coordination and communication that are specifically designed to organize the generation and the distribution of technological knowledge emerges a specific area of investigation and enquiry. Each mechanism and specifically intellectual property rights need to be assessed and considered into this broader framework.

The application of the basic tools of the economics of information, and specifically transaction cost economics, to the economics of knowledge seems useful. The integration of the transaction costs economics with the resource-based theory of the firm into a broader economics of knowledge governance provides an interpretative frame able to appreciate the variety of constraints and incentives of the different governance mechanisms which shape the generation of knowledge immediately relevant for economic action in a market economy. The economics of governance makes it possible to better understand the role of localized knowledge in the activities of coordination, transaction and production. In so doing it marks a progress with respect to transaction costs economics, where both technological and organizational knowledge are exogenous and given. The governance economics approach makes it possible to better grasp the effects of the interactions between organizational and technological knowledge and the constraints raised by organizational factors such as coordination and transaction costs in shaping the process of accumulation and generation of new knowledge (Stiglitz, 2000).

Governance however is a not a sufficient condition for dynamic efficiency to be assured in the market place. When increasing returns matter, such as in the case of knowledge cumulability, fungeability and complexity 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, governance mechanisms in place are not able to provide all the necessary coordination between the variety of agents that participate into 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 yet 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 the informational efficiency of knowledge governance can prove useful. Credible announcements about long terms research projects combined with substantial and well focused public procurement in well identified areas of knowledge can provide a proxy for the identification of the shape of the demand for knowledge in the future. Long term standardization committees provided with some enforcement capabilities by the public authority can contribute the better definition of the interfaces among the possessor of each single bit of knowledge so as to favor the generation of knowledge as a collective good.

The informational role of patents as carriers of relevant information about the actual levels of technological competence of agents and the availability of new bit of knowledge in now more and more appreciated. Technological signaling becomes relevant in this context as a device to reduce knowledge transaction and networking costs. The evolution of the intellectual property rights regime towards the separation between ownership and the exclusive right of access to knowledge can provide important opportunities for the systematic valorization of both the markets for technology and the interactions among holders of complementary bits of knowledge. The mandated right of interconnection to bits of knowledge owned by third parties can take place with the implementation of the liability rule and the ex-post payment of royalties without the preliminary consensus of the patents holders.

Patents are essential tools to signal the levels and the characteristics of the knowledge embodied in each organization. A new chapter in the economics of intellectual property rights emerges here. Patents are no longer regarded only as tools to increase appropriability, but also as devices to increase transparency in the knowledge markets and hence facilitate markets transactions. The new assessment of the informational role of intellectual property rights in terms of increased incentives to the production and trade of knowledge and hence a remedy to undersupply needs however to be reconsidered, because of the perverse effects of exclusion on the efficiency of the generation of new knowledge, especially when radical innovations are under question. The notion of knowledge as an essential facility becomes relevant. The extension and generalization of the notion of essential facility, elaborated in the telecommunications industry in the last decades of the XX century, is fruitful in the economics of knowledge and hence in the governance of knowledge commons.

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