Working Paper 99-17
Business Economics Series 4
February 1999

Departamento de Economía de la Empresa
Universidad Carlos III de Madrid
Calle Madrid, 126
28903 Getafe (Spain)
Fax (341) 6249608

MARKETS FOR TECHNOLOGY

(WHY DO WE SEE THEM, WHY DON'T WE SEE MORE OF THEM, AND WHY WE SHOULD CARE)

Ashish Arora*, Andrea Fosfuri ** and Alfonso Gambardella ***

Abstract

This essay explores the nature, the functioning, and the economic and policy implications of markets for technology. Today, the outsourcing of research and development activities is more common than in the past, and specialized technology suppliers have emerged in many industries. In a sense, the Schumpeterian vision of integrating R&D with manufacturing and distribution is being confronted by the older Smithian vision of division of labor.

The existence and efficacy of markets for technology can profoundly influence the creation and diffusion of new knowledge, and hence, economic growth of countries and the competitive position of companies. The economic and managerial literatures have touched upon some aspects of the nature of these markets. However, a thorough understanding of how markets for technology work is still lacking. In this essay we address two main questions. First, what are the factors that enable a market for technology to exist and function effectively?. Specifically we look at the role of industry structure, the nature of knowledge, and intellectual property rights and related institutions. Second, we ask what the implications of such markets are for the boundaries of the firm, the specialization and division of labor in the economy, industry structure, and economic growth. We build on this discussion to develop the implications of our work for public policy and corporate strategy.

Keywords: Markets for technology, division of innovative labor, licensing, technology policy, patents, R&D.

*Carnegie Mellon University, Pittsburgh, USA. E-mail:ashish@andrew.cmu.edu

** Universidad Carlos III de Madrid. Dept. Economía de la Empresa, C/ Madrid, 126, 28903 Getafe (Madrid). E-mail:fosfuri@emp.uc3m.es.

***University of Urbino. Urbino, Italy. E-mail:agambardella@info-net.it

1. Introduction

This essay explores the nature, the functioning, and the economic and policy implications of markets for the exchange of intermediate technological inputs. By the latter we mean inputs like pharmaceutical or chemical compounds discovered in laboratories, new product designs or prototypes, algorithms and basic software programs, process designs and technologies, engineering and other intangible knowledge embodied in blueprints and designs, or sold through consultancy services.

Markets for technology have become increasingly important. Since World War II, large firms have been responsible for the bulk of privately funded R&D, typically conducted in-house. However, over the last ten-fifteen years a variety of "outsourcing" arrangements ranging from R&D joint ventures and partnerships, to licensing contracts and contracted R&D appear to have grown substantially. Alongside, specialized technology suppliers have emerged in many industries.[1] Given the importance of innovation for economic growth and competitive success, it is important to understand when markets for technology arise and how they function.

Some of these topics have been studied in some detail. For instance, there is an extensive literature on technology licensing, international technology transfer, and on the economic and managerial consequences of outsourcing, particularly technology outsourcing. However, what is still lacking is a systematic understanding of how markets for technology work, what limits or gives rise to them, and what their economic and policy implications are. In other words, what we need is a comprehensive framework for integrating existing studies that shed light on the existence, working and the consequences of markets for technology. This essay is a first step in filling this gap.

We begin by reviewing the available evidence about markets for technology in Section 2. We offer several examples of industries and technologies to illustrate the main points. In the next section we discuss the main factors that limit their creation and the factors that can relax these constraints. While Section 4 addresses the relationship between market size, industry structure and the functioning of markets for technology, Section 5 explores the role of competition in spurring the growth of these markets. Section 6 focuses on an important challenge to the proper functioning of markets for technology: the fragmentation of intellectual property rights and the potential tragedy of the "anti-commons". Section 7 discusses the effects of markets for technology on the growth of the downstream industries and on the geographical distribution of technological activities. Section 8 looks at the implications for corporate strategy and economic and industrial policy. Section 9 concludes.

2. Markets for technology

2.1 The size and scope of markets for technology

Can and do markets for technology that is not embodied in physical artifacts exist? Lamoreaux and Sokoloff (1997 and 1998) have documented the presence of an active market for technology in the US during the late nineteenth and twentieth centuries. Based on a study of the glass industry, they also argue that a well-articulated organizational and geographical differentiation between inventive activity and commercialization of invention existed at that time. Mowery (1983) shows that before World War II, US corporations relied upon

[1] Markets for technology and outsourcing of research are not new. Mowery (1983), Mowery and Rosenberg (1989) discuss trends in the outsourcing of R&D in the early part of the 20th century in the US. Lameroux and Sokoloff (1998) document the existence of a market for patent licenses in the US in the late 19th century.

contracted R&D, although over time this dependence decreased.[2] Other papers attest to the market for technology for chemical processes (Freeman, 1968; Arora and Gambardella, 1998; Arora and Fosfuri, 1998a; Merges, 1998), and biotechnology (e.g., Arora and Gambardella, 1990; Powell and Brantley, 1992; and Zucker et al., 1998).

In recent years we have seen a number of examples of "strategic alliances", ranging from R&D joint ventures and partnerships, spin-offs, corporate venture capital, licensing deals, and a variety of "outsourcing" deals, signaling the increasing importance of transactions for intangible technology. Table 1 shows the total number and value of such transactions, by industrial sector, between 1985 and 1997. The data are from a commercial database provided by the Securities Data Corporation, the leading commercial provider of such data.[3] The value of a transaction is calculated here as the sum of licensing and royalty payments, and equity investments and R&D funding provided in return for licensing rights.

As table 1 shows, there have been over 7,800 transactions in technology with a total value of over $210 billion, implying an average of nearly 600 transactions worth $15 billion per year. To put these numbers in perspective, note that the total R&D spending in the US, Japan, Germany, UK, France, Italy and Canada was about $340 billion, and non-defense R&D spending was about $300 billion in 1995. Thus, the total technology transactions are of the order of 5% of total non-defense R&D spending in the developed countries.[4] Although markets for technology are still in their infancy in many cases, the value of the transactions is already substantial. Table 1 also shows that the transactions are concentrated in few sectors, notably chemicals, software, electrical and non-electrical machinery, and engineering and professional services. These sectors together account for the bulk of transactions (both source and recipient of technology), and as expected, are also a net source of technology for other sectors. Figure 1 shows that the number of these transactions has been steadily increasing over time (with the exception of the last two years in our sample, possibly reflecting incomplete reporting of transactions for these years).

These figures do not included mergers and acquisitions. To be sure, outright acquisition can also facilitate exchange of technology. Therefore, insofar as acquisitions are driven by the need to acquire external technology, these should be included in the market for technology. However, acquisitions bring not only technology, but also the capability and competence to develop new technologies. The set of issues that surround the acquisition of technological capability is rather different from that pertaining to the acquisition of technology. Therefore, in this essay, we shall exclude acquisitions from our purview.

We shall also largely ignore another important channel through which technological knowledge moves across firm boundaries both at the national and international level, namely the movement of people. The omission is not indicative of the importance. The diffusion of knowledge through the movement of people is one of the many ways in which knowledge is said to spillover across firms. The question of spillovers has attracted a great deal of attention from economists and there is a large theoretical literature analyzing the implications for the

---

[2] Mowery (1983) also notes that outsourced R&D was limited in scope and firms with strong in-house capabilities were more likely to outsource R&D as well.

[3] The SDC data are constructed from SEC filings (10-Qs), financial journals, news wire services, proxies and quarterly reports. We read through each transaction to verify that technology transfer was involved. From the description of the agreement, we also coded the granter or recipient of the technology, or whether there was a two-way flow of technology, such as a technology cross-licensing agreement.

[4] There are a number of possible biases going in both directions. For instance, the figures for equity purchase may include payments for non-technology assets. On the other hand, our database probably does not include a large number of smaller value transactions, and we are undercounting transactions from 1985 and 1986, as well as 1996 and 1997.

incentives to do R&D (e.g., Cohen and Levinthal, 1989), and another large empirical literature that attempts to measure the extent and impact of such spillovers on economic measures of performance such as productivity (e.g., Griliches, 1979; Jaffe, 1986). However, a part of what are called spillovers may in fact be market-mediated transfers of knowledge.[5] Indeed, Zucker et al. (1998) argue that knowledge spillovers across nearby universities and Californian biotechnology firms in California are in fact the outcome of identifiable market exchanges of technologies. We speculate that the neglect of the possibility of market mediated knowledge flows may have resulted in over-estimates of the importance of knowledge spillovers. However, ambitious as this paper is, to include inter-firm movement of engineers and researchers would be unworkable.[6]

2.2 The key benefits of a market for technology and division of innovative labor

The easiest way to describe a "market for technology" is by contrasting it with the dominant mode of organizing innovation in the 20th century -- vertical integration between invention and commercialization.[7] Although this arrangement offers the advantage of reducing transaction costs (both contractual and cognitive), it brings with it two major disadvantages that arise from the restricted use of technology.

The first disadvantage is that technology is under-utilized. Technology, once created, can be transferred elsewhere at only a fraction of the cost of developing it in the first place. Since there are limits to how large a firm can grow, a firm that develops a technology can potentially gain by selling it to other firms, including firms in other industries and countries. These benefits are even greater if the innovating firm is incapable or unwilling to exploit the technology itself. But when selling technology is difficult – i.e., when the market for technology is underdeveloped and inefficient -- these gains from trade cannot be realized. Until recently, most large firms have typically ignored such possible gains.[8] One explanation for this neglect is the infamous "Not-Invented-Here" syndrome, which is thought to inflict many large firms and which also leads them to reject already developed and possibly superior technologies in favor of in-house development (see for instance, Katz and Allen, 1982).[9]

The second disadvantage is that the rate of technological innovation itself may be lower when markets for technology are absent. With a tight organizational integration between invention and commercialization, firms that lack commercialization capabilities have

---

[5] Eric von Hippel's work on information exchange shows that non-market based information exchange is also prevalent in some sectors (von Hippel, 1988).

[6] The issue of international technology transfer through the movement of people has been addressed by several authors although rarely in a systematic way. See for instance, Bell and Pavitt, 1993; Caves, 1996; Blomström and Kokko, 1998; and Fosfuri et al., 1998. The importance of the movement of people as a key mechanism for the international transfer of technology has been emphasized also by economic historians. See for instance Jeremy (1981) for the later industrialization of North America and Landes (1969) and Henderson (1965) for the case of France and Germany.

[7] Research universities are of course not part of this vertical integration.

[8] A recent study by a British-based consulting company (BTG, 1998) surveyed 133 companies in the US, Western Europe and Japan. The study found that these companies ignore more than 35% of their patented technologies because they do not fit into their core business operations. Many of these so-called "orphan technologies" would have commercial value if they were licensed or sold. The study estimated that US companies do not profitably use about $115 billion of technology assets. Moreover, the study found that the reason why companies do not sell these technologies is not because licensing is unattractive but simply because they do not take this possibility into account. Even if the figures reported by BTG are overestimates, they are suggestive of the potential benefits of a market for technology.

[9] The European Union estimated that in Europe 20 billions US dollars are spent every year to develop new products or ideas that have already been developed elsewhere. (See www.european-patent-office.org/patinfopro/index.htm.)

no incentives to invest in innovation. Hence, the dominant mode of innovation acts as a drag on the innovative output of the economy. Small firms, which many studies have also found to be inventive, are the most penalized by this organizational arrangement. A market for technology, which enables inventors to sell their inventions to others that can commercialize and use them more efficiently, can address both of these issues.[10] Put differently, a division of labor between inventors and the users of inventions is likely to be beneficial (Arora and Gambardella, 1994).

Prior research suggests that such a division of labor would be beneficial. Merges (1998) interprets the property rights paradigm associated with Grossman-Hart-Moore as implying that research will typically be more efficient when "owned" by the research unit. Aghion and Tirole (1994) analyze a model where a research unit contracts with a prospective user (a licensee). In their model, the research unit should "own" the invention but if it faces capital constraints, it may be forced to concede ownership to the licensee. Ownership by the licensee, because it reduces the incentives of the research unit, results in inefficiently low levels of research effort. Arrow (1983) argues that small firms are more inventive because innovation flows more easily and incentives can be better aligned. Landau (1998), reflecting on his own experience as a founder and manager of an innovative chemical process technology firm, notes that smaller firms have a number of advantages: Better incentives for bench scientists, effective two way information flows between managers and researchers, and quick managerial decision making, including the ability to stop projects that appear unpromising.

The survey of empirical evidence in Cohen (1995), on balance, appears consistent with the idea that small firms are more innovative, at least in some respect, than large firms. (See for example Acs (1996) and Acs and Audretsch (1993).) However, Cohen and Klepper (1996) have argued that the greater R&D productivity of smaller firms may reflect greater incentives of larger firms to invest in R&D due to their ability to amortize R&D over a larger volume of sales. This leads large firms to invest in less promising projects as well, lowering the average productivity of R&D. Griliches (1990) has argued that the greater observed productivity may be a consequence of sample selection and under-reporting of R&D in small firms.

One problem with the empirical evidence is that it has tended to compare within industries. As our case studies below show, a division of innovative labor is likely to involve firms upstream and downstream of the industry in question. Put differently, the point of a division of innovative labor is that different types of firms are more efficient at different stages of economic activity. This point goes back at least to Jewkes et al. (1958) when they noted that technical advance in an industry depends on the interactions between firms that differ in expertise and other attributes, including size. Nelson, Peck and Kalachek (1967) and Scherer (1980), among others, have emphasized similar ideas. In sum, a key benefit of markets for technology is that they promote the division of labor in the production and use of technology.

Although a division of innovative labor is an important implication of markets for technology, the latter also includes the sale and transfer of comprehensive technology packages, particularly across national boundaries. The literature on international technology transfer is vast but has tended to focus on the desirability and problems of such transfers (see for instance, Lall, 1980; Frischtak and Rosenberg, 1985; Vaitsos, 1993), while others have focused on the contractual forms and their respective costs (see for instance, Contractor, 1981;

[10] This is strongly reminiscent of the classical argument by Smith (1776), Young (1929), and Stigler (1951) where the benefits from division of labor arise when a certain activity is characterized by increasing returns.

Vishwasrao, 1994; Wright, 1993). Perhaps understandably, this literature has largely remained confined to the field of international management and economic development, remaining quite distinct from the literature on innovation and technological change. One of our objectives in this essay is to build a conceptual framework that encompasses both technology transfer as well as the division of innovative labor.

As is often the case, real life markets for technology do not always involve neat and tidy sale and purchase of technology. As with many other types of markets involving differentiated and variegated products, transactions for technology are typically not merely "money for technology". Instead, they often involve formal and informal ties between parties, using a variety of institutional arrangements to facilitate the transaction. The point is that where such transactions are common, they encourage the growth of firms that specialize in the production and sale of new knowledge. Our three cases below illustrate this point.

2.3 Specialized engineering firms (SEFs) and the division of innovative labor in the chemical processing industry

Freeman's pioneering study (1968) pointed to the role of firms that provided design, engineering and construction services to the chemical and oil industry. More recent studies (Landau and Rosenberg, 1992; Arora and Gambardella, 1998; and Arora, Fosfuri and Gambardella, 1998) have provided further evidence on the role that some of these so-called "specialized engineering firms" (SEFs) have played in the development and improvement and diffusion of new chemical processes. Before world war II, most chemical processes were designed and engineered by the chemical firms themselves (Freeman, 1968). After world war II, the development of the discipline of chemical engineering provided a unifying basis for conceptualizing chemical processes as consisting of a combination of a basic "functional" elements that were common across different chemical processes. (See Rosenberg, 1998.) This encouraged the growth of specialized firms (the SEFs) engaged in the design and engineering of processes.

A study based on more than 20,000 plants constructed all over the world during the 1980s shows that SEFs provide the engineering expertise for more than two thirds of all chemical plants (Arora and Gambardella, 1998). They also license the technology for nearly 35% of all chemical plants constructed during this period (see figure 2).[11] SEFs have been particularly important in two areas: catalytic processes, and engineering design improvements. UOP has a number of innovative catalytic refining and reforming processes, which it has licensed widely. Scientific Design pioneered a number of new pathways to produce basic inputs for synthetic fibers and plastics, such as the air oxidation process for para-xylene (used for polyester). Other SEFs, such as Kellog (high-pressure processes for ammonia) and Badger (fluidized bed catalytic processes) have made significant contributions to engineering design. Not only are SEFs important sources of technology, but as we discuss in Section 5 below, the existence of independent technology suppliers also has an important impact on the incentives of the producers themselves to license their technologies (Arora, 1997; and Arora and Fosfuri, 1998b). Arora and Fosfuri (1998a) show that in chemical sub-sectors where SEFs are important sources of technology, chemical companies themselves tend to license their own technologies more actively.

[11] Interestingly enough, the role of SEFs as providers of engineering and design services has remained roughly constant since the 1960s, and their share of technology licenses seems to have risen slightly since then. (See Freeman, 1968.)

2.4 The division of innovative labor in life sciences

The story of biotechnology startups in generating new discoveries in life sciences is well known and well studied, and we will review it very briefly. (See for instance, Arora and Gambardella, 1990; Powell and Bantley, 1996; Zucker et al., 1998; Lerner and Merges, 1998). Initially these firms began by leveraging their superior access to recombinant DNA technology and hybridoma technology (monoclonal antibodies). Although most academic research in this area has conceived of the biotechnology firms as discovering new drugs, this is not the only type of division of labor that prevails in the biotechnology industry. Over time startups have established areas of comparative advantage in a variety of generic technologies for discovering and developing new drugs. These include PCR (Polymerase Chain Reaction), protein structure modeling, rapid computer based drug assay and testing, recombinant chemistry techniques, drug delivery systems, and chemical separation and purification.

Merges (1998) provides a number of examples of other types of firms that might be thought of as the SEFs of the pharmaceutical and fine chemicals industry. Firms such as Catalytica, ChemDesign and SepraChem are leveraging research and their expertise in asymmetric synthesis to develop new processes for the production of pharmaceuticals and key pharmaceutical intermediates.[12] These firms both develop proprietary technologies and, either license them to pharmaceutical and specialty chemical companies, or enter into alliances to supply the latter with purer and better inputs. Interestingly enough, Merges (1998) also notes that this trend has induced some established producers to spinning off units to provide contracted process development and manufacturing services to the pharmaceutical industry.

Although one can find reasons for a division of innovative labor to be more likely in the life sciences and chemicals, the phenomenon is not restricted to these two areas, as the next example shows.

2.5 Fabless fabs and the division of innovative labor in semiconductors

In the 1980s, the semiconductor industry witnessed the rise of the fabless fabs. Hitherto, semiconductor design was integrated with the manufacture, and the leaders in semiconductor design technology, such as Texas Instruments, Intel, and IBM were also major producers. The new startups specialized in designing semiconductors but did not have the production capabilities (and hence, were fabless). Correspondingly, merchant foundries, such as Taiwan Semiconductors emerged to fabricate the chips based on the designs being delivered by the design houses. The division of innovative labor proceeded with the rise of firms, such as Cadence Design Systems and Mentor Graphics, which developed software tools for designing chips.

More recently, as semiconductor chips have become more complex, this process has taken a further step with the emergence of firms that specialize in producing cores, or components of the overall semiconductor chip design (e.g., Advanced Risc in UK, Mips Technologies, Rambus, Phoenix Technologies and ISS). The great advantage is that the component may be used in several types of semiconductors, thus lowering overall costs. These developments have been helped by the Virtual Socket Interface Alliance, a consortium of over 180 firms that has tried to promote industry wide standards. Observers believe that if a market for chip design components – a market for technology – takes root in the semiconductor industry, it would enhance the prospects of being able to design a chip that incorporates all electronic functions, also called a "system on a chip". Industry sources

[12] In this case, a key expertise lies in being able to produce and isolate the desired chiral form of the molecule.

predict that the merchant intellectual property component market will grow from about $600 million in 1997 to $2 billion in 2001 (Grove, 1998a).

As these case studies show, the markets for technology can be structured in a variety of ways and evolve over time. The structure of the market has important implications for both corporate strategy and policy. For one, it conditions how the rents ("value" in management terms) are divided along the knowledge value chain. For instance, technology integrators that control scarce and difficult to replicate complementary assets may be able to extract a large fraction of the rents. By contrast, in more dispersed markets like semiconductors, the different parts of the knowledge value chain may be more balanced.

In some cases, such as biotechnology, the market structure is relatively straightforward. Biotechnology startups form the link between basic science (often at universities) and established pharmaceutical firms that typically develop drugs, obtain regulatory clearances and market the drugs. In a sense, the technology value chain is simple with relatively few branches. In chemicals, the value chain is more complicated, with major product and process innovations typically emerging from chemical and oil firms, but with detailed process development taking place in cooperation with SEFs. Further, SEFs typically improve and refine the process and frequently handle licensing arrangements as well. In other industries, such as aerospace engines, the division of innovative labor is centered around an integrator, typically engine producers such as Rolls Royce and General Electric. The technology integrators maintain a broad range of technical and scientific capabilities that cover the product in question.

3. Factors limiting the division of innovative labor

Markets for technology are not synonymous with a vertical division of labor between a specialized sector of upstream suppliers of the technologies and the downstream firms using them. The latter is, however, an important dimension of an analysis of markets for technology and many of the benefits of markets for technology come from the development of a division of innovative labor. Despite their many advantages, there are two main reasons why markets for technology may not function well, resulting in a very restricted division of labor in inventive activity.

The first reason is associated with cognitive aspects. Knowledge or technologies developed in a certain context may not be equally useful in other contexts. This is because there are context-dependent features in their production and in their use that cannot be readily translated when applied to different domains. Hence, the users may not find the technology useful when it is not developed by them, and tailored to their needs. Context dependence is also closely related to the tacitness of knowledge that many writers since Polanyi (1966) have noted. Tacitness of technology increases the cost of transferring technology across contexts such as from one firm to another.

The second reason is the one that has received most of the attention in the economics and managerial literature and is related to transaction costs and opportunism. When technologies are not embodied in tangible goods and cannot be protected by property rights, selling the technology becomes difficult. The economics literature has analyzed this situation as a problem of selling information. As Arrow (1962) first noted, seller and buyer may find difficult to put a value on the information without knowing it in detail. Furthermore, having learned the information, the potential buyer has no incentives to pay for it. Finally, information, once produced, can be reused without further cost. Opportunism may then prevent the realization of contracts for the exchange of information.[13]

Since real world contracts are of necessity incomplete (Dawson et al., 1982; Hart and Moore, 1988), these problems are compounded. Thus, the transaction cost perspective (Coase, 1937; Williamson, 1975) would imply that such transactions could be more efficiently executed inside firms rather than across firms. Teece (1986), in a seminal paper, made this link, arguing that firms wishing to capture the rents from new technology creation should acquire complementary capabilities for commercializing the technology, such as production and marketing capabilities.

We explore both these aspects below.

3.1 Cognitive determinants of a "division of innovative labor"

Division of labor requires that the task at hand be decomposed into smaller sub-tasks, and that the outputs of these subtasks be integrated effectively. There are two important considerations. First, the ability to conceive of the task in terms of combinations of sub-tasks, and second, to choose to partition tasks in such a way as to minimize the cost of information exchange across the sub-tasks. Eric von Hippel (1990 and 1994) has made a seminal contribution in this context.

As von Hippel has convincingly demonstrated, being able to break up or partition a problem-solving task increases efficiency and productivity. Partitioning, however, requires information exchange in order to integrate the results effectively and because one sub-task may require information generated elsewhere (e.g., Iansiti, 1995). The problem is that some information is "sticky" and difficult to move across contexts. This "stickiness" increases the costs of a division of labor because the latter would greatly increase the cost of information exchange. In a sense, von Hippel can be read as implicitly offering a theory of the division of innovative labor and the boundary of the firm. For instance he discusses the case of the information flows between the designers of the sheet-metal parts that make up the surface of an automobile, and the designers of the dies used to produce these parts. In this case the amount of overlapping information and joint problem-solving activity is so high that it would be hard to partition this problem into independent tasks, with the designers of the metal part being partaken from the die designers. Accordingly, it makes sense to integrate the design of dies and metal parts in the same organization. The point is that the extent to which the innovation process is integrated within one firm rather than decentralized depends importantly on the extent to which an innovation activity can be effectively task-partitioned.

In a subsequent paper, von Hippel (1998) noted that the if the sticky information could be "unstuck", interdependencies could be substantially reduced. He further argued that there are important asymmetries across users and producers in their ability and incentives to "unstick" this information. Specifically, he argued that it is more efficient for the supplier to "unstick" his information because it would imply a one time cost and because user context vary and may be harder to generalize. The development of computers has given a boost to this task partitioning because information can be embodied in software and made available cheaply and in a useful form. The burgeoning market for software tools and solutions of

[13] Zeckhauser (1996) has summarized many of the challenges in contracting for technological information. These include the fuzzy demarcation of intellectual boundaries by patents, the presence of asymmetric information, the complexity of the good at stake and the large tacit component of technological knowledge.

various kinds, ranging from production and inventory planning to semi-conductor design to solvers for optimization problems, attests to the power of this idea.[14]

A complementary perspective is provided by Arora and Gambardella (1994). Here, the focus is on the costs of information exchange, and how the nature of the information to be exchanged and the underlying knowledge base – the context – affects the cost of information exchange. Simply put, information is sticky because it is context dependent. Context dependence arises because we often lack a complete understanding of the technology. Firms have to produce goods, methods or processes that work in practice. In order to do so, often it is neither necessary nor sufficient to understand the scientific principles underlying the technology. For example, a pharmaceutical compound tested against a certain disease cannot be used for other diseases that may act on the same cells without a deep understanding of how the compound acts in the human organism. Absent such a deep understanding, humans use heuristics, shortcuts and rules of thumb, in order to structure problems (e.g., Simon, 1959). Such structuring provides the context and framework within which humans interpret information, but insofar as the frameworks differ between two people or firms, they also make it harder to transfer information. Thus the knowledge and the technologies developed by firms tend to be context-dependent, and difficult to transfer outside of the domain in which they are created.

A key factor in reducing the importance of this constraint is the growth in physical, biological and engineering sciences. This provides the opportunity of comprehending in new ways what is already known, *abstracting* from the idiosyncratic and contextual features of specific applications, so that what is known can be *generalized* to encompass several applications. Abstract and generalized knowledge tends to be better articulated and easier to codify in useful ways. In recent years, the growth of computing capabilities, both hardware and software, have given a big boost to the growth of such general and abstract knowledge. This has made possible a greater separation between the production of general-purpose knowledge -- of general and abstract knowledge -- and the use of such knowledge.[15]

Thus, Arora and Gambardella's analysis complements von Hippel's by exploring the determinants of "information stickiness". Unsticking information requires that the information be presented in a form that others outside the context can understand, use and manipulate. For this, the ability to comprehend the specific information in a general and abstract way becomes crucial. So is the ability to embed the information in a software program that others can use (and complement with their own context specific information). Together, they reduce the costs of information exchange and the division of labor.

We should emphasize that the separation does not imply that the application of the upstream knowledge is simple or straightforward. Neither does it imply that information flows only one way. It does imply that these information flows are more structured, with information flows from downstream applications feeding back into developing more general knowledge upstream, which is then made available in various ways for downstream application.

Indeed, successful users of technological knowledge themselves may need to be technologically very sophisticated, particularly in the case of the purchase of upstream, general knowledge. Such technological sophistication on the part of buyers may require them to maintain significant in-house research capabilities (Cohen and Levinthal, 1989; Rosenberg,

[14] Similarly, Langlois (1992) emphasized the importance of modularity in production and in R&D, and offered other examples drawn in particular from the electronics industry. (See also Langlois and Robertson, 1992.)

[15] The use of the knowledge may not be simple and straightforward. It may itself require creating new knowledge. The latter is likely, at least in the first instance, to be more limited in scope and application.

1990; Arora and Gambardella, 1994). Eventually, as the technological trajectory displays signs of maturity, the cognitive and other costs involved in technology transfer may overcome the advantages that outside specialists may enjoy.

In other words, the cognitive perspective suggests a dynamic process, with major new technological and scientific breakthroughs possibly resulting in the growth of specialized technology producers whose advantages diminish as increasingly knowledgeable buyers internalize research in-house. We speculate that this dynamic process underlies the historical trends observed over the last century. A market for technology appears to have flourished, at least in the US, around the turn of the century. This was supplanted by vertical integration between research and production beginning sometime in the early 1900s, with the 1980s again marking the growth of specialized technology suppliers.

3.2 Transaction costs and contracting for technology

Relaxing the cognitive constraint is only necessary, not sufficient, for a market for technology to be realized. The difficulties in writing contracts to sell technology are widely accepted. Arrow (1962) is widely regarded as the first formal statement of the problem, although Nelson (1959) clearly anticipated the basic argument. Williamson (1975) noted that contracts in general tend to be inefficient when there is uncertainty, small numbers bargaining, and when there are non-contractible aspects of the transaction. Typically, the literature has appealed to the tacit nature of technological knowledge and the ineffectiveness of intellectual property rights in preventing imitators from inventing around to argue that contracting for technology is likely to be difficult and costly (see for instance, Teece, 1988).[16] For instance, researchers have noted the problems posed by uncertainty (Bonaccorsi and Pammoli, 1996) and small numbers bargaining (Pisano, 1990) in contracting for technology. In a similar vein, there is a growing literature on international technology transfer which appeals to transaction costs to explain the use of wholly-owned subsidiary vis-à-vis arm's length contract as a means for the transfer of technology across national boundaries. (See for instance, Dunning 1981; Markusen, 1995.) The transaction cost argument underpins the widely held belief that tacitness of technology and the associated information asymmetries and uncertainty cause insurmountable difficulties in contracting for technology.

Although there is some truth to this view, it is too pessimistic. At least under some circumstances, the tacitness of technology by itself does not pose any major difficulties. Arora (1995) shows that, under certain conditions, one can write simple contracts for the exchange of tacit knowledge. The two key conditions under which these contracts can be written are that: a) the tacit and codified components of the technology are complementary, and they are bundled together in a technology package; b) the codified component is protected by intellectual property rights.[17]

The intuition of the model is simple. Suppose that the licensor and the licensee agree to exchange a certain amount of know-how X. The licensee pays an up-front fee of T_1, and the licensor supplies the know-how. Opportunism may arise because, once the know-how is

[16] The transaction costs view, by stressing the non-contractible nature of tacit knowledge, is linked to the property rights view of Coase (1937) and others. The latter underscores the importance of clearly defined property rights for a market to develop. We argue here that one does not need to have all the property rights defined and enforced for markets to function. However, as we argue here, markets for technology do require some intellectual property rights to be well defined and adequately protected.

[17] Although only straight licensing is analyzed in this model, clearly a variety of intermediate arrangements are possible, including cooperative R&D, buyback or supply arrangements, equity investments and option contracts, and joint-ventures. We cannot explore each of them in any detail. The essential point is that all these are means of facilitating the exchange between producers and users of technology.

transferred, the licensee may refuse to pay a second fee of T_2 that the parties agreed to pay after the know-how was supplied. Knowing this, the licensor may not supply the optimal amount of know-how, and the licensee may not agree to pay the initial fee in the first place, leading to the widely expected market failure.

But assume that the know-how can only be used with a complementary codified input which is protected by a patent. The licensor can always withdraw the license for the patented components, which would prevent the licensee to realize the full value of the know-how if she refuses to pay the second fee. This "credible" hostage encourages the licensee to pay the second fee. The model also assumes that the wider the scope of the patent, the smaller the value that can be realized by the licensee from the innovation if she refuses to pay the second period license, compared to the value that she would realize with the patented component. This is a reasonable assumption as broader patents make it more difficult to "invent around" (see for instance, Gallini, 1992).

The main result of the model is that if the scope of the patent is larger than a certain threshold, the parties can agree on two lump sum fees T_1 and T_2 such that the licensor has an incentive to provide the first best amount of know-how X. For patent scope smaller than the threshold, the amount of know-how that is exchanged increases with the scope of the patent. Moreover, the amount of know-how exchanged through the contract is higher the stronger the complementarity between the tacit and codified components. Thus, strong intellectual property rights are key for realizing the full benefits of a market for technology.[18]

This is more than a mere theoretical possibility. The model explains many real world features found in licensing contracts. For instance, as predicted by the model, Contractor (1981) finds that the amount of know-how and services that licensors provide is increasing in the first period payment. Direct testing of the theory would require detailed information on the tacit and codified components of licensed technologies, an unlikely possibility. However, indirect tests are possible. A key implication of the theory is that tacit know-how, when it is provided, should be bundled with complementary inputs on which licensor has well defined property rights. Arora (1996) using data from 144 technology import agreements by Indian firms during 1950-1975, confirms the supply of the technological services is more likely when the contracts involved associated complementary inputs such as patents. Thus, arm's length contracts can overcome the problems in contracting for know-how by bundling complementary inputs with know-how in a technology package, and leveraging the superior enforceability of contracts over the latter.

Further, although asymmetric information and moral hazard are serious problems, they can be mitigated through a variety of contractual and institutional responses. There is abundant research showing how non-disclosure agreements, long-term contracts, repeated contracting, reputation building and social norms can overcome many of the information based problems that are thought to afflict transactions for technology. Indeed, insofar as moral hazard, uncertainty and asymmetric information are likely to be more important at the early stages in the development of technology, the flourishing venture capital sector suggests that they do not pose an insurmountable problem to contracting.

3.3 Financial constraints to the rise of specialized technology suppliers

The issues involved in financing R&D are well known, have received a great deal of attention, and we shall review this topic only briefly. Raising capital to finance R&D, especially at the initial stage, is perceived as a major problem for many technology based

[18] The model is also robust to extensions like asymmetric information about the ability of the licensee to "invent around", and to re-negotiation proof contracts.

startups. Relatedly, the ability to provide and finance risky development was seen as an advantage of integrating R&D within large firms. Later research, surveyed in Cohen (1995), has questioned this assumption. Further, even if internal capital is cheaper than capital raised from the market because of a variety of problems related to asymmetric and imperfect information (e.g., Leland and Pyle, 1977), this advantage may be offset to some degree by incentive and commitment problems.

In recent years, financial intermediaries and especially venture capital firms, are playing an increasingly important role in financing high technology startups. In biotechnology, software, telecommunications and a variety of other sectors, technology-based firms with strong intellectual property protection now have access to a number of venture capital funds.[19] Although venture capitalists own only about 1% of U.S. equity, they fund a substantial share of the companies that go public, especially in the high-technology sectors. In addition to finance, financial intermediation is also thought to be valuable in providing startups with useful advice and guidance (Lerner, 1995). An important consequence of the development of the venture capital sector is that it is now reaching outside the US to fund promising technology specialists in countries such as UK, Israel, and even India.[20]

Although far from conclusive, the experience of the biotechnology, software, and telecommunication sector suggests that financial constraints on the division of innovative labor are not insurmountable, and that if allowed to, the financial sector does respond by developing institutions capable of supporting a division of innovative labor. Even a country as small as Israel has over fifty venture capital funds that finance Israeli startups. European and Japanese economies seem not to do as well, and the absence of venture capital has been noted as an important contributory factor. Perhaps banks can partially substitute for venture capital, but this is an area that requires further research.

4. The division of innovative labor and the extent of the market

The previous two sections suggested that general-purpose technologies, or generic knowledge bases, are key for the rise of markets for technology. In the first place, the breadth of their applications implies that the size of their market is larger than that of a single firm or industry, and this encourages the formation of firms specialized in the production of technology (see figure 3 for evidence from chemical industry). Second, although their production requires a great deal of tacit expertise, abstraction and generality are likely to imply stronger patent protection, that can make it easier to transfer the tacit and intangible components of technology too. Further, such knowledge is also easier to move across contexts and also provides the framework within which context specific information can be "unstuck", possibly by embedding in a software tool or development environment.

We next analyze the incentives that firms, typically the upstream technology suppliers, have to invest in creating general-purpose technologies. In particular, we examine how these

[19] Lerner and Merges (1998) show that US biotechnology firms raised over $4 billion from venture capital funds between 1989 and 1995. If one includes other sources such as R&D financing, private placement and equity issue, they were able to raise over $19 billion.

[20] Moreover, large established firms themselves are beginning to use venture investing as a means of acquiring technology. Corporate venturing, as this process is sometimes called, is gaining prominence over time (Fortune, Dec 1998). According to BioWorld Today, an industry newsletter, the total public capital raised from biotech initial and follow-on offerings in 1997 was approximately $2.5 billion, while the total amount that big pharmaceutical companies contributed to biotech companies, either through investment or alliance, was $4.5 billion (cited in Grove, 1998c). Companies are looking beyond national boundaries as well, with Japanese and European firms investing in US biotechnology firms (see for instance, Teece, 1992), and US firms investing overseas, particularly in the information technology sector.

incentives are conditioned by the size and structure of demand. The issue is important because there is a substantial difference between the production of general-purpose components and the development of specific technologies. The former implies a higher fixed cost, but a lower marginal cost for applying them to different uses. Dedicated technologies imply a smaller fixed cost but a higher marginal cost for using them in domains other than the one in which and for which they were created. Moreover, we saw that historically companies have not invested in general-purpose technologies or in generic knowledge bases, but mainly in technologies that work for their own specific purposes. For these reasons, it is important to explain why and when one observes that firms (or industries) invest in more general technologies and knowledge bases.

Bresnahan and Gambardella (1998) develop a model that addresses this issue. Consider a firm operating in one of the N distinct final markets where it is confronted with the following two choices. On the one hand, it can develop its own dedicated technology by incurring an application-specific fixed cost F. On the other hand, it can buy a general-purpose technology supplied by a specialized upstream technology sector. If so, it avoids the fixed cost F, but instead pays a price w per unit of the general-purpose input purchased.[21] A key feature of the model is that when firms buy the general-purpose input, the full price is $w + d$, where d is a unit cost increase due to the fact that, unlike dedicated technologies, the general-purpose inputs have standardized features that have to be customized to the firm's requirements. The model assumes that the upstream sector can lower d by incurring a fixed cost G. The variable d can then be thought of as the output of an activity carried out by the upstream sector to make the technology less "distant" from each applications, and more general purpose.

Suppose that there are N firms in the market, corresponding to N different applications, and these firms are monopolists in their own markets.[22] The potential size of the final markets of each application (firm) is denoted by S, which is a random variable. Note also that N and S measure two dimensions of the size of the market. N is the number of potentially different applications, S is the size of each application.

The key theorem of the model is that the upstream industry has a greater incentive to lower d the larger the number of downstream applications N, and the lower (in the sense of first order stochastic dominance) the distribution of S.[23] Thus, the development of general-purpose technologies is more likely in cases in which there is a larger differentiation of the final downstream markets. This creates greater opportunities for the upstream sector to invest in these technologies, and for the downstream sectors to buy them rather than producing dedicated technologies in-house. By contrast, a larger economy in the sense of larger size of the individual applications is one in which the upstream sector is smaller, and the upstream technology is more distant from the applications.

The model also shows that any exogenous factor that reduces the costs of developing the generic technology, such as an increase in the supply of trained engineers and scientists and exogenous advances in science and instrumentation, increases the output of the general purpose technology. This clarifies that the critical dimension of market size for the division

[21] For simplicity, one can think of more inputs as access to broader and deeper technological knowledge. In the software analogy, it may imply getting more functional modules and libraries.

[22] Assuming greater competition would complicate the model, but not change the basic results.

[23] The model shows that given d firms whose size S is larger than a certain threshold will make the technology in-house, while firms with S smaller than the threshold will buy the general-purpose input. The intuition is straightforward. Larger firms have larger internal markets to spread the fixed cost of dedicated technologies, and hence they are more likely to invest in their own technique. Another fairly natural implication of the model is increases in d lower the threshold beyond which firms rely on in-house technology.

of labor between firms is breadth of application rather than depth. Further, it reinforces and amplifies the importance of generality and abstraction of knowledge – the greater the generality, the lower the cost of adapting the knowledge to specific application. Finally, these results can also be reinterpreted as pointing to the role of software tools in reducing the economic distance between abstract knowledge and specific but differing applications.

The notion of general-purpose technology is related to Rosenberg's concept of technology convergence. In his study of the US machine tool sector in the 19th century, Rosenberg (1963 and 1976) noted that a variety of industries such as firearms, bicycles, sewing machines, typewriters and automobiles, had to perform metal cutting operations that were very similar to (e. g., boring, drilling, milling, planing, grinding, and polishing). Initially, the firearms makers produced their own machines, because firearms was among the first of these sectors to develop.[24] Over time it was recognized that a large number of application sectors, from sewing machines to automobiles, required a common set of metal cutting, bending and shaping operations. Once conceptualized thus in the abstract, lathes, mills and machine tools of various sorts that carry out these operations were developed and supplied by specialized machine-tool makers.

Rosenberg's machine tool sector exemplifies many of the important insights discussed here. Machine tools emerged as a separate general purpose technology sector when two conditions were satisfied. A large number of downstream application sectors developed, and these sectors were eventually seen to be relying on fundamentally similar technologies. Learning and knowledge from one application sector was received, conceptualized and captured in better, more accurate and more flexible machine tools, with the resultant productivity benefits accruing to all application sectors downstream. (See also Bresnahan and Trajtenberg, 1996.) Finally, innovations in machine tools became the responsibility of specialists, the upstream machine tool producers (although users may have played an important role as well).

5. Markets for technology, licensing, and the role of competition

The discussion thus far has focused on the emergence and growth of firms specialized in the supply of technology. However, when a market for technology develops, it lowers entry barriers and increases competition. Such competition affects the incentives of incumbent firms that hold proprietary technology to license it. Further, the presence of rival sources of technology, particularly from specialized firms, is a powerful spur to technology licensing. Thus, a market for technology may include technology being licensed and sold by large firms with significant production and commercialization capabilities as well.

For instance, Arora (1997) has documented extensive technology licensing by well known chemical firms such as Union Carbide, Dow, Du Pont, Exxon and Shell. Indeed, Dow and Exxon are actively competing to license their proprietary technologies for metallocene or single site catalyts for polyethylene and polypropylene, a market estimated to be worth over $2 billion. Many of these firms have explicitly set targets for their licensing revenues. Hoechst plans to earn over $100 million by the year 2000, while Du Pont hopes to reach that target a few years later. This trend is not confined to the chemical industry. In semiconductors, where the market for technology is also active, one sees a similar picture. In 1998, industry observers expect IBM to generate $750 million from its patent portfolio, twice

[24] The so-called American system of manufactures played an important role. In the US, articles such as rifles and muskets were produced as standardized modular commodities with interchangeable parts. By contrast, in Europe, rifles and muskets were produced to the physical specifications of the individual user, the difference being similar to the that between a tailor made suit and one sold off the rack (Rosenberg, 1976).

as much as it collected just four years earlier. Texas Instruments, which earned over $1 billion in the early 1990s, and $800 million from its patent portfolio in 1995, could earn even more in the future (Grove, 1998b).

This marks something of a challenge to traditional wisdom that holds that innovations are best exploited by commercializing them oneself (e.g., Teece, 1988). The reasons why companies may not wish to license their technologies are well known. Apart from the transaction cost arguments dealt with above, there is a straightforward reason: By licensing firms create new competitors, thereby reducing their profits. Put differently, licensing has a rent dissipation effect. But licensing also provides revenue from the sale of the technology. The question is then under what conditions the revenue effect is larger than the rent dissipation effect.

This way of approaching the problem has another twist that is worth emphasizing here. The theoretical literature on licensing has problems in providing a satisfactory answer to the question above because it typically assumes a monopolist technology holder.[25] By contrast, a substantial fraction of innovations do not provide the innovator complete monopoly in the product market. This creates a "commons" problem, where the profits from an oligopolistic market constitute the commons. A technology holder that can control entry is akin to an agent that holds the rights to access to the commons. As long as there are other users of the commons, i.e. the technology holder is not a monopolist, her incentives to sell access to the commons exceeds the collective interest -- the rent dissipation is shared with other users of the commons while the licensor alone gets the revenues. With more than one firm having proprietary technology, the commons problem is exacerbated.

This model is formalized by Arora and Fosfuri (1998b). Formally, if $\pi(N)$ is the profit of the typical firm when there are N firms in the industry, then an incumbent marginal payoff from licensing (assuming the licensor captures all surplus) is $2\pi(N+1) - \pi(N)$, which for $N > 1$ can be greater than zero. Thus, with more than one incumbent the revenue effect from licensing can be greater than the rent dissipation effect. As a result, not only may firms compete to supply products, but also to supply technologies.[26] Following this intuition, the model leads to three main results:

i) Stronger intellectual property rights decrease the transaction costs, which affect the licensor's payoff from licensing. Hence, stronger intellectual property rights increase the extent of licensing. Stronger intellectual property rights may also enable the licensor to capture a larger share of the rents, which also increases licensing.[27] However, insofar as broader patent scope results in greater product differentiation, broader patent scope will lower licensing. Similarly, insofar as a higher novelty bar reduces the number of technology holders, this too reduces licensing.

ii) Licensing is more widespread the lower the degree of product differentiation across competing technologies. Intuitively, this is because by licensing the firm would create a rival that is closer to him in the product space than to other incumbents. The rent

[25] See for instance Gallini (1984), Katz and Shapiro (1985), Shepard (1987), Gallini and Wright (1990).

[26] The reason why with more than one incumbent the possibility of licensing arises is that in this case the loss due to increased competition is shared with the other incumbents in the market, or put differently, the firms do not fully internalize the rent dissipation effect.

[27] Consider a situation where once the technology holder enters into licensing discussions with a potential licensee, the latter can use the information revealed to invent around (e.g., Gallini, 1992; Arora, 1995). The stronger the patent protection, the greater the cost of inventing around, and hence, the larger the share of the surplus that the licensor can capture in the subsequent negotiations.

dissipation effect is then internalized by the licensor to a greater extent, and this reduces the profitability of the licensing strategy.

iii) Technology suppliers that lack the downstream assets to operate in the final markets sell more licenses. While this result is completely intuitive (the technology suppliers have no rents to dissipate from greater downstream competition), the model also throws up a less straightforward result: The presence of such firms induce other downstream producers to license their technologies as well. This is because given that others license their technologies and create new competitors, the rent dissipation effect arises in any case, and therefore the downstream producers may well try to compete in the market for technology to sell some of their licenses.

The latter result is particularly interesting within the framework of this paper, as it suggests that independent technology suppliers (like the SEFs discussed in Section 2 or even universities) have the additional effect of inducing the downstream producers to become technology suppliers as well. Moreover, up to a point, licensing by rivals increases the propensity of other technology holders to license as well. In sum, licensing strategies snowball, gathering strength over time. This line of reasoning suggests that markets for technology may be quite robust once they arise.

Patterns of technology licensing in the chemical industry provide some support to the theoretical findings illustrated above. Arora and Fosfuri (1998a), using data on worldwide technology licensing in the chemical industry during the 1980s, find that the per-firm number of licenses decreases with the degree of product differentiation. Homogeneous sectors like air separation, pulp and paper, and petrochemicals are marked by extensive licensing, while only limited licensing is observed in differentiated product groups like pharmaceuticals and organic chemicals. More interesting, they also find that firms without downstream production facilities tend to license more and that in product groups where such firms operate more intensively, large chemical producers themselves tend to license more (see also figure 4).

6. Fragmentation of intellectual property rights and other challenges

The foregoing discussion has highlighted some of the benefits of markets for technology: They facilitate diffusion of technology, induce investment by downstream firms, and allow for firms in "smaller" markets to invest in "adapting" general-purpose technologies to the special needs of local users. However, when technologies, are cumulative and systemic, markets for technology may not always work well.

Complex systems are often made of many components, sub-components and parts. Thus, the pace of technological progress depends on the actions of many firms responsible for the production of the components. The problem is that if property rights on technology components are assigned to different agents, each patent holder can have the right to exclude the others from the use of her component. This implies that in order to use the technology one has to collect all the rights for the use of its components.

In a world with no transaction costs, agents will bargain to a Pareto superior solution given any initial distribution of property rights over the components. In a more realistic world, the required collection of property rights, although socially efficient, might not occur because of transaction costs and "hold-up" problems. An agent holding a patent on an important component ("blocking patent") may use her patent as a "hold-up" right in an attempt to extract as much of the value of her innovation as possible.

Suppose that the development of a new technology involves the use of components invented and patented by other firms. In order to assemble the new technology either the firm has to buy licenses on the components or alternatively it has to make the components in-house. The licensing fee for each component is set up through a bargaining process.

The analysis of this simple framework emphasizes three reasons that may induce a market failure in the presence of "blocking patents": a) lack of alternatives, b) excessive fragmentation of intellectual property, c) "hold-up" problems. These forces act as follows:

i) The more difficult it is to develop the components in-house, the more likely it is that the technology will not be assembled in the first place. This is because when there are no alternative sources for the components, the bargaining position of the component holders is very strong.

ii) The more fragmented the property of the components, the greater the number of transactions required, and hence, the less likely it is that the investment for the development of the technology will be undertaken.

iii) When transactions in technology components occur sequentially, the system developer will retain only a small share of the total surplus. This is because once the system developer has purchased some of the components and these costs are sunk, the system developer's bargaining power is reduced.

iv) Non-manufacturing firms that hold patents on key components are likely to bargain more aggressively for licensing fees. The strategies of firms that have significant market shares in the downstream markets (in which the technology is applicable) are more complex. However, they are likely to cooperate, particularly if there is a stable group of such firms.

One example of what might occur when several companies hold patents on different components is provided by the early development of the radio (Merges and Nelson, 1990). The Marconi Wireless and Telegraph Company, AT&T, General Electric, Westinghouse all held important patent positions in the early stages of the development of the industry. The ensuing fragmentation of property rights is said to have caused serious delays in the pace of technological innovation. For instance, the basic patent on the diode was granted to Marconi, while the patent on the triode vacuum tube was assigned to AT&T. Marconi's patent was needed for using the triode technology, yet neither party would license the other and, as a consequence, no one used the revolutionary triode for some time.

Similar situations arose in the early stages of development of the automobile and aircraft industry and in the chemical process technology industry. A more recent case is biomedical research. Heller and Eisenberg (1998) are especially concerned with the increasing practice in biomedical research of defining property rights around isolated gene fragments. Since many commercial products, such as therapeutic proteins or genetic diagnostic tests, are likely to require the use of multiple fragments, a proliferation of such patents, held by different owners and licensed with stringent "pass through" provisions, imply large costs for future transactions aimed at bundling the patents together.[28]

These concerns have been echoed by industry participants as well. Cecil Quillen, former Senior Vice President and General Counsel of the Eastman Kodak Company, claims that since the early 1980's, the legal costs of intellectual property protection has risen dramatically to the point of substantially raising the cost of innovation itself. Michael Rostoker, former head of LSI Logic, a semiconductor manufacturer, has also suggested that, due to stronger patent protection, firms holding old technology have been in a position to command licensing fees from a current generation of innovators even while the original patent

[28] Pass-through provisions allow the technology holder to receive royalties on future innovations produced by using the licensed technology. These provisions are a matter of considerable debate in the biotechnology industry.

holders have long ceased advancing the state of the art, leading to a stacking of licensing fees that impede the development of new generations of chips (Hadley, 1998).

When transaction costs make it difficult to put together the pieces of intellectual property required to commercialize a technology, not only is commercialization of technology delayed, other types of consequences follow as well. Some firms may cut back on R&D or move their research to other areas.[29] Firms may also patent very aggressively, particularly if they foresee complicated cross-licensing negotiations with rivals. In turn, this may push firms into the "tragedy of the anti-commons" situation described by Eisenberg and Heller (1998). Based on their survey of industrial R&D Cohen et al. (1997) conjecture that the rapid increase in patent rates and infringement suits since the early 1980's may partly reflect the growing use of patents as weapons in mutually reinforcing, non-cooperative strategic interactions.

Although fragmentation is a serious problem, there are a number of responses that can ameliorate it. Cross-licensing agreements, although costly to negotiate, are a partial solution. For instance, Anand and Khanna (1997) find that cross-licensing agreements are common in electronics and semi-conductors. Grindley and Teece (1995) attribute the extensive use of cross-licensing agreements in electronics and semiconductors, where innovations are typically based on hundreds of different existing patents, to the large transaction costs required to bundle together patent portfolios. Similarly, in biotechnology, firms holding complementary technologies do license each other, and firms with generic research tools such as PCR offer these on a non-exclusive basis. Patent pools are another traditional solution that has been applied in the oil refining industry, and more recently, in the semi-conductor industry.[30]

In the chemical process industry, technology-sharing agreements were established to alleviate the transaction costs involved in market relationships (Arora, 1997). The case of the chemical process industry is interesting for another reason as well. SEFs have sometimes acted as technology integrators that have helped in getting around the "hold-up" problem of fragmented property rights. Thus, another potential benefit of specialized technology suppliers is that they can act as technology integrators to limit the hold-up problem created by the fragmentation of intellectual property rights.

Sensible public policy can also do much to mitigate the worst consequences of fragmentation of intellectual property rights. In many instances, the fault may be with patent offices that issue overly broad and imperfectly specified patents. Given the presumption of validity, such patents can serve as blocking patents. Often, broad and imprecise patents are issued because patent offices are under-funded, the patent examiners not adequately trained and lacking the necessary capabilities to search for the prior art. In software, for instance, the US patent office has issued what are widely seen as overly broad patents, in large measure because the examiners rely very heavily upon previous patent applications to discover prior art. Since software patents are relatively new (copyrights having been the typical way of protecting software until recently), the result is bad and socially harmful patents, which nonetheless carry with them the presumption of validity.

In some cases, policies designed in the naïve hope of encouraging small inventors have encouraged the abuse of the patent system. In the US, for instance, there have been well known cases where patents filed in the 1950s ultimately issued more than twenty years later. In the meantime, the patentee could legally amend the application so that it covered

[29] Lerner's research (Lerner, 1995) shows that small, less well funded biotechnology firms tend to stay away from research areas populated by larger, better capitalized competitors.

[30] More nuanced institutional arrangements are also possible. For copyrights, organizations such as ESCAP that hold the copyrights of individual song writers and singers and collect fixed royalty payments for their use on behalf of the artists, have worked well.

inventions made well after the filing date. Since patents in the US are published only upon issue, many established firms have been surprised by such patents (sometimes referred to as 'submarine' patents because they are not visible for long periods after they are filed). The move towards patent harmonization, which will require publication of all patent applications after a certain period, will be helpful in this respect.

Another important public policy intervention would be to pay more attention to patenting requirements. Specifically, in the US, the patentee is required to "reduce to practice" the invention, demonstrate the best known way the invention is to be used or "enabled" and show the usefulness or "utility". Over the last few years, these requirements have not been enforced very seriously, at least in certain well known cases. For instance, patents on gene fragments (ESTs) have been issued without any clear knowledge of what proteins the gene fragment was coded for, and what functions the proteins performed. In principle, these fragments may prove to be useful in a broad spectrum of applications, as yet unknown. If granted, the patent holder may be able to demand a large share of the rents from any such applications or even block such applications, without having contributed to their discovery. Public policy can also help by encouraging patent pooling and cross-licensing (after verifying the absence of anti-trust motives).

A second set of, more controversial, policies whose merits remain under debate is the extension of "eminent domain" (i.e., the legal doctrine that allows the government to take over private property for public purpose) to intellectual property. In principle, the threat that the government may step in and buy out a patent holder at a "fair" price can be a powerful deterrent to the sort of opportunism that underlies the fragmentation problem. But governments may not be the best agencies to take over a technology where public good considerations might be quite indirect. Determining the price for the patent is an important challenge. A recent paper by Michael Kremer (1998) suggests using an auction as mechanism to determine the private value of patents. The government would use this price to buy out the patents and place them in the public domain.[31] Alternatively, the law may simply allow for "efficient breach" – i.e. let people "infringe" the patent and leave the courts decide about a "fair" royalty". The latter is very similar in spirit to the compulsory licensing provisions and provisions that require the patent to be "worked". Both of these provisions have been present in many countries, especially in the past, and require courts to intervene more aggressively than it is probably desirable.[32]

7. The effects of markets for technology

7.1 Division of labor, investment and technology spillovers

Not only does a division of innovative labor promote the development of technologies, but it also enables these technologies to be utilized more effectively. Put differently, markets for technology enhance both the generation and the diffusion of technology. The logic is simple – technology specialists have an incentive to seek out buyers for their services and help them use the technology. In this way, growth impulses can be transferred from the early movers to the late comers. In a seminal paper, Rosenberg (1966) describes how automobile producers benefited from the technologies and tools developed for the bicycle producers in the 19th century. At a later stage, these same machine tool producers also helped develop

[31] However, in order to provide auction participants with an incentive to truthfully reveal their valuations, the government would randomly select a few patents that would be sold to the highest bidder.

[32] "Eminent domain" and "efficient breach" entail very different visions about intellectual property rights. Most likely, they require a "sector by sector" approach which can only be used to a limited extent.

manufacturing industries outside the US. Similarly, the textile machinery suppliers of Manchester promoted the diffusion of textile technology to Japan, India, and China.

The chemical industry provides a more recent example of the same phenomenon whereby the development of an upstream industry of specialized technology suppliers improves access, lowers investment costs, and reduces barriers to entry in the downstream industry, with implied beneficial effects on aggregate investment in the latter.[33] As described earlier, beginning in the 1930s and continuing into the 1960s, the rapid growth of the chemical industry in the developed countries ('first world') stimulated the growth of firms that specialized in the design and engineering of the chemical processes – the SEFs. This also implied that, since the 1970s, as a modern chemical industry emerged in the less developed countries (LDCs), it benefited from the presence of an upstream sector of technology suppliers in the first world. SEFs had already accumulated expertise in plant design and technology, which could be supplied to the chemical firms in LDCs without having to invest again in the fixed costs that were necessary to accumulate this expertise. Simply put, the growth of the chemical industry in the first world created an upstream sector, which later spurred the growth of the chemical industry in the developing countries.

Figure 5 illustrates the two effects that we want to highlight. First, the growth of the first world market for a given chemical process encourages the rise of engineering firms specialized in the design of chemical plants for that process. This only requires that entry as an SEF have a fixed cost (corresponding to the cost of acquiring technical expertise), and that the price-cost margins (profits per unit of output) that SEFs earn, decline with the number of SEFs in that sector.

The second effect is from the SEFs in the first world to the size of the LDC market. To understand this effect suppose that first world SEFs could not supply LDCs. Then, apart from relying on multinationals, LDC firms would have to provide the services themselves or rely on domestic SEFs that may exist. In either case, LDC firms would face very high costs. As a result, fewer investments in chemical plants would be built. Given the high transportation costs for many chemical products, this would imply slower growth of chemicals, and industrial activity more generally in LDCs.

This simple story relies on the assumption that the critical input – technology and engineering expertise -- is easily 'tradable' across countries. It is then important to understand why is this input tradable. Even though an ammonia plant in the US is a different object from an ammonia plant in India, what remains unchanged are the basic principles of how an ammonia plant should be designed and engineered. Clearly, applying what one has learnt in one place in another is not always easy, and the literature has shown that technology transfer is not costless (see Section 2). The important point, however, is that the transfer cost are substantially smaller than the cost of developing the technology, an assumption that fits especially well in the case of engineering services, and more generally in the case of "generic" technologies which can be applied at low additional cost in different locations and contexts. Note that from the point of view of the LDCs, the number of potential suppliers (first world SEFs) is determined by the extent of division of labor in the first world, which occurred prior to the rise of LDC chemical markets. Thus, the organization of the industry in the first world, or to be precise, the extent of division of labor in the first world, enhances the growth of the market (chemical industry) in the LDCs.

Arora, Fosfuri and Gambardella (1998) provide quantitative estimates of the importance of a division of labor in the chemical industry, using data data on nearly 140 of

[33] This section draws heavily upon Arora, Fosfuri and Gambardella (1998).

the leading chemical technologies.[34] The empirical analysis shows that investments in chemical plants in the LDCs are greater, the greater the number of technology suppliers (SEFs) that operate in the first world. Moreover, as predicted by their theoretical model, the effect of SEFs is greater for chemical firms from developing countries rather than for MNCs investing in developing countries.

In more quantitative terms, the results imply that in a typical chemical technology, an additional SEF would imply additional investment of about $5.4 million over the ten year period from 1980-90, with the increases being larger in larger countries like China and India, and smaller in smaller countries (see figure 6). For the LDCs as a whole, the increase in investment would be more than $205 million per process, about 6.5% of the investment per process in developing countries as a whole (which is about $3.3 billion over the ten year period). To get further perspective, note that the average cost of a plant in our data is about $121 million. Thus, for a typical process, two additional SEF would result in about three additional plants in the developing world over a ten year period.

In a somewhat different context, one might have conceptualized the phenomenon discussed in this section as international technology transfer. Undoubtedly, SEFs are important sources of chemical technology, but many large chemical firms also transfer technology overseas. However, as discussed in Section 5 above, chemical producers have to tradeoff the gains from selling technology against the loss in actual or potential revenues from selling the downstream product. On the other hand, SEFs provide technology with few strings attached and will sell their technology and expertise to all. In so doing, they have truly helped create a market for technology, from which many developing countries have benefited. Thus, in addition to the classical gains from productivity improvements, specialization and division of labor can have other benefits for industrial growth that are sometimes overlooked.

7.2 Division of Innovative labor and the locus of inventive activity

Markets for technology also impinge on another important issue – the localization of inventive activities. Although the analysis will be centered on the geographical distribution of these activities, we will see that the term localization can be interpreted broadly, to mean for instance whether inventive activities should be located near the users vis-à-vis the producers, or the organization of innovative activities within multinational enterprises. These issues have ramifications for broader economic questions of regional economic growth and divergence across regions and are widely debated today both in the economic (e.g., Krugman, 1991) and in the management literature (e.g., Porter, 1998).[35]

However, the debate has largely revolved around the trade-off between the advantage of being close to the user, which argues for locally based innovative activity, and the fixed cost aspect of research, which argues for centralized research. The conceptual apparatus developed for analyzing markets for technology, especially the idea of generic, basic knowledge that acts as the foundation for general purpose technologies, helps advance this debate.[36]

[34] Data on chemical plants in LDCs are drawn from our Chemintell (1998) database described in Arora, Fosfuri and Gambardella (1998).

[35] Granovetter (1985) has emphasized the importance of being "embedded" in the local context as a source of competitive advantage for firms. Against this, others have argued that small market size disadvantages regions in a globalizing world because locally based inventive activity will be overwhelmed by the fixed cost advantage enjoyed by firms based in larger regions.

[36] This section draws upon Arora, Gambardella and Rullani (1997).

The starting point of the analysis is a stylized distinction between two modes of producing innovations. The first mode is the one we label "technological integration". In this regime, research and the other activities leading to the development of innovations cannot be separated in space or across organizations. Following the points already made, this is a regime where feed-backs and interactions between various stages of the innovation process require physical proximity (in one interpretation) or being part of the same organization. The second regime, which we label "technological modularity", is one in which the different stages of the innovation process, particularly research and the adaptation of innovations to the users, can be separated. This is typically the case of general-purpose technologies or generic competencies that can be produced in one place and transferred to others at relatively low "transportation" costs.

Which of these two modes will prevail and under what conditions? Put differently, under what conditions are innovations generated more efficiently by firms "embedded" in the contexts where the innovations have to be produced and sold, vis-a-vis firms located in areas that are distant from these contexts? Arora, Gambardella and Rullani (1997) develop a simple model to address this question. In their model, firms incur a fixed research cost and an application development cost that increases with the number of "variants" of the innovation to be produced for each distinct user located in a given market. Among other things, the development costs of the variants depend on "communication" costs with the users, and these are proportional to the number of users with which the firm interacts, i.e. with the size of the local market. Moreover, firms located near users incur a lower unit communication costs because of the natural advantages of physical proximity.

Under a regime of technological integration, firms face the familiar tradeoff. If they locate near the users, they can lower communication costs but other locations may be better for research because of better technological infrastructures or technological spillovers from other firms. If the two activities – research and application development – cannot be separated, smaller markets will probably be served from distant locations as compared to larger markets, where the cost saving from lower communication costs will be greater.

The possibility of separating the production of upstream technological inputs and their downstream adaptation changes the terms of this trade-off. Each activity can in fact be located where there are better economies for their production. The key issue then becomes at what cost can the innovators embedded in local contexts acquire the technologies produced where the (fixed) research costs are smaller. This will depend on the "transportation" costs . Unlike tangible inputs, basic knowledge or technologies, once produced, can be transported at low costs. As long as these transportation costs are small enough, it is always profitable for the local firms to acquire them from "global specialists".

Moreover, as long as local firms can acquire the technologies cheaply from outside, they have an advantage in adapting the innovations to the needs of the local users compared with outside firms. The point is that, under this regime, local markets are not penalized by their size. Thus, while with technological integration no inventive activity will take place in smaller markets, technological modularity implies that smaller markets will host adaptive innovation processes.

In sum, compared with technological integration, technological modularity will lead to greater geographical concentration of the production of generic technologies and knowledge bases in areas that are more efficient at producing them. But this process will also encourage the growth of downstream innovation activities in smaller markets. Thus, greater (international) concentration of upstream technological activities will be paralleled by greater decentralization of activities aimed at adapting these innovations to the final users. With technological integration, technologies that reduce the communication costs from a distance will further concentrate the innovation process in larger markets (because the opportunities of communicating with the users from a distance will be less costly). By contrast, with technological modularity, this will reduce the costs of moving the upstream technologies, and thus reinforce the centralization of upstream technological production, and the decentralization of adaptive innovation processes in local markets.

As far as the geographical distribution of inventive activities is concerned, the analysis has an important normative implication for the growth of local innovation processes. With technological modularity, less developed regions can also be successful innovators provided that they effectively use a market for technology – that is, if they do not attempt to produce locally the full set of technologies that they need, but instead invest in monitoring and acquiring generic technologies from elsewhere. The absence of markets for technology would imply the entire R&D processes would be concentrated in larger or more advanced regions.

The normative implications extend to other contexts as well. In the managerial literature, for instance, Norman and Ramirez (1993) argued that users increasingly "co-produce" their goods and services with the producers by customizing goods to suit their needs. Insofar as this personalization is costly for the buyers, they may well choose to select the solutions provided by the producers. Clearly, in this respect, Norman and Ramirez (1993) have in mind what we have labeled a regime of technological integration. Since users pay a higher fixed cost than specialized producers to develop the innovation in-house, and they cannot spread the fixed cost over a large enough base of uses, they may well choose to use the solutions provided by the producers. This process is likely to involve costly and imperfect communications as users communicate their needs to producers. By contrast, with technological modularity, while the specialized producers incur the fixed costs of producing the generic "modules" or technologies, the users will adapt them to their needs as they will have better information on their special requirements.

The case of software illustrates these issues particularly well. Prior to the development of broad, generic platforms such as Oracle for databases, typically users either developed their own software systems or used very restricted systems available. With the availability of broad platforms, users can now develop highly customized systems suited to their own needs. In so doing, the users minimize their own investments in understanding and developing the platform. Conversely, the users do not need to communicate their requirements to the platform developer.[37] However, as discussed in Section 2 earlier, platform developers, in order to develop truly general purpose software, need to have a comprehensive understanding of the diverse user contexts. Similarly, Advanced RISC Machines, an innovative chip design company, licenses a flexible design and lets its customers enhance them with proprietary extensions according to their needs (Zerego, 1999). Typically such an understanding is built upon abstract models of user behavior in different contexts.

Finally, the presence of markets for technology may also influence industry and product life cycles. For instance, Klepper (1996) provides a simple and persuasive model of industry evolution. In his model, early entrants that succeed in growing can spread the fixed cost of their innovative activity over a greater volume of sales. Consequently, they have a greater incentive to invest in R&D compared with later entrants, which tend to be smaller. This simple model gives rise to dynamics that can closely mimic how product markets such as

[37] It is true, however, the most applications are actually developed by outside consultants for the end users. Oracle and IBM are among the market leaders in providing such consulting services. The essential point remains unchanged.

televisions and tires have evolved. The absence of markets for technology is critical to Klepper's model – if firms can sell their innovation, smaller but more innovative firms may have a greater incentive to invest in R&D. Conversely, other entrants (similar to firms in less developed regions) can exploit other sources of competitive advantage by buying the technology they need.

9. Implications for business and public policy

8.1 Implications for corporate strategy

An obvious implication of the rise of markets for technology is to increase the "penalty" of company strategies based on the notorious "Not-Invented-Here" syndrome. By taking advantage of technology being developed by other companies more efficient at that task, firms can exploit their comparative advantage, providing more value to their customers. All in all, by relying on technology markets, companies can take advantage of the economies that can be generated on an industry- rather than firm-wide scale.

However, we must repeat what has been noted earlier: Outsourcing R&D is different from other types of outsourcing. Indeed, as Arrow (1962) pointed out, in order to buy information, one must already possess a great deal of it. Thus, Cohen and Levinthal (1989) and Rosenberg (1990) have argued that even when relying upon markets for technology, firms need substantial in-house technological capabilities. In turn, such capabilities may require that firms invest in R&D. Therefore, markets for technology are unlikely to imply that firms should scrap their in-house R&D departments. Instead, they are likely to imply that R&D projects and capabilities should be developed so that the firm can effectively acquire technologies from outside, and efficiently use those technologies in ways that leverage its own distinctive capabilities.

The second implication is about corporate diversification. It is well known at least since Nelson's (1959) study, that technology-driven diversification is both the cause and the effect of investments in upstream "basic" research or technologies. Put differently, larger and more diversified firms have greater incentives to invest in "generic" technologies because they can spread the associated fixed cost on a larger number of internal products. (See also Chandler, 1990.) In fact, our analysis suggests that the implicit assumption of this argument is that the intra-organizational transfer of generic technologies and knowledge is markedly more effective than transfer between organizations. Once this limitation is removed, however, and markets for technology develop, diversification based on technological economies of scope becomes less compelling. Instead, diversification is more likely to be based on more idiosyncratic and specific capabilities such as supplier and customer relationships, and knowledge and experience in selling downstream. (See for instance Gambardella and Torrisi, 1998.) More precisely, technology-based diversification makes sense only when the technology in question is proprietary to the firm *and* is best exploited through internal investment rather than through a market for technology.

In other words, when faced with reasonably well developed markets for technology, even large firms may consider licensing their technology to others. As noted earlier, an industry study by the BTG (1998) estimated that US companies hold about 115 billion dollars of technology assets that they do not utilize. These are typically assets developed by their R&D departments which are not used because they do not belong to their core business or simply because these companies do not have enough incentives to develop them in-house to commercialize the products. By selling the available technologies, these companies can increase their returns to R&D, and their overall market evaluation. Even if $115 billion of untapped technology is an overestimate, it does point to the attitude of most established large corporations towards technology: In-house technology is like the crown jewels, and technology offered by outsiders is inferior and treated with suspicion.[38]

The importance of licensing strategies is confirmed by the analytical model of licensing competition discussed earlier (see Section 5). There we showed that leading producers in a market can be induced to sell their technologies if their competitors do so as well, or if upstream technology specialists are active. As a positive statement we maintain that, as licensing strategies become more popular in a given industry, one ought to observe that companies will pay increasing attention to the opportunities that arise from selling their technologies. As a normative statement, we argue that companies should be increasingly attentive to these strategies especially if their competitors intend to license as well, or if specialized technology suppliers enter the market.

Our final issue is about the fragmentation of intellectual property rights, which can pose a challenge to the functioning of a market for technology because of "hold-up" or related problems. As a result, patenting policies can become another critical area for company strategy. In addition, this can be a new important reason for developing technologies in-house. If the rights on a given technology requires the consensus of a large number of patent holders, companies may have to develop the full technology in-house. We believe that this, rather the inability to utilize externally developed technologies, may in some industries be the critical limitation to the growth of a market for technology, and may push companies back towards full in-house integration of technological developments. Industry leaders can play an important role here through institutional mechanisms that ensure that inventors and patent holders, and technology commercializers, both share othe rents and neither acts to block the others. Through industry level discussions, firms holding broad, generic patents can also be persuaded to provide non-exclusive license on reasonable terms. In specific cases, groups of firms can enter into cross-licensing, patent pooling, or other types of arrangements that overcome fragmentation.

8.2 Implications for public policy

In common with any type of vertical disintegration, the presence of independent technology suppliers reduces the barriers to entry, especially for small firms and firms operating in less developed countries. It is these firms that benefit the most from not having to rely on developing technology themselves. In turn, their viability increases competition and variety in the industry. Furthermore, if generic technologies are available through a market, even small firms and firms located in underdeveloped areas can innovate. One can distinguish between two sets of policy measures –measures aimed at creating a division of innovative labor that underpins markets for technology and policy measures aimed at exploiting the advantages of such a division of labor.

We have already discussed the role of intellectual property rights in facilitating contracts for technology. Policy measures aimed at encouraging the formation of a competitive industry of independent technology suppliers may also be important for the growth of markets for technology. These firms tend to license their technologies, and in so

[38] An interview in 1995 with the then CEO of Dow Corporation, Frank Poppof confirms the essential truth of this exaggerated stereotype. He noted that before the late 1980s, one needed written authorization from the highest level in the company's management in order to buy or sell technology. He also agreed that things had changed dramatically and that Dow's investments in R&D were based, in part, on expectations of licensing revenues. Dow's current open attitude towards licensing metallocene (single site) catalysts is consistent with the changed attitude Poppof articulated.

doing, they also encourage downstream producers to license. Policy measures for creating an industry of specialist technology suppliers range from the development of venture capital markets, direct or indirect R&D support to the creation of technology spin-off or start-up companies, and the creation of specialized technology intermediaries that monitor systematically the availability of "orphan technologies" and find potential customers for them.

Strong intellectual property rights also encourage the rise of such firms. Intellectual property rights are of greater "value" to these firms than to large established technology holders. The latter have several means to protect their innovations – for instance through their extensive downstream manufacturing and commercialization assets. (See for instance Merges and Nelson, 1990.) By contrast, independent technology suppliers have fewer opportunities to appropriate their innovations other than legal protections. As a result, these are likely to have greater effects on the ex-ante innovation incentives of the technology specialists vis-à-vis the established producers.

A key issue in the case of intellectual property rights are the legal costs of enforcing them.[39] Recent research supports popular belief that patent battles are very costly (e.g., Lerner, 1995). Thus, small innovative companies that are undercapitalized may become victims of better funded rivals who may lack strong patents but can credibly threaten to costly law suits. A part of the problem is simply that legal costs in the US are high. The other part of the problem is the uncertainty inherent in the way patents are examined and issued. In this respect, the development of alternative institutions for resolving patent related disputes is very important. In other countries, although legal costs may not be high, delays and lack of transparency can prevent the effective enforcement of patents. The increasing globalization also increases the value of greater harmonization of patents.

Policies aimed at strengthening the ability of universities to diffuse their technologies are also likely to have significant benefits, as universities are typical cases of technology suppliers with no downstream assets. This suggests that, among other things, greater support to university research may have the additional advantage of inducing final producers to diffuse their technologies, with the related economic effects on investment, reduction of barriers to entry, and competition discussed above. However, there are a number of issues that arise in the context of greater university involvement in commercial activities. One of the thorniest of these is the deleterious impact upon academic norms within universities, with the erosion of collegiality and open science. As such, a full discussion of these issues is beyond the scope of this paper. See, *inter alia,* David (1992), Dasgupta and David (1994), Cohen and Florida (1999), and Rosenberg (1999) for further discussion.

The other set of policies are those that maximize the realized advantages from markets for technology and the division of innovative labor. Simply put, as markets for technology arise, technology policies should aim not simply at generating new technologies but also at exploiting the use of existing technologies. We saw in Section 7 that a market for technology can enable less developed regions and firms to innovate. But public policy can help by discouraging these firms and regions from "re-inventing the wheel".

Policy measures of this sort would require the creation of stimuli to monitor external (international) technological developments, develop local human capital, and set up local "absorptive" capability for acquiring externally developed technologies. In fact, this may imply that in these areas governments have to support, at least in part, local research of the same type as the one conducted in the leading regions. Absorptive capacity is quite often related to the ability of a given agent, area, or organization to perform research that is similar

---

[39] These costs increase with the degree of fragmentation of property rights. For a full discussion of possible policy interventions in situations of highly fragmented intellectual property rights, we refer to Section 7 above.

to the one that is acquired from the external sources. Nonetheless, it is also natural that the extent of this investment is probably smaller if the objective is to acquire rather than produce. More importantly, policy must guard against a "Not-Invented-Here" syndrome masquerading under the guise of self-reliance, patriotism or anti-imperialism. Dynamic learning considerations may suggest encouraging local inventive activity, perhaps even fundamental research work, in order to build capability so that the country or the region does not remain a follower forever. However, this would suggest focusing and targeting certain areas for fundamental research. Furthermore, a variety of policies and incentives that encourage the discarding of outside technology in favor of indigenously developed technology must be re-evaluated.[40]

Greater support should therefore be given to institutions, organizations and firms for monitoring technological developments outside, and for research that uses the more basic technologies to develop localized applications. Many of these measures have already entered the agenda of policy makers in leading nations. For instance, a good deal of these issues are being discussed by institutions like the European Union (e.g., Lundvall and Borras, 1998), and similarly in the US.

9. Conclusion

Markets for technology have become increasingly important. However, the economic and managerial literatures, which have approached the analysis of these markets from different perspectives, lack a systematic and general view of the issues at stake. This essay has attempted to develop a comprehensive framework for a thorough understanding of how markets for technology work, what limits or gives rise to them, and what are their implications for corporate strategy and economic policy.

[40] Although indigenously developed technologies may be useful for many reasons, not the least because they may serve as exemplars and encourage other local firms and institutions to innovate, in many nations, the development of indigenous technologies has become an end in itself.

References

Acs, Z.J., (ed.), 1996, *Small firms and economic growth,* Volume 2, Elgar Reference Collection, Cheltenham, UK.

Acs, Z.J., and Audretsch, D.B., (eds.), 1993, *Small firms and entrepreneurship: An East-West perspective,* Cambridge, Cambridge University Press.

Aghion, P., and Tirole, J., 1994, "The Management of Innovation", *Quarterly Journal of Economics* 109, 1185-1209.

Anand, B.N., and Khanna, T., 1997, "Intellectual property rights and contract structure", WP 97-016, Harvard Business School.

Arora, A., 1995, "Licensing Tacit Knowledge: Intellectual Property Rights and the Market for Know-How", *Economics of Innovation and New Technology* 4, 41-59.

Arora, A., 1996, "Contracting for Tacit Knowledge: The Provision of Technical Services in Technology Licensing Contracts", *Journal of Development Economics* 50, 1-23.

Arora, A., 1997, "Patent, Licensing and Market Structure in the Chemical Industry", *Research Policy* 26, 391-403.

Arora, A., and Fosfuri, A., 1998a, "Licensing in the chemical industry", paper presented at the conference on "Intellectual Property and Industry Competitive Standards" at Stanford, April 16-17, forthcoming, *Stanford Technology Law Review.*

Arora, A., and Fosfuri, A., 1998b, "Licensing in the presence of competing technologies", WP 98-72, Universidad Carlos III de Madrid, Spain, October.

Arora, A., Fosfuri, A., and Gambardella, A., 1998, "Division of Labor, Market for Technology and Investment", revised version of "Division of Labor and the Transmission of Growth", Stanford Discussion Paper Series, 474, July 1996.

Arora, A., and Gambardella, A., 1990, "Complementarity and External Linkages: The Strategies of the Large Firms in Biotechnology", *Journal of Industrial Economics* 38, 361-379.

Arora, A., and Gambardella, A., 1994, "The changing technology of technological change: General and abstract knowledge and the division of innovative labour", *Research Policy* 23, 523-532.

Arora, A., and Gambardella, A., 1998, "Evolution of Industry Structure in the Chemical Industry", in Arora, A., Landau, R., and Rosenberg, N., (eds.) *Chemicals and Long Term Growth*, John Wiley and Sons, New York.

Arora, A, Gambardella, A., and Rullani, E., 1997, "Division of Labour and the Locus of Inventive Activity", *Journal of Management and Governance* 1, 123-140.

Arrow, K.J., 1962, "Economic Welfare and the Allocation of Resources for Invention", in National Bureau of Economic Research, *The Rate and Direction of Inventive Activity*, Princeton University Press, Princeton NJ.

Arrow K.J., 1983, "Innovation in Large and Small Firms", in Ronen, J., (ed.), *Entrepreneurship*, Lexington Books, Lexington.

Bell, M., and Pavitt, K., 1993, "Technological Accumulation and Industrial Growth: Contrasts Between Developed and Developing Countries", *Industrial and Corporate Change* 2, 157-209.

Blomström, M., and Kokko, A., 1998, "Multinational Corporations and Spillovers", *Journal of Economic Survey.*

Bonaccorsi, A. and Pammoli, F., 1996, "The economics of technical development and the nature of design knowledge", *International Journal of Technology Management.*

Bresnahan, T., and Gambardella, A., 1998, "The Division of Inventive Labor and the Extent of the Market", in Helpman, E., (ed.), *General-Purpose Technologies and Economic Growth*, MIT Press, Cambridge.

Bresnahan, T., and Trajtenberg, M., 1995, "General-Purpose Technologies – Engines of Growth?", *Journal of Econometrics* 65(1), 83-108.

British Technology Group (BTG), 1998, www.btgplc.com.

Caves, R.E., 1996, *Multinational Enterprise and Economic Analysis*, Second Edition, Cambridge, Cambridge University Press.

Chemintell (1998), Reed Elsevier Ltd., London.

Chandler, A., 1990, *Scale and Scope: The Dynamics of Industrial Capitalism,* The Belknap Press of Harvard University Press, Cambridge MA.

Coase, R., 1937, "The Nature of the Firm", *Economica* 4, 386-405.

Cohen, W., and Levinthal, D., 1989 "Innovation and Learning: The Two Faces of R&D", *Economic Journal* 99, 569-596.

Cohen, W., 1995, "Empirical studies of innovative activity" in Stoneman, P., (ed.), *Handbook of the Economics of Innovation and Technological Change*, Oxford, Blackwell Publishers.

Cohen, W., and Florida, R., 1999, *For Knowledge and Profit*, forthcoming, Oxford University Press.

Cohen, W., and Klepper, S., 1996, "Firm Size and the Nature of Innovation within Industries: The Case of Process and Product R&D", *Review of Economics and Statistics* 78(2), 232-243.
Cohen, W., Nelson, R., and Walsh, J., 1997, "Appropriability conditions and why firms patent and why they do not in the U.S. manufacturing sector", Carnegie Mellon University, working paper.
Contractor, F., 1981, *International Technology Transfer*, D C Heath and Company, Lexington.
Dasgupta, P., and David, P., 1994, "Towards a New Economics of Science", *Research Policy* 23, 487-521
David, P.A., 1992, "Intellectual property institutions and the panda's thumb: Patents, copyrights, and trade secrets in economic theory and history", WP 287, CEPR, Stanford, CA.
Dawson, J., Harvey, W., and Henderson, S., 1982, *Contracts – Cases and Comment*, 4th Edition, Foundation Press.
Dunning, J.H., 1981, *International production and the multinational enterprise*, Allen and Unwing, London.
Fosfuri, A., Motta, M., and Ronde, T., 1998, "Foreign Direct Investments and Spillovers through Workers' Mobility", Universitat Pompeu Fabra, WP 248, January.
Freeman, C., 1968, "Chemical Process Plant: Innovation and the World Market", *National Institute Economic Review* 45, 29-51, August.
Frischtak, C., and Rosenberg, N., 1985, *International Technology Transfer: Concepts, Measures, and Comparisons*, Praeger, New York.
Gallini, N.T., 1984, "Deterrence through Market Sharing: A Strategic Incentive for Licensing", *American Economic Review* 74, 931-941.
Gallini, N.T., 1992, "Patent policy and costly imitation", *Rand Journal of Economics* 23(1).
Gallini, N.T., and Wright, B.D., 1990, "Technology Transfer under Asymmetric Information", *Rand Journal of Economics* 21(1), 147-160.
Gambardella, A., and Torrisi, S., 1998, "Does Technological Convergence implies Convergence in Markets ? Evidence from the Electronics Industry", *Research Policy*, forthcoming.
Granovetter, M., 1985, "Economic Action and Social Structure. The Problem of Embeddedness", *American Journal of Sociology* 91(3).
Griliches, Z., 1979, "Issues in Assessing the Contribution of Research and Development to Productivity Growth", *Bell Journal of Economics* 10(1), 92-116.
Griliches, Z., (ed.), 1984, *R&D, Patents, and Productivity*, Chicago, University of Chicago Press.
Griliches, Z., 1990, "Patent statistics as indicators: A survey", *Journal of Economic Literature* 28, 1661-1707.
Grindley, P., and Teece, D., 1997, "Licensing and Cross licensing in Semiconductors and Electronics", *California Management Review*.
Grove, A., 1998a, "Developing a complex : The intricate maze of intellectual property on today's chips is driving vcs nuts", *The Red Herring Magazine*, April, http://www.redherring.com/mag/issue53/whispers.html.
Grove, A., 1998b, "Safeguarding Intellectual Property", *The Red Herring Magazine*, May, http://www.redherring.com/mag/issue54/safe.html.
Grove, A., 1998c, "Better living through chemistry", *The Red Herring Magazine*, May. http://www.redherring.com/mag/issue54/whispers.html.
Hart, O., and Moore, J., 1988, "Incomplete contracts and renegotiation", *Econometrica* 56(4), 755-785.
Hadley, W., 1998, *Repporteur's report*, Conference on Intellectual Property Rights and Competition Policy, mimeo, Stanford Law School, Stanford, April.
Heller, M., 1998, "The Tragedy of the Anticommons: Property in the Transition from Marx to Markets", *Harvard Law Review* 111, 621-688.
Heller, M., and Eisenberg, R., 1998, "Can Patents Deter Innovation? The Anticommons in Biomedical Research", *Science* 28, May 1st, 698-701.
Henderson, W.O., 1965, *Britain and Industrial Europe 1750-1870: Studies in British Influence on the Industrial Revolution in Western Europe*, Leicester University Press, Leicester.
Iansiti, M., 1995, "Technology Integration: Managing Technological Evolution in a Complex Environment", *Research Policy* 24, 521-42.
Jaffe, A., 1986, "Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits and Market Value", *American Economic Review* 76(5), 984-1001.
Jeremy, D.J., 1981, *Transatlantic Industrial Revolution: The Diffusion of Textile Technologies Between Britain and America, 1790-18*30s, Basil Blackwell, Oxford.
Katz, R., and Allen, T.J., 1982, "Investigating the Not-Invented-Here (NIH) Syndrome: A Look at the Performance, Tenure, and Communications Patterns of 50 R&D Project Groups", *R&D Management* 12(1), 7-19.
Katz, M., and Shapiro, C., 1985, "On the Licensing of Innovations", *Rand Journal of Economics* 16, 504-520.

Klepper, S., 1996, "Entry, Exit and Innovation over the Product Life Cycle", *American Economic Review* 86(3), 562-583.
Kremer, M., 1998, "Patent buyouts: A mechanism for encouraging innovation", *Quarterly Journal of Economics* 113, 1137-1167.
Krugman, P., 1991, *Geography and trade*, Cambridge, Mass., MIT Press.
Lall, S., 1980, "Developing Countries as Exporters of Industrial Technology", *Research Policy* 9, 24-51.
Lamoreaux, N., and Sokoloff, K., 1997, "Location and Technological Change in the American Glass Industry during the Late Nineteenth and Early Twentieth Centuries", NBER WP 5938, NBER, Cambridge MA.
Lamoreaux, N., and Sokoloff, K., 1998, "Inventors, Firms, and the Market for Technology: US Manufacturing in the Late Nineteenth and Early Twentieth Centuries", in Lamoreaux, N., Raff, D., and Temin, P., (eds.), *Learning by Firms, Organizations, and Nations*, forthcoming.
Landes, D.S., 1969, *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present*, Cambridge University Press, Cambridge.
Landau, R., 1998, "The Process of Innovation", in Arora, A., Landau, R., and Rosenberg, N., (eds.), *Chemicals and Long Term Growth*, John Wiley and Sons, New York.
Landau, R., and Rosenberg, N., 1992, "Successful Commercialization in the Chemical Process Industries", in Landau, R., Mowery, D., and Rosenberg, N., (eds.), *Technology and the Wealth of Nations*, Stanford University Press, Stanford, CA.
Langlois, R.N., 1992, "External Economies and Economic Progress: The Case of the Microcomputer Industry", *Business History Review* 66, Spring, 1-50.
Langlois, R.N., and Robertson, P.L., 1992, "Networks and Innovation in a Modular System: Lessons from the Microcomputer and Stereo Component Industries", *Research Policy* 21, 297-313.
Leland, H. E., and Pyle, D. H., 1977, "Informational Asymmetries, Financial Structure, and Financial Intermediation", *Journal of Finance* 33, 371-87.
Lerner, J., 1995, "Venture Capitalists and the oversight of Private Firms", *Journal of Finance* 51, 301-318.
Lerner, J., and Merges, R., 1998, "Control of Technology Alliances in Biotechnology", *Journal of Industrial Economics* 46(2), 125-156.
Lundvall, B.A., and Borras, S., 1998, "Innovation Policy in the Globalising Learning Economy", European Union, DG XII, Bruselles.
Markusen, J., 1995, "The Boundaries of Multinational Enterprises and the Theory of International Trade", *Journal of Economic Perspective* 9(2), 169-189.
Merges, R., 1998, "Intellectual Property Rights, Input Markets, and the Value of Intangible Assets", mimeo, UC Berkeley School of Law, CA.
Merges, R., and Nelson, R.R., 1990, "On the Complex Economics of Patent Scope", *Columbia Law Review* 90(4), 839-916.
Mowery, D., 1983, "The Relationship between Intrafirm and Contractual Forms of Industrial Research in American Manufacturing, 1900-1940", *Explorations in Economic History* 20, 351-374
Mowery, D., and Rosenberg, N., 1989, *Technology and the Pursuit of Economic Growth*, Cambridge University Press, Cambridge.
Nelson, R.R., 1959, "The Simple Economics of Basic Scientific Research", *Journal of Political Economy* 67(2), 297-306.
Nelson, R.R., Peck, M.J., and Kalachek, E.D., 1967, *Technology, Economic Growth and Public Policy*, Brookings Institution, Washington DC.
Norman, R., and Ramirez, R., 1993, "From Value Chain to Value Constellation: Designing Interactive Strategies", *Harvard Business Review*, July-August, 65-77.
Pisano, 1990, "The R&D boundaries of the firm: An empirical analysis", *Administrative Science Quarterly* 35, 153-176
Polanyi, M., 1966, *The Tacit Dimension*, Anchor Day.
Porter, 1998, "Clusters and the New Economics of Competition," *Harvard Business Review*, Nov-Dec, 77-90.
Powell, W. W. and Brantley, P, 1992, "Competitive cooperation in biotechnology", in Nohria, N., and Eccles., R., (eds.), *Networks and Organizations*, Boston, Harvard Business School Press.
Rosenberg, N., 1976, "Technological change in the machine tool industry, 1840-1910", in Rosenberg, N., *Perspectives on Technology*, Cambridge University Press, Cambridge UK.
Rosenberg, N., 1990, "Why Do Firms Do Basic Research?", *Research Policy* 19, 165-174.
Rosenberg, N., 1998, "Technological Change in Chemicals: The Role of University-Industry Relations", in Arora, A., Landau, R., and Rosenberg, N., (eds.), *Chemicals and Long-Term Economic Growth*, John Wiley & Sons, New York.
Rosenberg, N., 1999, "Universities as Economic Institutions", unpublished draft, Stanford, CA.

Scherer, F.M., 1980, *Industrial Market Structure and Economic Performance*, 2nd edition, Rand McNally, Chicago.

Securities Data Company (SDC), Newark NJ, USA

Shepard, A., 1987, "Licensing to Enhance the Demand for New Technology", *Rand Journal of Economics* 18, 360-368.

Simon, H., 1959, "Theories of Decision Making in Economics", *American Economic Review* 49, 253-283.

Smith, A., 1776, *The Wealth of Nations*, Penguin Papers, Harmondsworth, UK, 1983 edition.

Stigler, G., 1951, "The division of labor is limited by the extent of the market", *Journal of Political Economy* 59(3), June.

Teece, D.J., 1986, "Profiting from Technological Innovation", *Research Policy*, December.

Teece, D., 1988, "Technological Change and the Nature of the Firm", in Dosi, G., et al., (eds.), *Technological Change and Economic Theory*, Francis Printer, London.

Teece, D., 1992, "Foreign Investment and Technological Development in Silicon Valley", *California Management Review*, 88-106.

Vaitsos, C., 1993, "The process of commercialization of technology in the Andean Pact", in Chen, E.K.J., (ed.), *Transnational Corporations and Technology Transfer to Developing Countries*, Routledge, New York, 197-228.

Vishwasrao, S., 1994, "Intellectual property rights and the mode of technology transfer", *Journal of Development Economics* 44, 381-402.

von Hippel, E., 1988, *The Sources of Innovation*, Oxford University Press, New York.

von Hippel, E., 1990, "Task Partitioning: An Innovation Process Variable", *Research Policy* 19, 407-418.

von Hippel, E., 1994, " 'Sticky Information' and the Locus of Problem Solving: Implications for Innovation", *Management Science* 40(4), 429-439.

von Hippel, E., 1998, "Economics of Product Development by Users: The Impact of 'Sticky' Local Information, *Management Science* 44 (5), 629-643.

Williamson, O., 1975, *Markets and Hierarchies: Analysis and Antitrust Implications*, Free Press, New York.

Wright, D.J., 1993, "International technology transfer with an information asymmetry and endogenous research and development", *Journal of International Economics* 35, 47-67.

Young, A., 1929, "Increasing Returns and Economic Progress", *Economic Journal* 38, 539, December.

Zucker, L., Darby, M., and Armstrong, J., 1998, "Geographically localized knowledge: Spillovers or markets?", *Economic Inquiry* 36, January, 65-86.

Zeckhauser, R., 1996 "The challenge of contracting for technological information", Proceedings for the National Academy of Science, USA 93, 12743-12748.

Zerego, B., 1999, *The Red Herring*, February, page 54.

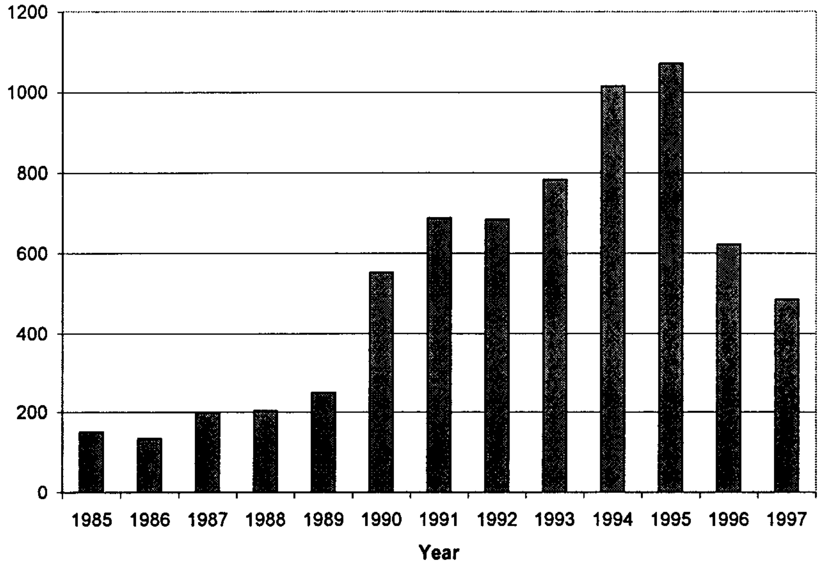
Table 1: *Number and value of technology transactions, by sector of origin of technology, all countries, 1985-97*

	Number	Value ($ million)
Chemicals & Allied Products	1615	34832
Business Services (Software)	1427	42299
Electronic & Other Electric Equipment	1089	60318
Industrial Machinery And Equipment	899	17115
Engineering & Management Services	754	21080
Instruments And Related Products	504	11745
Health Services	254	4071
Wholesale Trade—Durable Goods	122	1220
Transportation Equipment	116	1044
Communication	100	9450
Educational Services	82	5344
Rest	889	4445
TOTAL	7836	212962

Source: Our calculations from the SDC Joint Venture database

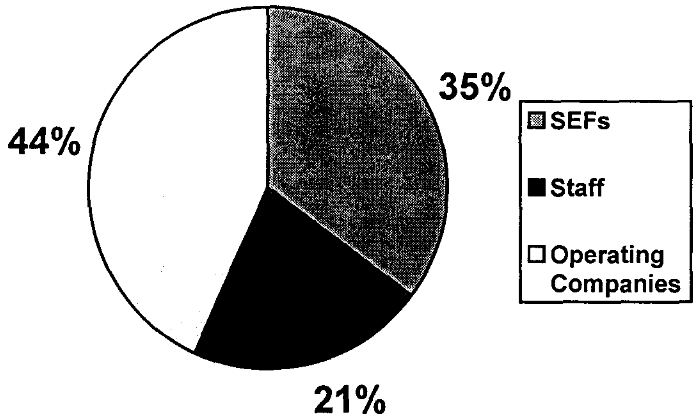
Methodological Note: The figures are calculating by weighting the number of transactions by the average value of transactions for that sector. The value of the transaction consists of the licensing and royalty payments, equity purchase in technology source and R&D funding to technology source. Each transaction was verified to ensure that it involved a transfer of technology. The firm(s) granting the technology were coded separately from the firm(s) receiving the technology. In case of a cross-licensing agreement, the value was split equally between the firms. The averages are taken for all sectors for which four or more observations are available for licensing and royalty payments, and equity purchase and R&D funding. For the remaining sectors, we used the median of the transaction value, $5 million.

Figure 1: *Number of Technology Transactions by Year, 1985-97*



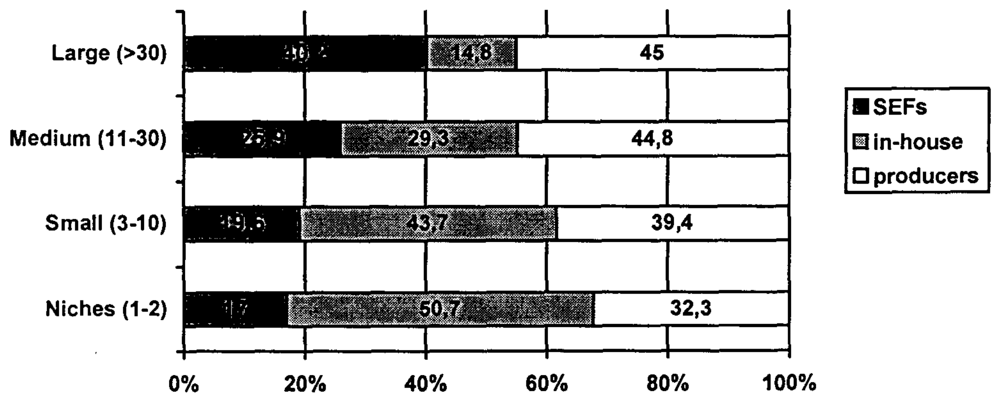
Source: Our calculations from the SDC Joint Venture database

Figure 2: *Share of chemical process technology licenses, 1980-90*



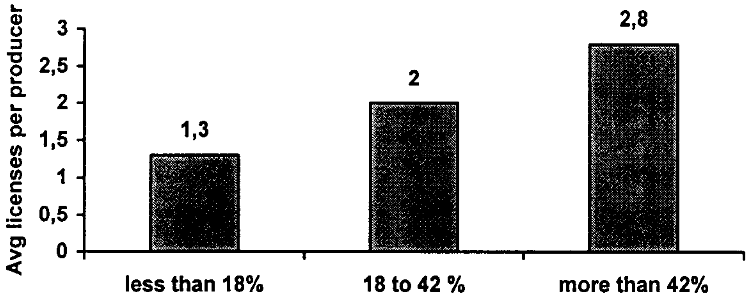
Source: Arora and Fosfuri (1998a)

Figure 3: *Share of SEFs Licensing by Market Size*
(measure by number of plants in 1980-1990)



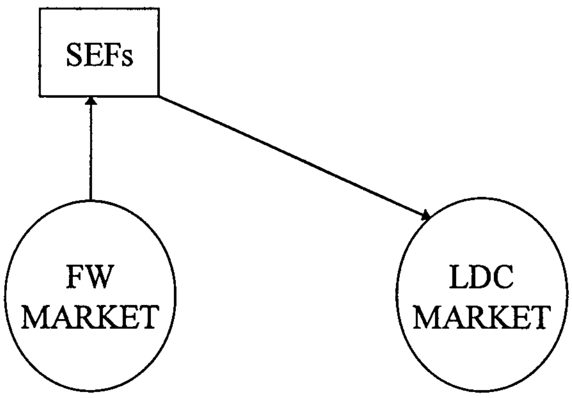
Source: Arora and Fosfuri (1998a)

Figure 4: Market *share of SEFs and propensity to license by chemical producers*



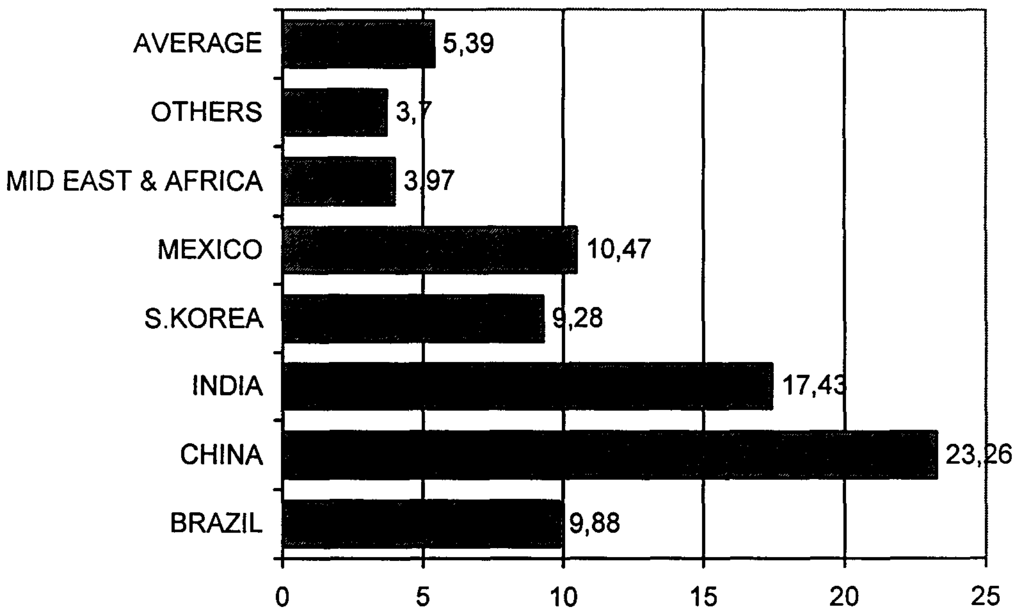
Source: Arora and Fosfuri (1998a)

Figure 5: *The transmission of growth impulses*



Source: Arora, Fosfuri and Gambardella (1998)

Figure 6: *Impact of an additional SEF:*
Additional investment per process, by country, in millions of US dollars



Source: Arora, Fosfuri and Gambardella (1998)