Licensing in the chemical industry

by
Ashish Arora
Carnegie Mellon University, Pittsburgh

and
Andrea Fosfuri
Universitat Pompeu Fabra, Barcelona, Spain

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1. INTRODUCTION

A patent confers on the patentee the right to exclude others from the use of the knowledge that the patent covers. Patents, however, are not the only feasible way to reach exclusiveness and other economic means might be used as well. Indeed, the alternatives are often thought to be more effective at enabling the inventor to benefit from the innovation than patenting itself (Levin et al., 1987; Cohen et al., 1996). The instrument of exclusion is, however, not a matter of indifference for society. The way in which patents are used (or not used) affects the evolution of the industrial structure and the technology itself. Specifically, unlike such alternatives as lead time, first mover advantage and secrecy, patents can be used to sell technology, typically through license contracts. Simply put, patents can play a key role in facilitating the purchase and sale of technology.

This essay moves beyond the traditional approach to patents that has mainly focused on patents as means to exclude others and highlights the role of the market for technology. A market for technology not only helps diffuse existing technology more efficiently, it also enables firms to specialize in the generation of new technology. In turn, such specialization is likely to hasten the pace of technological change itself. However, the development of a market for technology is not an automatic outcome, and depends upon a number of factors that include the strength of patent rights, as well as the nature of the technology and the industry structure itself.

The chemical industry provides a natural framework within which to explore these themes. It is a technology-based industry with a long history of patenting. Further, as we show in this essay, transactions in technology have become widespread, and have increased in frequency and importance over the last couple of decades. In developing our argument we will both draw upon the rich historical context offered by the industry and on our analysis of a large data set on investment and licensing in chemical plants during the 1980s.

The remainder of this essay is organized as follows. The next section presents the theoretical underpinnings upon which we draw in the discussion of the historical facts. In section 3 we show how, in the past, chemical firms have used patents as one of the ways of excluding competitors and creating monopolies. But as section 4 argues, patents have also facilitated the entry of new firms and a progressive division of labor. These changes are reflected in the widespread licensing of chemical process technologies. Furthermore, these changes have profoundly influenced how even large chemical producers appropriate rents from their innovations. Section 5 presents evidence on the patterns of transactions in the market for technology during the 1980s. Section 6 discusses the specific features of the chemical industry that have favored the creation of a market for technology. Section 7 summarizes and concludes the discussion.

2. PATENTS, INNOVATION, AND DIFFUSION: THEORETICAL PERSPECTIVES

Much of the early economics literature on patents focused upon the trade-off between the social inefficiency due to monopoly and the social benefits from the innovation. The major policy question related to the optimum length (and later, length and breadth) of the temporary monopoly to be granted (see for instance Gilbert and Shapiro, 1990, and Klemperer, 1990). Implicitly, a one-to-one relationship was assumed between a patent and an innovation. Although analytically convenient, this assumption obscured the point that in technologies that are cumulative or systemic, an innovation may require many different pieces of knowledge, some of which may be patented and owned by people with conflicting interests. As Paul David

(1993) has noted, knowledge is different from the prototypical public goods such as lighthouses and airport beacons. One important point of differentiation is that the acquisition of knowledge is cumulative and inter-active: knowledge itself is an important input into the production of knowledge.

With cumulative and systemic technologies, an agent holding a patent on an important component may cause severe "holdup" problems, retarding the development of the technology. (See also Scotchmer, 1991, and Green and Scotchmer, 1993, for further discussion.) In a similar vein, Merges and Nelson (1990, 1993) argue that broad patents increase the likelihood that an innovator would try to control future innovations based upon its own innovation, thereby slowing down the pace of technological progress.[1] The Merges and Nelson argument is based on the assumption that technological development tends to proceed more vigorously and creatively under a regime where there are many rival sources of invention, than in a setting where one or a few organizations control developments.

However, the essential problem is not caused by patents, but by factors (such as negotiation costs) that prevent agents from entering into contracts for the use of patents. Thus the issue at stake is the impact that better defined patent rights would have on transaction costs. In a more recent paper, Merges (1998) uses the incomplete contracting approach (Grossman and Hart, 1986; Hart and Moore, 1990) to argue that well defined patents reduce transaction costs, and thereby help increase transactions in technology. As the examples of technology

[1] In a recent paper, Matutes et al. (1996) study how the patent protection regime might affect the pattern of development of subsequent innovations based on significant breakthroughs. They argue that, in the absence of patent protection, an innovator who has made a significant breakthrough would be tempted to get a head start in developing the applications of the new discovery before commercializing any product. Such delay is socially undesirable. They show that the scope of the patent (breadth) is the dimension that should be used to induce early disclosure of fundamental innovations while still preserving firms' incentive to do R&D.

sharing agreements in the chemical industry, discussed below, show, patents play an important role in structuring complex contracts involving the exchange of technology between large firms.[2]

Efficient contracting for technology is particularly important because innovations may systematically originate in firms that will not develop and utilize the knowledge themselves. Rather, a division of labor in innovative activity can exist, whereby innovations are transferred to other firms that develop and commercialize them further (Arora and Gambardella, 1994). Patents can play an important role in determining the efficiency of knowledge flows, which are critical to any knowledge-based division of labor. This aspect of the role of patents has not been given adequate attention in the literature, which has mainly focused on patents as means of exclusion.

This neglect of the possibility of sale of technology is rooted partly in the well-known fact that licensing contracts in the past have tended to be imperfect. As a result, innovators have been unable to appropriate a substantial share of the rents from the innovation. Arrow (1962: 355) notes that:

> "Patent royalties are generally so low that the profits from exploiting one's own invention are not appreciably greater than those derived from the use of others' knowledge. It really calls for some explanation why the firm that has developed the knowledge cannot demand a greater share of the resulting profits."

Bounded rationality is undoubtedly an important part of the reason why licensing is sometimes not an efficient way to appropriate rents from innovation. Another reason may have to do with the tacit component of technology. Economic models of innovation have implicitly

[2] This is not specific to the chemical industry. Grindley and Teece (1995) report that, in cross-licensing agreements in electronics and semiconductors, the quality and the market coverage of the patent portfolios of each party is used in the calculation of balancing royalty payments.

assumed that all useful technological knowledge, once produced is costlessly transmittable. In the vast majority of cases, this is simply untrue. In practice, much of the useful knowledge is not codified in the form of patents and blueprints.[3] Often, the innovator has some discretion in how she codifies, stores, and organizes this information. Strong patent protection provides incentives to codify new knowledge in ways that are meaningful and useful to others. Moreover, to the extent that the tacitness of know-how raises problems for the efficiency of contracts for knowledge, patent protection also directly affects the efficiency of the contracting process itself (Arora, 1995).

3. PATENTS AND OTHER RENT APPROPRIATION MECHANISMS IN THE DYESTUFFS SECTOR[4]

The way in which patents have been used in the chemical industry has evolved over time. Patents played an important role in the development of organic dyestuffs, the first major product area of the modern organic chemical industry, in the mid 19^{th} century. Marsh (1994) has argued that serious research in German chemical firms started with the passage of the German Patent Law in 1877, because the new law prevented companies from simply copying new chemical processes, as they had done earlier.[5] However, cause and effect are difficult to separate because this was also the period when significant advances in the scientific understanding of synthetic dyes were recorded. As some scholars have argued, patent law may itself respond to changing social needs (e.g. Merges, 1998). Thus it may well be that German companies and the German patent law were both responding to the possibilities for commercial

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[3] Over two thirds of the British firms interviewed by Taylor and Silberston (1973) said that know-how transfer was the main (or one of the main motives) behind their patent licensing agreements.

[4] This section draws heavily on Arora (1997).

[5] For instance, Spitz (1988: 19) cites the 1877 case of a BASF patent on a dye called methylene blue, discovered by Heinrich Caro. Hoechst challenged the patent claiming prior art. BASF hired August Kekule, the discoverer of the ring structure of benzene to (successfully) defend its claim.

application opened up by scientific advances. German companies were quick to grasp the potential that the patent system provided for systematically excluding competitors, both at home and abroad.[6]

Interestingly enough, they used patents in conjunction with other methods. For instance, Hounshell and Smith (1988: 89-90) describe how German companies skillfully combined patents and secrecy to keep potential imitators at bay in dyestuffs. The dyestuffs would be composed of a number of different compounds, the precise composition kept secret, but the individual compounds protected by patents. In other instances, dyes patents described the results of a certain process. To minimize the information disclosed, German firms also issued misleading "evasion" patents. In other cases, entire groups of compounds would be patented, with only a fraction having properties similar to the dye of interest, so that a rival would have to undertake elaborate and costly experimentation to discover the actual composition of the dyestuff placed on the market. The net effect was that competitors found it very difficult establish a clear relationship between dyestuff patents and the dyestuffs sold on the markets. These so called "unclassified" dyes commanded significant price premia, often selling for 40-50% over the standard colors whose composition was known.

This combination of secrecy and patent protection was probably a response to two factors. First, early German law provided for process patents but not for product patents. Second, some aspects of the process were difficult to codify and protect as patents. Thus,

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[6] Liebenau (1992: 65) states that "In outline, the strategy involved patenting as many potentially interesting products of industrial R&D as possible. ... Patents were taken out to build walls around whole research areas. ... This strategy was certainly recognized by the three leading German firms by the end of the 19th century. From that time, the big three, Bayer, BASF, and Hoechst owned between them 66% of all German held US chemical patents." This strategy was continued by IG Farben. In 1936, IG Farben held 4,000 patents in the US, and was receiving new ones at the rate of about 300 per year (Smith, 1992: 147).

not only was the composition kept secret, other characteristics of the dyestuff critical to its performance, such as the way in which the elements were ground and mixed, were often not codified. This tacit know-how was part of the knowledge based capabilities of the German chemical companies. The importance of know-how is amply illustrated by the difficulty that Du Pont and other US chemical firms faced in entering the dyestuffs industry during WWI and afterwards, despite the confiscation of German patents. Indeed, Du Pont even had to entice away several German and Swiss chemists (in clear violation of trade secrecy laws).[7]

4. THE EARLY BEGINNING OF A MARKET FOR TECHNOLOGY: PATENTS FOR STRUCTURING TECHNOLOGY-SHARING ARRANGEMENTS

The history of the chemical industry also shows how patents can be used to structure technology sharing cartels. The pre-WWII international chemical market has been characterized by many as a sort of a "gentlemen's club" (*e.g.* Spitz, 1988; Smith, 1992). These cartels used a number of instruments, including patent licensing agreements, to maintain market shares and deter entry.[8] The consensus appears to be that cartels such as the dynamite cartel and the alkali cartel did succeed in keeping price above competitive levels by restricting entry, rationing capacity and moderating technological change (see Reader, 1970: 486-9).

Some cartels were organized around a common technology, and were often initiated by the patent holder. The patent would be licensed, often in return for an equity stake, with technology flow-back agreements. For instance, the Solvay process licensees were required to

[7] Another well-known example concerns the Haber-Bosch process. The Japanese government during WWI confiscated the patents for this process. Patents alone proved insufficient for the commercial application of the technology. After the war, some leading Japanese firms tried to approach BASF for purchasing know-how, but without success (Kudo, 1993).

[8] Specifically, even if collusion in the product market is prohibited, firms might design a cross licensing agreement which sets royalties in a way such that the resultant non-cooperative oligopolistic game yields

share all improvements with the Solvay company, and the latter would share it with other licensees. To the extent that there were benefits to all licensees from having the Solvay process become the standard process for the production of alkali, such technology sharing cartels were mutually beneficial. In other cases, particularly during the 1920s and 1930s, there were some prominent technology and market sharing agreements, with the agreement Standard and IG Farben that involved technology sharing in butyl rubber, TEL and arc acetylene (from Standard), and Buna S (from IG Farben) being one of the best known examples.

Though anti-competitive in intent, these arrangements did economize on scarce assets. For instance, although ICI obtained the basic patent on polyester, Du Pont had developed significant expertise in the production process based on its experience in nylon, and controlled the melt-spinning process that was crucial for successful commercialization. ICI and Du Pont had a long standing agreement that involved technology licensing as well as the extensive sharing of information and know-how. As a result, the two companies quickly settled on a suitable cross-licensing agreement.

One may be tempted to conclude that the effect of an *ex-ante* research agreement would be to reduce the incentives of the participating firms to do research. The historical evidence suggests a more nuance picture. For instance, the agreement between ICI and Du Pont was not a mere patent pooling agreement but also had provisions for compensation for the technology that was transferred. This implied that even when one company had control over the basic patents, both companies would have incentives to carry out further research in improving and developing complementary innovations. This implication is borne out by the

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equilibrium profits identical to the cooperative outcome (see for instance Fershtman and Kamien, 1992).

available historical evidence, which suggests that both firms invested heavily in research in order to better their bargaining positions.[9]

5. LICENSING AND MARKET STRUCTURE: SPECIALIZED ENGINEERING FIRMS AND DIVISION OF LABOR

The post WWII period illustrates the deep ramifications for technology and market structure when firms use licensing to profit from innovation. The use of licensing has been most marked in processing technology for petrochemicals. These developments, in turn, are linked to the tremendous growth in the use of petrochemicals derived from oil and natural gas as feedstocks for much of the chemical industry.[10] There were two important implications of the growth of petrochemicals. First, many oil companies became important players in the petrochemical market. Second, a class of specialized process design and engineering firms came to play a major role in the creation and improvement of new process technologies and process know-how.

Oil companies had long paid attention to improving their processes. Some oil firms, such as Standard Oil of New Jersey, and Shell had developed an interest in chemical processes fairly early, in the 1920s, partly stimulated by the coal-hydrogenation technology of IG Farben (which produced gasoline). The interest of oil companies was also stimulated by the possibility of using refinery byproducts or natural gas to produce useful chemicals. Oil companies were more open about their technical operations, in contrast to chemical firms. Indeed, from very

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[9] ICI also licensed Du Pont to produce polyethylene, on which ICI had obtained a basic, "composition of matter" patent. Prior to the license, as a part of the general long terms agreement, both companies shared information on the area. Taylor and Sudnik (1984) quote an ICI manager as claiming that Du Pont deliberately carried out research in polyethylene process technology to gain better terms for licensing. (See also Ordover, 1991, for a more detailed analysis of cross-licensing and *ex-ante* agreements between rivals to cross-license.)

[10] Prior to the 1940s, most of the feedstocks were based upon coal based aromatics, from steam reforming of coal (as in ammonia) or from coke-oven gasses from steel works. Oil based feedstocks were the by-products of oil

early in this century, the oil firms used specialized sub-contractors in various capacities: to procure or manufacture equipment such as pumps and compressors, valves, and heat exchangers, and to provide specialized sub-systems such as piping and the electrical systems. As these specialized engineering-construction firms (henceforth SEFs) grew in their ability to handle more sophisticated tasks, process design became a part of their activities as well. By the 1960s, SEFs dominated the design and construction of new plants and were important sources of process innovation (Freeman, 1968: 30; Mansfield et al., 1977).[11]

The importance of the SEFs lies not only in the fact that they were sources of innovations but also in how they appropriated the rents from innovation. Lacking the downstream assets required to commercialize their innovations themselves, SEFs used licensing as the principal way of profiting from their innovations. Freeman (1968) showed that for the period 1960-66, SEFs as a group accounted for about 30% of all licenses. During the 1980s the importance of SEFs as a source of technology for chemical producers has increased somewhat. Figure 1 shows that in the last decade SEFs supplied the technology for more the one third of plant investments in the world as a whole.[12] Notice that almost 80% of

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refining.

[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. See also last column of table 2.

[12] All figures reported in this essay refer to our calculations of Chemical Age Project File, a comprehensive data set on investments in chemical plants worldwide during the 1980s, compiled by Pergamon Press, London. For a description of the data set and a list of the reported variables, see Arora et al. (1998).

technologies were purchased from firms not linked through ownership ties, either from SEFs or from other operating companies.[13]

SEFs originated as an American phenomenon. During the 1950s and the 1960s US SEFs made inroads into Europe and Japan. Soon, however, Europe and Japan developed their own SEFs, and some of these companies became major competitors of the US SEFs. Table 1 shows that in the 1980s, US SEFs still appeared to have a competitive edge over their European and Japanese rivals (accounting for about half of the total number of licenses sold by SEFs), with a substantial portion of their licenses sold in the First World.[14] German SEFs accounted for around a quarter of all technologies supplied by SEFs. Table 2 lists the 15 SEFs that have been more active in licensing their technologies in the last decade. Notice that some of these firms were mainly supplying their services to third world markets (for instance third world markets accounted for more than 80% of the activity of Karl Fischer and Zimmer). This underlines the role played by SEFs in the worldwide diffusion of chemical technologies, a point to which we shall return.

5.1 SEFs and Market Structure

The creation of an upstream sector specialized in the production of the technology had profound implications for the industrial structure. The availability of process technologies and engineering know-how greatly enhanced the entry into the industry. Spitz (1988: 313) notes

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[13] Our data set contains information about the licensor in only 44% of the cases. We have mainly focused our analysis on the available information. If missing information on licensors is assumed to indicate use of in-house technology, SEFs as a group would account for about 15% of all plants, but still for about 45% of all technologies purchased from unaffiliated firms.

[14] Here and in the following tables, we use "First World" to refer to USA, Canada, Japan and all Western European countries. All the remaining countries are included in the "Third World" group.

that in most major products, the number of producers was between five and fifteen. By contrast, in the pre-WWII era, it was unusual to have more than three producers.

There also exists more indirect support for the idea that the SEFs were major suppliers of technology and know-how to new entrants. In a study of 39 commodity chemicals in the US in a period from the mid '50s to the mid '70s, Lieberman (1989) found that controlling for demand conditions, experience accumulated by incumbents did not act to deter new entry. Given the importance of learning by doing, this suggests that entrants had access to other sources of know-how, most likely from SEFs. This interpretation is further supported by Lieberman's findings that entry into concentrated markets, which were also characterized by low rates of patenting by non-producers (both foreign firms and SEFs), usually required that the entrant had developed its own technology. By contrast, less concentrated markets were associated with high rates of patenting by non-producers and high rates of licensing to entrants. In a related study (of a subset of 24 chemicals) Lieberman (1987) found that high rates of patenting by non-producers were also associated with faster rates of decline in prices.

5.2 Licensing by SEFs

Our data indicate that, in the 1980s, SEFs were more important sources of technology for firms that lacked the technological capability to develop the technology in-house, namely small chemical companies and third world firms. For instance, large chemical companies (those investing in 30 plants or more during the 1980s) purchased around 30% of their technologies from SEFs. For smaller firms (fewer than 30 plants) this percentage was around 40%. From a different perspective, SEFs directed about 60% of their activity to small firms which accounted for half of total investment (as measured by the number of plants), suggesting a small bias towards small firms in SEF licensing.

A Smithian perspective suggests that SEFs should be more active in larger markets (e.g., Stigler, 1951). Figure 2 supports this notion. It shows that SEFs accounted for a larger share of total licensing in larger product markets. Furthermore, although not evident from the figure, larger markets also tend to have a larger fraction of the total investment from small firms.[15] In other words, the evidence is consistent with the notion that SEFs encourage investment, particularly by small firms, and in turn, small firms encourage SEF activity. Table 3 provides further evidence consistent with this idea. It shows that SEFs were more likely to supply technology to third world chemical firms rather than to chemical firms from advanced countries, and of the latter, SEFs are more likely to supply technologies to smaller firms.

Indeed, SEFs led the diffusion and spread of modern technology, first to Europe, and then world wide, to Asia, East Europe, Latin America, and the Middle East, making chemicals a truly global industry. In Arora, Fosfuri and Gambardella (1998) we focus on the benefits that the creation of an upstream sector in the first world had on the growth of the chemical industry in the third world. We estimate that an additional SEF in a typical process technology would generate an increase in investment in the third world as a whole of more than $200 million per process, with the benefits being larger for larger countries like India and China and for more mature technologies.

In the aggregate, technology licensing is most common in sectors with large scale production facilities, with relatively homogenous products, and with a large number of new plants. It is less common in sectors marked by product differentiation, custom tailoring of products for customers, and small scales of production. Our data for the period 1980-90

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[15] Using our data set we found that the market share of big chemical companies (i.e. all firms with a turnover of more than $1 billion in the year 1988) is less than 28% in 'large' product markets (more than 30 plants), whereas it is about 45% in 'niche' product markets (1-2 plants).

indicate that the percentage of plants which involve an explicit reported licensing transaction varies from about 60% for petrochemicals to about 15% for pharmaceuticals (see table 4). Of these reported licensing arrangements, a little less than 80% involve sales of technology between firms that are not linked through ownership ties (see also figure 1), with significant variations across different sub-sectors (from less than 10% in Paper, Gas Handling, Fertilizers, Industrial Gasses and Organic Refining to more than 50% in Agricultural Products, Engineering Materials and Pharmaceuticals). A little less than 45 % of all purchased technology (i.e. technologies coming from unaffiliated sources) are supplied by SEFs. But the role of SEFs varies dramatically across different sub-sectors. For instance, in Pharmaceuticals, Plastics, and Agricultural Products, SEFs account for less than 10% of all technologies from unaffiliated firms, compared to 60% in sub-sectors like Fertilizers, and Textile and Fibers.

5.3 Licensing by Chemical Firms

The licensing activities of the SEFs have had a major effect on the rent appropriation strategies of the other players in the market as well. In marked departure from their pre WWII strategy of closely holding onto their technology, a number of chemical and oil companies began to use licensing as an important (although not the only) means of profiting from innovation.[16] Licensing by chemical producers is now a significant share of all licensing in the industry. As figure 1 shows, although SEFs play a major role as licensors, at least half of the licenses sold to unaffiliated firms are by other chemical producers themselves.

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[16] Landau (1966: 4) noted that the "... the partial breakdown of secrecy barriers in the chemical industry is increasing ... the trend toward more licensing of processes". Spitz (1988: 318) observed that "... some brand new technologies, developed by operating (chemical) companies, were made available for license to any and all comers. A good example is the Hercules-Distillers phenol/acetone process, which was commercialized in 1953 and forever changed the way that phenol would be produced."

Table 5 highlights that, like US SEFs, US chemical firms have played an important role as technology licensors during the 1980s. Notice that about 20% of the licenses sold by US chemical firms were for plants located in the US market itself. In effect, by licensing, these firms were creating potential competitors. Notice also that in contrast to German SEFs (see table 2), German chemical firms did not license much during the 1980s, consistent with the traditionally non-liberal technology policy reportedly pursued by German chemical producers (see for instance Barna et al., 1980).

A recent search of the trade publications turned up further anecdotal evidence that shows that at least in some markets, chemical and oil companies are aggressively competing to sell technology, often in collaboration with an SEF which undertakes the provision of the engineering and other know-how. Sometimes, competitors in the market for licenses are other chemical producers. In other cases, the major competition is provided by SEFs.[17] Shell, Mobil, BP, and Phillips Petroleum are some of the oil companies that have actively marketed their technologies. Some chemical companies that have been major licensors of their patented technologies include: ICI in ammonia, Union Carbide in polyethylene/polypropylene and air separation technologies, and Montecatini and its associated companies (such as Himont) in polypropylene.

Table 6 shows the investment behaviors, technology purchasing strategies and licensing strategies of the 20 largest chemical corporations as chemical turnover reported in the year

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[17] For instance, Dow, a company that has a reputation of very closely holding onto its technology, has recently decided to sell licenses in the chlor-alkali area (Brooks and Watzman, 1986). Union Carbide and Himont compete with each other in selling polypropylene licenses, along with Amoco, which is a more recent entrant (Morris, 1989). BP and Du Pont compete in polyethylene process technology (Mullin, 1993). In methyl *tert* butyl ethers (MTBE), UOP, Mobil-BP, and Phillips Petroleum are amongst the competing licensors (Rotman, 1993a); in cumene, Mobil/Badger are the latest entrants in the licensing market which includes UOP, ABB Lummus Crest, and Monsanto / Kellog (Rotman, 1993b).

1988 (Aftalian, 1991).[18] First of all, many of these firms have made a large share of their investments in foreign countries. On average, the home market accounts for less than 40% of the investment of large chemical companies in chemical plant (measured by number of plants). Put differently, large chemical firms are truly 'global' companies. Second, big corporations tend to develop their technologies in-house. Less than 40% of the technology is due to unaffiliated sources (with a relatively marginal role played by SEFs), whereas figure 1 has shown that in the aggregate this share raises at about 80%. This also confirms our previous findings that SEFs are mainly a source of technology for small firms which lack technological capability.

Finally, the last columns of the table show that even the largest chemical firms license out their technologies, and some do so quite actively. It is also clear that there are significant differences across companies in the extent to which they use licensing to capture rents from their technology (with oil companies licensing more intensively). All companies are more likely to use licensing in dealing with overseas investments, although some firms (e.g. Union Carbide, Monsanto, Exxon) also license considerably to entrants in their market of origin.

Not only do firms license extensively, many of them now explicitly consider licensing revenues as a part of the overall return from investing in technology. For instance, Du Pont expects to earn $100 million in licensing revenues by 2005, while Dow hopes to reach the same target by 2000. Even Hoechst is reported to be contemplating a reorganization of its R&D structure, with an explicit emphasis on licensing technologies developed in-house (Chemical Week, 1996). By comparison, Union Carbide is reported to have earned $300 million from its polyolefin licensing in 1992 (Grindley and Nickerson, 1996).

[18] Proctor and Gamble has been omitted because of very few plants listed in the data set.

Increasingly, technology is being licensed even in the early stages of development. The most vivid example is provided by the case of metallocene catalysts, regarded as probably the most significant process innovations in recent years since they provide better properties such as impact strength and toughness, melt characteristics and clarity in films. The total investment in metallocene research has been estimated at close to $4 billion (Thayer, 1995). Commercially first used in the production of polyethylene in 1991, metallocene catalysts are being applied to a wide variety of polymers, exemplifying the inherent economies of scope in the technology.

A number of firms are active in this research area: Dow and Exxon are regarded as being ahead of the rest especially in polyethylene, although BASF, Hoechst, Mitsui Toatsu and Fina are also active in polypropylene, while Du Pont and Nova are working to develop alternative catalyst systems. Both the leaders, Dow and Exxon, have allied with other process innovators to combine the catalyst system with a processing technology largely specific to the polymer. For instance, Union Carbide has formed a technology joint venture, Univation, with Exxon, combining its Unipol technology with Exxon's catalyst (Chemical Week, 1997a). Dow and BP have a similar understanding.[19] What is noteworthy is that both groups are actively trying to license their technology for commodity grade (but not specialty-grade) polymer. This has encouraged other firms to develop complementary technologies. For instance, BASF, Phillips Petroleum and BP are developing ways of using metallocene catalysts in existing slurry processes, many of which will be licensed (Chemical Week, 1997b).

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[19] There are other technology sharing alliances as well in this area, including Dow-Idemetsu, and Exxon-Mitsui Petrochemicals in polyethylene, and Dow-Montell, Hoechst-Exxon, Hoechst-Mitsui Petrochemicals, and Fina-Mitsui Toatsu in polypropylene.

5.4 Why Is There So Much Licensing By Chemical Producers?

This behavior of the chemical firms runs contrary to the orthodox management prescriptions (e.g. Teece, 1988). Indeed, the question of whether or not licensing is sensible has been a matter of considerable debate in the industry.[20] Traditional wisdom holds that innovations are best exploited by commercializing them oneself. In this view, licensing is undesirable because the innovator has to share the rents with the licensee, and especially because licensing also implies increased competition and rent dissipation.

How does one explain the widespread use of licensing by major producers? Strategies of rent appropriation depend upon the existing market structure. Specifically, the presence of competing technologies drastically changes the payoff to the strategy of trying to keep one's technology in-house. For instance, suppose there are two viable processes for the production of a particular product, each owned by a different firm. If one of the firms is going to license out (sell) her technology, the best response of the other innovator may well be to license out (sell) as well. The reason is that the rent dissipation will be shared by both the licensor as well as the non-licensor.

In other words, licensing imposes a negative pecuniary externality upon other incumbents, which is not taken into account by the licensor. As a result, licensing can be privately profitable. In turn, it also implies that if there are two or more incumbent firms that have proprietary technologies that are substitutes for each other, both firms would find it privately profitable to license, although their joint profits may well be higher in the absence of any licensing. In other words, unless restrained by mutual agreements, firms would compete

[20] For instance, an industry consultant criticized Union Carbide for its liberal licensing of its polypropylene/polyethylene Unipol process, claiming that licensing reduced profitability, both for the industry, and also for Union Carbide itself (Spalding, 1986). See also Spitz (1988) for similar views.

not only to supply products but also to supply their technologies.[21] Oligopoly theory suggests that collusive agreements are hard to enforce when the number of potential licensors and the number of incumbents is large. Licensing has been most prevalent in petrochemicals, where the number of producers was relatively large. Soon after WWII, a number of firms, including firms from Asia and east European countries, entered in products such as fertilizers and basic chemicals. The relatively large number of producers would have strongly discouraged any ambitions to use patents to monopolize markets.

In Arora and Fosfuri (1998) we consider the case where at least one of the competing innovations is patented by an SEF. As noted earlier, SEFs usually lack the ability to undertake production on their own. In addition, attempts to go into the production of chemicals for themselves would put them in direct competition with their customers. An SEF, therefore, has little option but to license its technology to others.[22] Therefore, when one of the innovators is an SEF, the other innovator's dominant strategy would be to license its innovation as well.[23] The evidence is consistent, although not conclusive. For instance, figure 3 shows that in all sub-sectors in which SEFs had more than 42% of market share during the 1980s, the average

[21] The intuition is more easily understood in terms of the textbook example of Cournot oligopoly with constant (and symmetric) marginal costs and linear demand. In the context of this familiar model of oligopoly, the opportunity cost of licensing is related to the decrease in profits as a result of entry. This is less than the profits of the entrant, as long as the existing market structure is not a monopoly. However, all other producers experience a reduction in their profits. In Arora and Fosfuri (1998) we build up a model which also accounts for product differentiation. We show that the average number of licenses sold out by technology holders is a decreasing function of the degree of product differentiation (which is also borne out by table 6). The reason being that the more the product is differentiated the more the licensor internalizes the negative externality related to the decrease in profits.

[22] Our data confirm that the average number of licenses sold out by SEFs is larger than the average number of licenses sold out by producers in basically all chemical sub-sectors.

[23] Even when the rival is not an SEF, in many situations it would still require some type of co-operative arrangement between the owners of the competing technologies to dissuade them from licensing.

number of licenses sold out by chemical producers was 2.8, whereas in the sub-sectors in which SEFs had less than 18% of the market, it was as little as 1.3.[24]

In many cases, chemical producers use SEFs as licensing agents. A chemical firm will license the its technology to an SEF. The latter offers a complete technology package, consisting of the core technology licensed from a chemical producer, along with know-how and installation and engineering services. This arrangement enables the licensor to benefit from the superior ability of SEFs to manage technology transfer. It also provides a buffer between the chemical firm and its licensees, limiting accidental leakage of information. From the point of view of the customer, dealing with a single source for technology, construction and engineering reduces transaction costs. The SEF can also provide better operational guarantee than if the contract were a pure technology licensing contract. (See Grindley and Nickerson, 1996, for further discussion of this topic.)

Licensing in chemicals has another interesting feature -- most of the licensing takes place for processes. New products are far less likely to be licensed, at least in the initial stage of their life cycles.[25] Almost by definition, a new product implies a degree of monopoly for the owner of the innovation. Arrow's famous result suggests that a monopolist is unlikely to license her innovation. Thus, new products are typically not licensed by chemical firms.[26]

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[24] Using information about our 23 chemical sub-sectors we find that the correlation between the SEFs' market share and average number of licenses by chemical companies is equal to +0.42, with a t-statistics of +2.17.

[25] Du Pont licensed out Nylon only to ICI and others with whom it had prior understanding and arrangement. It was only the pressure from anti-trust authorities that induced it to license to a domestic competitor, Chemstrand, in 1951 for $110 million, a very substantial sum. Du Pont also licensed a number of overseas producers. Similarly, ICI was forced to license polyethylene, on which it had a composition of matter patent (a product patent), in the US market by US anti-trust authorities. However, Stobaugh (1988) found that new products were rarely licensed unless it was to achieve some strategic objective.

[26] For an existing producer that discovers a new process, the advantages to license would have to be balanced against the opportunity costs in the form of heightened competition. The latter could take two forms: lowering the marginal costs of the other existing producers, and new entry. The former can be offset to some extent by appropriately designing the licensing contracts. This line of reasoning also suggests why process licenses are

SEFs, if they were to develop new products, would have to license them, as most biotech firms do for new pharmaceutical products. However, SEFs concentrate upon processes, rather than products. SEFs stay away from product innovation mainly because product innovation requires close links with downstream buyers, and often, the technical ability and financial resources to undertake costly market development. These requirements favor large firms with a diversified chemical portfolio. Hounshell and Smith (1988) provide an extremely rich and interesting description of how technically demanding and expensive it is to tailor new materials to fit different market segments. In synthetic fibers for instance, product innovation requires links with downstream textile producers, makers of textile machinery, tire manufacturers etc. Even a company as large and experienced as ICI in the 1930s, when offered a license on Nylon, preferred to exploit it as a joint venture with Courtaulds, an established producer of man-made fibers.[27]

6. WHY IN CHEMICALS?

The importance of licensing may be a distinguishing characteristics of the chemical sector. In most other industries, when licensing does take place is likely to be either cross-licensing, or overseas licensing. Anand and Khanna (1997) present evidence which suggests that the use of licensing as a strategy of rent appropriation is much less frequent outside of

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usually not exclusive.

[27] As Reader (1970: 365) put it

"Plastics and fibers shared similar technology, but in ICI they were seen as presenting vastly different commercial problems. With plastics, people in ICI felt fairly happy. They represented business of a kind they understood and which, they considered, fell fairly within their field: business, that is to say, in supplying other manufacturers with materials for their own activities. Fibers were different altogether. The field was dominated by Courtaulds -- rich, successful, supposedly technically very expert, and a valued customer of ICI. Little was known in ICI about the technique of spinning and there were alleged to be arcane mysteries in the marketing of fibers to the textile industry. Moreover, the consumer market-- the fashion trade, even-- lay not far away, and that was no place for a self-respecting chemical firm."

chemicals. We submit that the extensive licensing seen in the chemical sector is a consequence of three interrelated factors: the strength of patents, the existence of SEFs, and the characteristics of the technology and of the industry.

It is tempting to see the effectiveness of patents in chemicals solely as a creature of patent policy. However, one must also keep in mind the role of the underlying knowledge base, because ultimately, patents pertain to that part of the discovery that is codified. Therefore the effectiveness of patents also depends on how cheaply and effectively new ideas and knowledge can be articulated in terms of universal categories. Nelson (1990) identifies codified knowledge with what he calls the "generic" parts of technological knowledge. However, David (1993) argues that the extent of codification is a choice variable for economic agents. As Arora and Gambardella (1994) point out, an important determinant of the costs and benefits of codification is the stage of development of the underlying knowledge base. For instance, there are aspects of technological knowledge that are more readily codifiable because these are most closely identifiable with engineering principles and physical and chemical "laws".

The development of chemical engineering played an important role, not only in fostering process innovations but also permitting such innovations to be protected more effectively through patents. Chemical engineering developed more general and abstract ways of conceptualizing chemical processes, initially in the form of unit operations, and later in terms of concepts such as mass and energy transfer. A number of different processes could be conceived of in terms of these more elementary units. A chemical engineer could therefore see common elements across a number of processes which might appear very different and diverse to a chemist from an earlier generation. Chemical engineering (and the concomitant developments in polymer science and surface chemistry) thus provided the language for describing more precisely the innovations to be protected.[28] Simultaneously, these developments also allowed a better appreciation of the obvious extensions of the innovation - the scope of the innovation.

Patents work well in the chemical industry because the object of discovery can be described clearly in terms of formulae, reaction pathways, operating conditions and the like (e.g. Levin et al., 1987). But it is not merely that the object of discovery is more discrete in the sense of being a particular compound. Rather, it is the ability to relate the "essential" structure of the compound to its function. This allows a patent to include within its ambit inessential variations in structure, as in minor modifications in side chains of a pesticide.[29] In fact, chemical patents frequently use Markush structures to define the scope of the claim. The use of Markush structures permits a succinct and compact description of the claims and allows the inventor to protect the invention for sets of related compounds without the expense (and tedium) of testing and listing the entire set.[30] The ability to explicate the underlying scientific basis of the innovation allows the scope of the patent to be delimited more clearly. The obvious extensions can be foreseen more easily and described more compactly.[31]

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[28] Von Hippel (1990) has very interesting parallels with the ideas presented above. To use Von Hippel's terminology, more general and abstract knowledge would make specific information less "sticky", while chemical engineering made possible a partitioning of the product and process developments.

[29] In some instances, seemingly minor variations in side chains can have significant biological effects. Therefore, what is a "minor" variation is itself determined by the state of the current understanding of the relation between structure and function.

[30] A Markush structure is best understood as a language for specifying chemical structures of compounds, which allows generic representation for an entire set of related compounds. See Maynard and Peters (1991: 71) for details.

[31] The patent dispute involving the rival claims of Karl Ziegler and Giulio Natta in polypropylene are instructive. From McMillan's description, Ziegler appears as an inductive empiricist, never willing to speculate on the physical properties as a function of structure. Ziegler's inductive mind set is consistent with his polyethylene patent being written too narrowly. Hence, even though there is a near consensus that Ziegler had made the more fundamental discoveries, including the discovery of the catalyst system, Natta managed to obtain the fundamental patent on polypropylene. McMillan (1979: 124) suggests that Natta's superior patent position is attributable in large measure to Natta's "... elegant elucidation and proof of the structure and morphology of the

When innovations can not be described in terms of universal and general categories, sensible patent law can only provide narrow patent protection. During the 1860s, when synthetic dyestuffs first appeared, their structure was poorly understood, and hence also were the reaction pathways and processes. Thus broad patents led to litigation and, in some cases, unwarranted monopolies. In France, an excessively broad patent on analine red was construed to include all processes for making the red aniline based dye, even though it was quite clear that the structure of aniline dyes was as yet unknown. There were long and bitter disputes in England about the validity of the Medlock patent for *magenta* (another aniline dye) that turned on the appropriate definition of "dry" arsenic acid (with or without the water of hydration). In the case of *aniline blue,* the dispute rested on whether the substitution of an organic acid for an inorganic acid was enough to avoid infringement (see Travis, 1993: 104-137). The British courts interpreted the patents narrowly, with the result that competition in the British organic dyestuffs industry remained vigorous, until the industry itself was overwhelmed by its German rivals. By contrast, the *Fuchsine* monopoly in France is said to have contributed to the migration of the French organic dyestuffs industry to nearby Basle in Switzerland.

7. CONCLUSIONS

In this essay, we have relied on a combination of historical examples and detailed data on chemical investments during the last decade to illustrate how the use of patents has evolved over time. We have argued that in chemicals, there exists a functioning market, where process technologies are sold through arm's length license contracts. Not only does the extent of

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new high polymer he had discovered ... ." McMillan notes in this context that Natta published over 170 papers in five years on the subject of stereospecific polymerization.

licensing distinguish the chemical industry, so does the active licensing of technology by chemical producers. In other words, chemical producers have exploited their innovations in the classical manner by incorporating them in new plants and products; however, prompted in part by the willingness of SEFs to supply technology, producers have also exploited their innovations by licensing them to other firms. This process has progressed to the point where licensing is an integral part of the technology strategies of even the largest chemical firms. We have documented the substantial extent of technology licensing in the chemical industry, involving both specialized engineering firms and chemical producers themselves. The existence of this market for technology has contributed to a faster worldwide diffusion of the chemical technology and to make the chemical industry a truly global industry.

Such widespread licensing would be unlikely without a well-functioning patent system: transaction costs involved in contracting for technology would be larger and contracts for know-how less efficient. With a functioning market for technology, the current scale of operations is less of a limiting factor in conditioning the incentives to invest. Indeed, the possibility of profitably licensing their innovations might induce firms without access to production or commercialization capabilities to specialize in the production of the technology.

While patents are necessary for a market for technology, they are by no means sufficient. Although further research is needed, we believe that patents have worked well in the chemical industry because the underlying knowledge base – chemistry and chemical engineering – has been very successful in clarifying the relationship between structure and function. A chemical invention can be described clearly in terms of structure, reaction pathways, or operating conditions, with a reasonably clear sense of the limits of the invention. If so, a key consideration in framing patent policy must be the state of the scientific understanding of the phenomena involved, and the availability of suitable abstractions for representing the phenomena.

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Figure 1: *Who was licensing chemical technologies during the 1980s*

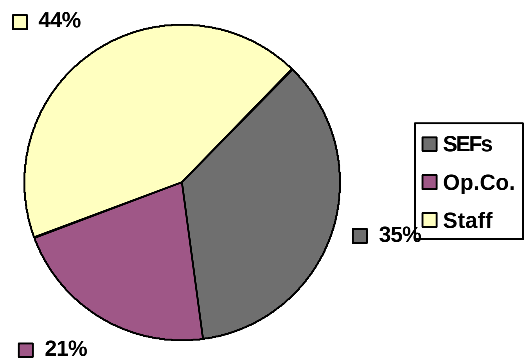

Table 1: *Licensing activity of SEFs during the 1980s by nationality*

	Share of all licenses	Licenses per firm	Total number of licenses	Licenses in home markets	Licenses in the rest of first world	Licenses in the third world
USA	43 %	29	1356	265 (20%)	284 (21%)	807 (59%)
WGE	25 %	34	802	84 (10%)	204 (25%)	514 (65%)
NET	7 %	77	230	12 (5%)	71 (31%)	147 (64%)
UK	7 %	11	214	26 (12%)	66 (31%)	122 (57%)
ITA	5 %	12	143	21 (15%)	9 (6%)	113 (79%)
DEN	4 %	124	124	0 (0%)	29 (23%)	95 (77%)
JAP	3 %	9	89	27 (30%)	5 (6%)	57 (64%)
FRA	2 %	7	60	4 (7%)	11 (18%)	45 (75%)
TOTAL	96 %	24	3018	439 (15%)	679 (22%)	1900 (63%)

Table 2: *The top 15 SEFs as licensing contracts during the 1980s*

SEFs' name	country of origin	Number of licenses	Licenses in home market	Licenses in the rest of first world	Licenses in the third world	Total US Patents 1981-90(*)
UOP	USA	508	70 (14%)	196 (39%)	242 (47%)	1159
Kellogg	USA	244	41 (17%)	64 (26%)	139 (57%)	51
Lurgi	WGE	237	29 (12%)	96 (41%)	112 (47%)	3
Linde	WGE	181	28 (15%)	72 (40%)	81 (45%)	288
Lummus	USA	152	24 (16%)	63 (41%)	65 (43%)	111
Topsoe	DEN	124	0 (0%)	39 (31%)	85 (69%)	15
Uhde	WGE	117	3 (3%)	46 (39%)	68 (58%)	58
Stamicarbon	NET	115	4 (3%)	30 (26%)	81 (71%)	249
Zimmer	WGE	98	3 (3%)	16 (16%)	79 (81%)	86
Snamprogetti	ITA	96	17 (18%)	17 (18%)	62 (64%)	99
KTI	NET	80	5 (6%)	43 (54%)	32 (40%)	1
Davy McKee	UK	71	1 (1%)	36 (51%)	34 (48%)	85
Stone & Webster	USA	62	7 (11%)	21 (34%)	34 (55%)	56
Howe-Baker	USA	52	18 (35%)	15 (29%)	19 (36%)	2
Karl Fischer	WGE	44	1 (2%)	6 (14%)	37 (84%)	16

(*) Total number of patents assigned to the firm in the period 1981-1990. Data are from the US Patent Office.

Table 3: *Buyers of technologies*

Technology Buyer	total number of plants	share of licenses from SEFs	share of in-house technology	share of licenses from other producers
Third World Companies	4068	43 %	3 %	54 %
First World Companies	4905	28 %	37 %	45 %
Large First World Companies[32]	2836	22 %	52 %	26 %
Small First World Companies	2069	37 %	16 %	45 %

[32] This is a sample of 153 first world chemical firms that have reported a chemical turnover of more than 1 billion of US dollars in the year 1988.

Table 4: *Licensing patterns in major chemical sub-sectors*

Sub-sector	Total plants	Formal License (%)	Share of in-house tech. (%)	Licenses from unaffiliated sources (%)	Licenses from SEFs (%)	Avg number of licenses per firm
Agricultural Products	155	23.9	73.0	27.0	0	0.5
Air Separation	670	52.7	27.8	72.2	49.0	10.2
Engineering Materials	150	50.0	56.0	44.0	21.2	0.8
Fertilizers	1539	55.5	4.9	95.1	64.8	8.0
Food Products	368	24.5	18.9	81.1	54.8	1.6
Gas Handling	1172	27.0	4.4	95.6	67.8	4.1
Inorganic Chemical	1726	39.5	24.6	75.4	41.7	3.1
Industrial Gasses	697	60.1	8.4	81.6	47.4	4.8
Metals	871	22.6	23.9	76.1	34.0	2.0
Organic Chemicals	1401	34.0	48.7	51.3	36.9	1.2
Organic Refining	2720	51.0	9.7	90.3	51.8	9.1
Petrochemicals	3581	54.5	18.9	81.1	41.7	6.5
Pharmaceuticals	923	17.4	54.0	46.0	8.1	0.8
Plastics	2314	49.3	39.6	60.4	9.3	3.7
Paper	579	17.3	2.0	98.0	48.0	3.6
Synfuels	305	56.7	27.2	72.8	41.3	1.6
Textile and fibers	562	59.6	19.4	80.6	64.1	3.9
ALL SECTORS	20581	43.6	21.5	78.5	44.8	9.5

Figure 2: Share of SEFs Licensing by Size of Market (measured by number of plants in 1980-90)

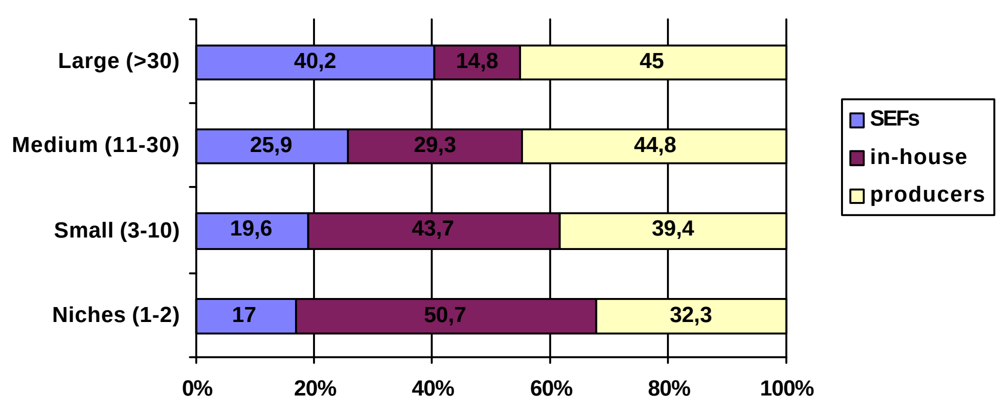

Table 5: *Licensing activity of chemical firms during the 1980s by nationality*

	Licenses by chemical firms as a % of all licenses	**a**Avg number of licenses per firm	Geographical Distribution of Licenses			
			Total	**At home**	**Rest of first world**	**Third world**
USA	40 %	6.8	1543	314 (20%)	382 (25%)	847 (55%)
JAP	12 %	5.4	473	34 (7%)	123 (26%)	316 (67%)
FRA	12 %	16.9	452	25 (5%)	130 (29%)	297 (66%)
UK	7 %	5.2	268	11 (4%)	90 (34%)	167 (62%)
WGE	5 %	4.6	209	18 (9%)	70 (33%)	121 (58%)
NET	3 %	10.9	131	4 (3%)	51 (39%)	76 (58%)
ITA	3 %	5.0	110	8 (7%)	21 (19%)	81 (74%)
SWE	2 %	4.2	96	4 (5%)	35 (36%)	57 (59%)
TOTAL	84 %	6.6	3282	418 (13%)	902 (27%)	1962 (60%)

Figure 3:
Market share of SEFs and propensity to license by chemical producers

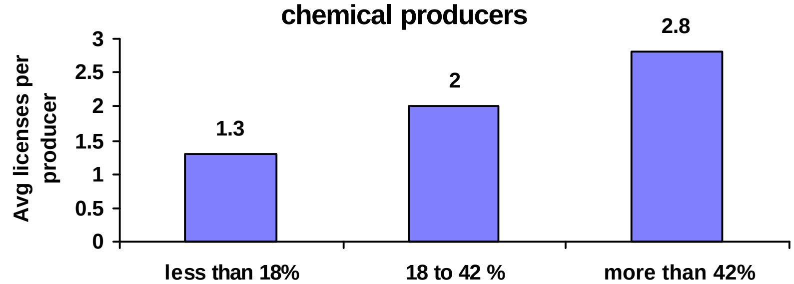

Table 6: *Investment strategies, technology purchasing strategies and licensing strategies of large chemical corporations (1980-1990)*

Firm's characteristics			**Investment behavior: Total number of plants**			**Technology purchasing strategy**			**Licensing strategy**					
Company	Nation -ality.	Sales[1] (1988, $M)	Total A	At home B	Abroad C	In-house (%)	From SEFs (%)	From producers (%)	Total D	At home E	Abroad F	D/ A+D	E/ B+E	F/ C+F
Akzo	NET	7846	66	25	41	57.6	12.1	30.3	7	0	7	0.10	0.00	0.15
BASF	WGE	21543	210	63	147	62.5	19.8	17.7	47	1	46	0.18	0.02	0.24
Bayer	WGE	22694	102	39	63	55.0	20.0	25.0	15	3	12	0.13	0.07	0.16
Ciba-Geigy	SWI	11018	57	3	54	66.7	22.2	11.1	6	0	6	0.10	0.00	0.10
Dow Chemical	USA	16659	208	80	128	84.2	7.9	7.9	26	4	22	0.11	0.05	0.15
Du Pont	USA	19608	261	138	123	64.7	15.8	19.5	48	1	47	0.16	0.01	0.28
Eastmann Kodak	USA	6724	56	47	9	39.3	25.0	35.7	3	1	2	0.05	0.02	0.18
Elf Aquitaine	FRA	8216	43	29	14	17.4	30.4	52.2	2	0	2	0.04	0.00	0.12
Exxon	USA	9892	261	73	188	53.5	20.2	26.3	43	10	33	0.14	0.13	0.15
Hoechst	WGE	21948	211	57	154	59.6	7.1	33.3	48	0	48	0.19	0.00	0.24
ICI	UK	21125	237	110	127	67.3	8.7	24.0	117	0	117	0.33	0.00	0.48
Mitsubishi Chem.	JAP	8095	72	41	31	62.9	5.7	31.4	10	1	9	0.12	0.02	0.22
Monsanto	USA	7453	81	40	41	84.8	8.7	6.5	126	29	97	0.61	0.42	0.70
Montedison	ITA	7725	110	60	50	52.7	14.6	32.7	35	0	35	0.24	0.00	0.41
Rhone-Poulenc	FRA	10802	129	54	75	75.0	6.3	18.7	52	0	52	0.29	0.00	0.41
Shell	UK-NET	11848	428	86	342	45.5	28.7	25.8	112	3	109	0.21	0.04	0.24
Solvay	BEL	6836	58	8	50	79.4	0.0	20.6	6	0	6	0.09	0.00	0.11
Sumitomo	JAP	6532	43	39	4	44.4	16.7	38.9	25	2	23	0.37	0.05	0.85
Unilever	UK-NET	12338	56	23	33	21.4	28.6	50.0	1	0	1	0.02	0.00	0.03
Union Carbide	USA	8324	129	101	28	73.8	8.2	18.0	145	27	118	0.53	0.21	0.81
Total/Average			2818	1116	1702	60.5	15.6	23.9	874	82	792	0.24	0.07	0.32

1. Chemical sales only for companies with significant non-chemical businesses.