Firms' Knowledge-Sharing Strategies in the Global Innovation System: Empirical Evidence from the Flat Panel Display Industry

Author(s): Jennifer W. Spencer

Source: *Strategic Management Journal*, Mar., 2003, Vol. 24, No. 3 (Mar., 2003), pp. 217-233

Published by: Wiley

Stable URL: https://www.jstor.org/stable/20060526

Strategic Management Journal
Strat. Mgmt. J., **24**: 217–233 (2003)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/smj.290

FIRMS' KNOWLEDGE-SHARING STRATEGIES IN THE GLOBAL INNOVATION SYSTEM: EMPIRICAL EVIDENCE FROM THE FLAT PANEL DISPLAY INDUSTRY

JENNIFER W. SPENCER*
Department of International Business, George Washington University, Washington, DC, U.S.A.

This paper explores the relationship between firms' strategies to share knowledge with their innovation system and innovative performance. The empirical analysis showed that many firms designed strategies to share technological knowledge with competitors, and those firms that shared knowledge with their innovation system earned higher innovative performance than firms that did not share knowledge. In addition, firms that interacted with their global innovation system earned higher innovative performance than firms that interacted with only their national innovation system. These results should help managers and researchers understand how to devise technology strategies in globally integrated industries. Copyright © 2003 John Wiley & Sons, Ltd.

Conventional wisdom holds that innovating firms that protect their technological knowledge will achieve higher performance than firms that share their knowledge with competitors. Indeed, some researchers have identified a firm's ability to protect its knowledge from appropriation by rivals as one of the most critical capabilities that it can develop (Liebeskind, 1996, 1997). This paper considers firms' knowledge-sharing activities from a different angle by exploring whether, in some circumstances, firms' strategies to share knowledge with other innovating firms can associate with *higher* performance.

Researchers have noted that a firm's ability to successfully commercialize a new product depends not only on its own technology strategy, but also on activities performed by a wide range of organizations in its innovation system (Cohen and Levinthal, 1990; Rappa and Debackere, 1992a; Van de Ven, 1993). An innovation system consists of resources and institutions, built through interactions among universities, research institutes, and innovating firms, that a company can harness to successfully commercialize innovations. A national innovation system (NIS) reflects the resources and institutions in a given country that domestic firms can leverage to support their own innovative efforts. Researchers have pointed out that national innovation systems display unique characters (Nelson and Rosenberg, 1993; Lundvall, 1992), and have highlighted their importance by showing that knowledge spillovers tend to be localized within countries and regions (Jaffe, Trajtenberg, and Henderson, 1993; Almeida and Kogut, 1999).

At the same time, the increasingly international flavor of high-technology innovation has caused some researchers to suggest that innovation systems are becoming global. A global innovation system (GIS) consists of resources and institutions that are built through interactions among organizations from many countries and are accessible by firms from around the world. Kobrin (1991) argued that capital requirements and economies

Key words: knowledge-sharing strategies; industry emergence; innovation strategies
*Correspondence to: Jennifer W. Spencer, Department of International Business, George Washington University, Washington, DC 20052, USA. E-mail: Jspencer@gwu.edu

Received 15 October 1999
Final revision received 8 August 2002

of scale mandate that some industries become globally integrated. One would expect that globally integrated industries would be embedded primarily in a well-integrated GIS, and that firms in those industries would display the highest performance when they interacted extensively with this GIS. This study explores firms' efforts to participate in the knowledge-diffusion networks present in both national and global innovation systems.

The external acquisition of knowledge has emerged as a central theme in both sociological research on technological communities of innovators (Rappa and Debackere, 1992a) and economics literature on the effect of technological spillovers on firms' competitive positioning (Cohen and Levinthal, 1990). By acquiring knowledge from the innovation system, a firm can leverage its R&D expenditures to attain a greater understanding of its technology than it could have developed by relying only on its internal laboratories. A firm that chooses not to acquire knowledge from the innovation system risks falling behind the state of the art, and reduces the probability that it will make a technological breakthrough that will lead to a commercial product. Few scholars disagree, then, that firms can increase their innovative performance by acquiring some technological knowledge from the innovation system for the use of their own industrial researchers. Why, then, would innovating firms *share* technological knowledge with their innovation system?

Researchers have explained firms' decisions to publish papers in scientific journals, present papers at technical conferences, and otherwise disseminate the results of their research by framing knowledge sharing as an accommodation to firms' scientists. Prior research has shown that firms may allow their researchers to publish academic papers in order to recruit new employees, monitor and motivate their research staff (Henderson and Cockburn, 1994), promote internal incentives for basic research (Cockburn, Henderson, and Stern, 1999), or build greater absorptive capacity (Cockburn and Henderson, 1998).

At the same time, knowledge-sharing activities impose clear costs on organizations. Knowledge sharing costs an organization the time that its researchers consume conveying information to others—for example, writing a scientific article and completing the publication process. Publication can also compromise a firm's intellectual property protection (Cockburn *et al.*, 1999). Indeed, even after a technology has received patent protection, publications and conference presentations convey additional insight to competitors, and likely disseminate the firm's R&D breakthroughs more broadly and more rapidly than a patent application. The resource-based view holds that a firm can sustain a competitive advantage only if the foundation for that advantage lies in resources that are valuable, rare, imperfectly imitable, and not substitutable (Barney, 1991; Collis and Montgomery, 1995). When knowledge is viewed as a resource that accelerates technical progress, a firm's decision to share it openly is seen to erode its competitive advantage by transforming a valuable resource into a public good that contributes to the research efforts of all innovating firms. If a firm's managers perceive that sharing knowledge with their technological community would place their firm at a strategic disadvantage, they would surely find other, less costly, methods of monitoring or rewarding employees.

This paper builds a theoretical argument suggesting that, under some conditions, firms that share technological knowledge may achieve higher innovative performance than firms that do not share knowledge because knowledge-sharing strategies can help a firm shape the institutional environment in favor of its own technological design. The paper then explores firms' strategies in the global flat panel display (FPD) industry to determine whether the patterns of knowledge sharing and performance in that industry are consistent with these theoretical arguments. FPDs are thin display screens used in a wide range of end products, from laptop computers to airplane cockpits to personal digital assistants. The earliest technological breakthroughs on FPDs took place in corporate and university laboratories in the 1960s. However, it was not until about 20 years later that one product design, the liquid crystal display (LCD), emerged as the dominant design for laptop computer applications, and FPD firms began large-scale manufacturing and marketing of laptop-sized screens. Approximately 115 firms actively participated in the FPD industry at one time or another across those two decades.

A firm's *innovative performance* refers to its ability to develop and hold intellectual property protection over a technology that is demanded by large commercial markets. Firms that earn high innovative performance possess one of the resources necessary to capture market share and achieve high commercial performance in an emerging industry. Firms that display low innovative performance will likely find themselves incapable of attaining high performance as their industry moves into the commercial period, and may even be technologically locked out of their industry (Schilling, 1998).

While innovative performance contributes to a firm's later commercial profitability and market share, it is only one of many relevant inputs. A firm's commercial performance also depends upon incremental innovations in materials, product designs, and manufacturing capabilities (Gomory, 1989). In addition, in the commercial phase of innovation, firms can maintain a technology advantage over competitors by maintaining transitory, first-mover monopoly positions that allow them to obtain a deeper appreciation of new technologies, and gain an advantage by moving rapidly along learning curves (Garud and Kumaraswamy, 1993). Strong commercial performance also depends on a firm's financial strength, marketing and distribution networks, complementary product lines, and other strategic variables. In order to avoid misspecification of a complex model that includes a wide range of potential variables, this paper focuses only on the relationship between a firm's knowledge-sharing strategy and its innovative performance during the precommercial phase of industry emergence.

The term *technological knowledge* refers to knowledge regarding scientific and technical advances on an applied, high-technology product. While firms can share technological knowledge with their innovation system in a number of ways, this paper focuses on the sharing of explicit knowledge by publishing advances in scientific journals and presenting papers at technical conferences.

In the next section, I will suggest that in the precommercial phase of some emerging industries, including FPDs, firms can use a knowledge-sharing strategy to shape the institutional environment in favor of their own technological design. In this way, a firm can achieve higher innovative performance by sharing its technological knowledge with the innovation system than by keeping that knowledge secret. I then propose that in industries that are globally integrated, firms will achieve higher innovative performance by sharing knowledge with their *global* innovation system than by sharing knowledge with merely their *national* innovation system. I will then describe the methodology and report results of regression analyses designed to test the relationship between knowledge sharing and innovative performance in the FPD industry.

KNOWLEDGE-SHARING STRATEGIES AND INNOVATIVE PERFORMANCE

Precommercial and commercial competition

Management scholars have long recognized that in many industries the nature of competition changes over the course of innovation and commercialization. Early on, during an initial 'era of ferment' (Anderson and Tushman, 1990), rivalry centers on differences in the fundamental designs of firms' products (Teece, 1987). As they dedicate investments to a new technology, industrial researchers hold divergent beliefs about the advantages and disadvantages of any given technological approach (Nelson and Winter, 1982). Once a firm begins to devote resources to one approach, its competencies become specialized, and early technological choices constrain future options (Arthur, 1988). Thus, when this path dependence drives technological progress, innovating firms often lie dispersed across distinct technological trajectories. And even within one trajectory, diverse product designs compete on more specific product attributes. In industries characterized by this type of precommercial competition, only one trajectory will likely emerge as the dominant design for any given end application. Each firm, therefore, has a tremendous interest in seeing its own trajectory win out as that dominant design.

The commercial phase of innovation begins when the marketplace chooses one technology as the dominant design for any application. The dominant design identifies the single product design or technology that emerges as the commercial favorite. This design limits the scope of subsequent technical progress on a given in the technology (Sahal, 1981). By facilitating product standardization, the establishment of the dominant design encourages investment into complementary products and industry infrastructure, and promotes investments necessary for production economies (Utterback and Suarez, 1993). Firms continue to improve their products throughout the commercial phase of competition. However, the focus of these efforts shifts towards incremental refinements within one trajectory (Abernathy and Clark, 1985). The basis for competition shifts away from differences in product designs and toward the price of the new product (Teece, 1987). In about 1989, one product design, the LCD, emerged as the dominant design for laptop computer applications (Murtha, Spencer, and Lenway, 1996). FPD firms shifted from primarily engaging in R&D to pursuing large-scale manufacturing and marketing of their products, and virtually all laptop computers produced after 1989 contained an LCD screen.

Like most institutional arrangements, dominant designs generally persist over extended periods of time, but are not immutable. Technological discontinuities in the industry can launch a new era of ferment that may result in a shift in the dominant design (Anderson and Tushman, 1990). For instance, Anderson and Tushman (1991) found that a new dominant design arose three times over 25 years in the minicomputer industry.

Firms' strategies to shape their institutional environments

Many of the innovations that win out as the dominant design for a given application actually fall short of the technical performance offered by alternatives (David, 1985; Arthur, 1988; Anderson and Tushman, 1990). Researchers have explained this paradox by arguing that the emergence of a dominant design depends not only on the product's technical performance, but also on the institutional environment that constrains and guides industry emergence (Usher, 1954; Constant, 1980; Bijker, Hughes, and Pinch, 1987).

An institutional environment sets the framework for market transactions and provides important resources for economic actors. Institutions define the alternative courses of action that are open to firms, dictate the potential pay-offs from different activities, legitimate organizational forms and technologies, and assign rights to use resources and capture residual profits from economic activities (Ruttan and Hayami, 1984; North, 1990; Van de Ven, 1993). In emerging high-technology industries, a central component of this institutional environment consists of technological and evaluation standards that influence a product's development. Technological standards dictate the set of technical interfaces through which a new product interacts with existing and future complementary products, and evaluation standards specify the set of criteria that is used to judge the merits of the innovation. Researchers have shown that this institutional environment coevolves with the technical advances of innovating firms via interactions among innovators, suppliers, end-users, and regulators (Van de Ven and Garud, 1989, 1993; Garud and Rappa, 1994).

Because technological and evaluation standards emerge endogenously, every innovator can influence their character (Das, 1994). It follows, then, that a firm can increase its own innovative performance by pursuing strategies to actively shape the institutional environment in favor of its own technology. This paper suggests that by sharing technological knowledge with external researchers, a firm can influence the institutional environment in at least two ways. First, firms can shape the technological and evaluation standards in their institutional environments by directing the industry-wide conversation that takes place concerning the advancement of their technology. One important way that a firm can influence this industry-wide technical discussion is by sharing some of its own knowledge with the technological community. Second, the firm can attract other innovators to its technological trajectory and, thus, form a critical mass of firms with a vested interest in the success of the technology.

Shaping evaluation standards

A firm can increase its innovative performance by shaping the criteria used to evaluate its emerging technology. A firm's technology has a greater chance of being selected as the favorite design for a given application if emerging evaluation criteria fit well with the attributes of the firm's design. By publicizing its own research activities, a firm can influence other researchers' opinions concerning the most critical characteristics of the emerging technology. Therefore, a firm may attain higher innovative performance if it shares knowledge with other innovating firms than if it keeps that knowledge secret.

Let's consider this argument in greater detail. First, I argued that a firm has greater odds of achieving high innovative performance if it can shape the criteria used to evaluate the new technology to favor the firm's design. By calling the innovation system's attention to a certain class of issues, the firm can influence all researchers' perceptions concerning which technical attributes are most critical to improve before commercialization, and which product characteristics are unimportant. By shaping the technical priorities of all external researchers, the firm can affect the criteria used to judge the company's design. The firm's published scientific advances reflect its own technical priorities and successes. Therefore, evaluation standards based on these advances should improve the firm's innovative performance.

For example, FPD product designs reflect a series of trade-offs between different technical attributes such as breadth of viewing angle, weight, resolution, and power consumption. By sharing knowledge concerning one method of improving a display's resolution, a firm may focus the technological community's attention away from making improvements on the dimensions of weight and power consumption and toward developing high-resolution screens. Since the firm's researchers perceive resolution as a priority and have devoted resources toward the issue, its interests lie in ensuring that the industry acknowledges the importance of that dimension. A firm is more likely to win the precommercial competition if the evaluation criteria that become standardized in the institutional environment reflect the firm's own vision of a high-resolution design. In sum, by influencing all researchers' priorities, the firm can persuade innovators along all technological trajectories to compete on the firm's own terms.

Next, I argued that by sharing its R&D knowledge with the innovation system, a firm can influence all innovators' technical priorities. Scientists' selection of research questions depends heavily on the opinions of other scientists in their field (Zuckerman, 1978; Rappa and Debackere, 1992b; Tushman and Rosenkopf, 1992), as well as on their assessments of what is 'fashionable' in the scientific community (Crane, 1969; Barber, 1990). Merton (1938: 219) argued that scientists' behaviors reflect 'reactions to the inferred critical attitudes or actual criticism of other scientists and ... an adjustment of behavior in accordance with these attitudes.' This literature suggests that there is clear potential for a researcher to influence other scientists' choices concerning which research questions are most important to address. By publishing scientific papers and participating in technical conferences, a firm can draw attention to a certain class of research questions and, thus, influence other researchers' opinions about the most important attributes of the new technology. If the characteristics that emerge as critical in the innovation system favor the firm's own design, it will achieve higher innovative performance.

Attracting new entrants

A firm's innovative performance depends on whether its technological trajectory wins out as dominant design in the industry. There is a greater probability that a given technological trajectory will become the industry's dominant design when the trajectory houses a critical mass of well-respected firms. By sharing R&D knowledge with its innovation system, a firm can attract other organizations to its own trajectory and, therefore, increase its probability of achieving high innovative performance.

Once again, let's consider this argument in greater detail. First, I argued that the probability that a given technological trajectory will win out as the dominant design depends on the number and reputation of firms pursuing that product design. When many firms pursue a given product design, the total quantity of resources devoted to that technology increases, and progress toward a technically and commercially viable product will accelerate (Podolny and Stuart, 1995). Industry observers often justify the dominance of one product design over another by citing the speed of advance of the dominant technology. Some FPD makers, for instance, point out that a number of technical advances occurred in LCD technologies in the 1980s that paved the way for their selection as a dominant design. The speed of a technology's advance may depend partially on characteristics inherent in the technology, itself. However, dominant technologies also enjoy rapid advancement due to the sheer volume of effort devoted to their progression.

Further, as technologies approach commercialization, producers of complementary and supporting products begin to make their own investments. Fostering these complementary and supporting investments is critical for high-technology designs such as FPDs that require production tools and materials to be developed specifically for the new technology. Additionally, as prototypes become available at trade shows, innovators can guide the expectations of potential end-users in favor of their own product attributes. Beyond this, Van de Ven (1993) reasoned that firms that cooperate while they compete can take turns performing various functions necessary for industry emergence. Finally, when a technological trajectory houses a large chorus of innovating firms with a vested interest in one technology, firms on that trajectory may simply speak with a louder voice to influence their institutional environment.

Next, I argued that by sharing R&D knowledge with the innovation system a firm can attract other innovators onto its technological trajectory. By sharing technological knowledge, the firm describes the state of its current research and offers clues about methods to overcome specific technical obstacles. Knowledge sharing also allows outside researchers to confirm or disconfirm theories without their own costly experiments. Each of these contributions reduces barriers to entry onto the technological trajectory.

In addition, when an innovating firm of high status resides on a given trajectory, it is likely to attract other high-status innovators to that technology (Podolny and Stuart, 1995). Merton (1968) reasoned that the uncertainty present very early in the innovation process ensures that no innovating firm can be confident about which technology will become the industry favorite. To respond to that uncertainty, innovators imitate high-status firms. Rappa and Debackere (1992a) argued that firms can improve their own reputations by sharing technological advances with the innovation system. Knowledge sharing, therefore, can help a firm attract high-status innovators to its own technological trajectory.

A firm's strategy to increase the number of firms marketing similar technologies would be unthinkable during the commercial phase of competition. In some industries, such tactics will improve a firm's innovative performance, however, by increasing the probability that the firm's own technological trajectory will become the dominant design. Therefore, by sharing its technological knowledge openly, a firm will likely sacrifice market share within its technological trajectory. However, if the marketplace rewards the firm's technology by making it the dominant design in an application with large end-product demand, all firms pursuing that technological path will achieve higher innovative performance than if they had been relegated to the 'losing' path.

Proposition 1: Under conditions of precommercial competition, FPD firms that share technological knowledge with their innovation system will achieve higher innovative performance than firms that do not share knowledge with their innovation system.

This paper draws from published scientific literature to measure two related dimensions of a knowledge-sharing strategy: sharing a large *quantity* of knowledge, and sharing high-quality, or *relevant*, knowledge with the innovation system. Hypotheses 1 and 2 reflect these related dimensions of knowledge sharing:

Hypothesis 1: Firms that share a large quantity *of knowledge with their innovation system will achieve higher innovative performance than firms that do not share.*

Hypothesis 2: Firms that share high-quality, relevant *knowledge with their innovation system will achieve higher innovative performance than firms that do not share.*

Sharing knowledge with the global innovation system

The question of whether a firm's innovative performance depends on its national or global innovation system holds important implications for high-technology firms. An NIS consists of the resources and institutions that are built and used primarily by individuals and organizations within a given country. The GIS includes resources and institutions built and used by parties from around the world. If different technologies win out as dominant designs in various countries, then the NIS would be the most relevant frame of reference for an innovating firm because distinctions in countries' institutional environments could cause evaluation standards to vary cross-nationally. If an industry's dominant design were to emerge nationally, rather than globally, a firm would find its best interests served by tailoring its knowledge-sharing strategy to only one country.

As a globally integrated industry, however, FPDs may have outgrown national innovation systems. Kobrin (1991) has argued that in a growing number of high-technology industries national markets no longer encompass sufficient geographic space to serve as minimally efficient markets. He showed empirically that innovations that require particularly high upfront R&D expenditures tend to be associated with globally integrated industries. Similarly, Murtha *et al.* (1996) suggested that in a globally integrated industry such as FPDs manufacturing requirements, issues of product legitimacy, and global product markets mandate that a similar dominant design emerge for products manufactured and sold around the world.

In a globally integrated industry, firms from all countries respond to common technological and evaluation standards, and sell their high-technology products to customers around the world. Any firm that intends to influence the emergence of technological and evaluation standards within a globally integrated industry must, then, influence the emergence of these institutions within the GIS, and not only its own NIS. Therefore, I propose that firms with the highest innovative performance in globally integrated industries will be those that target their knowledge-sharing strategies toward the GIS, rather than merely their own NIS.

> *Proposition 2: Under conditions of precommercial competition, firms will achieve higher innovative performance when they share technological knowledge with their global innovation system as well as their national innovation system.*

The paper draws, again, on the published literature to operationalize two related dimensions of knowledge sharing in the NIS and GIS. Hypotheses 3 and 4 reflect these measures:

> *Hypothesis 3: Firms will achieve higher innovative performance when they share a larger* quantity *of technological knowledge with their global innovation system, beyond the quantity of knowledge they share with their national innovation system.*

> *Hypothesis 4: Firms will achieve higher innovative performance when they share more* relevant *technological knowledge with their global innovation system, beyond their efforts to share relevant knowledge with their national innovation system.*

RESEARCH DESIGN

I tested these four hypotheses using data contained in the scientific papers and patents of firms in the global FPD industry. Much like knowledge dissemination among academic researchers, one of the most effective ways for industrial researchers to share knowledge with colleagues is to publish articles in scientific journals and present technical papers at conferences. In fact, in a survey of academic and industrial researchers across two commercial technologies, both academic and industrial researchers reported that they wished to disseminate their technical results to peers, with academic researchers giving knowledge dissemination only slightly greater priority than their counterparts based in industry (Debackere and Rappa, 1994).

Citation patterns indicate the usefulness of the firm's knowledge to subsequent researchers. Similar bibliometric approaches have substantial precedent in empirical studies on industrial researchers' contributions to the scientific community (e.g., Rappa and Garud, 1992), communication patterns among scientists (e.g., Lievrouw, 1989), and the international diffusion of scholarly information (e.g., Schott, 1988).

This paper reports results from regression analyses of firms' strategies through the entire precommercial phase of innovation, from 1969 to 1989. Not every FPD firm was active for the entire time period. Therefore, firms were included in the sample for the span of time bounded by years in which the firm either (a) published an FPD paper, (b) received a patent on an FPD technology, or (c) employed at least one employee who held membership in the industry trade association, the Society for Information Display. This amounted to 1154 firm-year observations.

Innovative performance

Innovative performance consists of a firm's ability to develop and obtain intellectual property protection for a product demanded by large commercial markets. The act of creating a technological advance that is unique, and therefore patentable, is not enough. The technological advance must have some commercial value in the marketplace once the commercial phase of industry emergence begins. Innovative performance reflects the value of an innovation itself, rather than a firm's skills at manufacturing and marketing the resulting commercial product.

The value of a firm's product innovations parallels the value of its patent portfolio. Holding a valuable patent portfolio leaves the firm positioned to manufacture the product and capture market share in the commercial phase of innovation. Alternatively, firms without strong production capabilities can earn rents from their patents by licensing them to others (Hall and Ziedonis, 2001). And other innovators may choose to take out patents strategically in order to block the commercialization efforts of rivals pursuing similar designs (Cohen, Nelson, and Walsh, 2000).

Patent renewal method as an estimate of patent portfolio value

A simple count of the patents awarded to a firm is a very poor measure of the *value* of that firm's patent portfolio and the value of its innovations (Pakes and Schankerman, 1984; Griliches, 1990; Lanjouw, 1993). In fact, research has shown that simple patent counts are highly associated with total resources that a firm puts *in* to the innovation process, but relatively poor predictors of outcomes, such as the firm's innovative performance (Griliches, 1990). Therefore, to ascertain the value of a firm's patented innovations, I followed Pakes and Schankerman (1984), Schankerman and Pakes (1986), and Lanjouw (1993), and estimated the value of each firm's patent portfolio by tracking innovators' annual decisions to either renew their FPD patents or allow them to lapse.

In some European countries, innovators must pay an annual fee to maintain intellectual property protection for their patented technology, with fee schedules demanding relatively small payments in the early years, and more expensive fees as a patent ages. The patent renewal methodology assumes that firms will renew patents as long as they are useful for the firm, and allow unproductive patents to lapse. From this assumption, Lanjouw (1992) developed a model to assess the relative value of a given patent. The model assumes that firms choose to pay renewal fees only when the expected revenue from the following year's patent protection plus the value of the option to renew the patent *is greater than* the renewal cost plus the expected value of legal fees required to defend the patent.[1] Those patents that hold value and retain that value over time will tend to be renewed for many years. Patents that hold little value or lose value over time will be left to expire early on. Therefore, this measure of innovative performance reflects not only the number of patents a firm was awarded, but also the relative utility of the patents in its portfolio. In her tests validating the patent renewal methodology, Lanjouw (1993) found that weighting patents by their renewal data removed 39–56 percent of the variance of patent value found in simple counts of patent awards.

In order for their innovation to enjoy intellectual property protection in all industrialized markets, firms based in Japan, the United States, and all European countries must receive a patent in every industrialized country. Because Lanjouw (1993) validated the method using German patent fee schedules, I chose to use German patent renewal data to assess the innovative performance of FPD firms from all over the world.[2]

Lanjouw (1993) estimated parameters for the probability of obsolescence and the real discount rate of a patent using renewal fee schedules and data on 15,000 German patents across four technology areas. I calculated relative values for all FPD firms' German patents using Lanjouw's findings concerning relative differences in the value of German computer patents renewed in any given year. In total, FPD firms from around the world were awarded 1253 German FPD patents through the precommercial phase of competition. The innovative performance for a given firm during a given year is based on the value of its German FPD patents[3] commencing during that single year.

This patent renewal methodology allows us to explore the relationship between a firm's knowledge-sharing strategy and the utility of the innovations developed during the same period of time. Although each observation includes only a single year's patent awards, the use of the patent renewal methodology means that the dependent variable reflects how the value of each patent unfolded

[1] Potential costs of defending a patent against infringement increase expected costs substantially, and Lanjouw (1993) found that firms' decisions to maintain patent protection depended in part on their evaluation of these costs.

[2] Firms based in Germany were eliminated from the analysis.

[3] Patents were identified from International Patent Classes G02F, G09G, and G09F and were assigned to known FPD firms. Traditional display technologies such as cathode ray tubes are explicitly excluded from these patent classes.

over time into the commercial phase of innovation. The longer the firm chose to protect the patent, the greater the commercial value it is estimated to hold. In this way, we can link a firm's knowledge-sharing strategy to its concurrent innovation activity.

Knowledge sharing

A firm shares knowledge by making its scientific and technological knowledge public. This paper considers only the sharing of explicit knowledge, which can be transferred through detailed documentation, and not tacit knowledge, which is transferred only through richer channels such as extensive person-to-person communication (Polanyi, 1962; Winter, 1987). Knowledge sharing must take place in a public forum such as a scientific journal or technical conference that is open to scientists from a number of different organizations.

I distinguished between firms' decisions to share knowledge with their national and global innovation systems. A firm shares knowledge with its NIS by attending local and regional technical conferences, publishing papers in domestic outlets, and distributing papers to domestic colleagues. It shares knowledge with its GIS by attending foreign conferences, publishing papers in foreign scientific journals, publishing papers in foreign languages, and publishing in outlets that are widely read (and, thus, widely cited) internationally.[4] Table 1 lists the two dimensions of sharing knowledge with the NIS and GIS.

[4] In all cases but one, firms' national innovation systems reflected the country of the firm's main headquarters. However, since IBM headed its worldwide FPD operations in Japan (Murtha, Lenway, and Hart, 2001), publications and citations in Japan reflected knowledge sharing in the NIS, and publications and citations in the United States and Europe constituted knowledge sharing in the GIS.

The first dimension for each measure represented the *quantity* of knowledge each firm shared with its innovation system. One would expect that firms pursuing a knowledge-sharing strategy would publish more journal articles and present more papers at technical conferences than firms that prefer to protect their technological knowledge. The second dimension reflects the *relevance* of knowledge that each firm shared. Firms that published only knowledge that was well established in the industrial community, that scrubbed their articles so clean that the publications conveyed little real information, or that published on relatively obscure topics, should rarely be cited by external firms. I considered a firm's decision of publication outlet to be a strategic one. However, I standardized the second dimension to account for variations in the size of firms' NIS and GIS, and centered the data around zero. Finally, the quantity and relevance of total knowledge shared was calculated as: $\text{Quantity}_{\text{TOTAL}} = \text{Quantity}_{\text{NIS}} + \text{Quantity}_{\text{GIS}}$ and $\text{Relevance}_{\text{TOTAL}} = \text{Relevance}_{\text{NIS}} + \text{Relevance}_{\text{GIS}}$.

Research effort

The size of a firm's research effort in the FPD area has strong implications for its ability to develop a technically viable, patented product. Therefore, it is critical to understand the relationship between knowledge sharing and innovative performance, controlling for the size of each firm's research effort.

I included two independent measures of firms' research efforts. The first measure reflects the number of scientists devoted to research on FPD technologies, as indicated by the number of researchers in each firm who held membership in the Society for Information Display (SID). Because SID offered researchers benefits such as trade magazines, scholarly journals, and regular industry conferences in Asia, Europe, and North America,

Table 1. Sharing with the NIS and GIS

	Sharing with the NIS	Sharing with the GIS
Quantity	Number of articles and presentations by the firm's researchers in outlets in the firm's *home* country	Number of articles and presentations by the firm's researchers in outlets in *foreign* countries
Relevance	The number of times scientists in other *domestic* organizations cited the firm's publications and conference papers, divided by number of researchers in the NIS	The number of times scientists in *foreign* organizations cited the firm's publications and conference papers, divided by number of researchers in the GIS

industrial researchers received incentives to join the association. Because SID did not publish a membership directory during every year from 1969 to 1989, firms' membership levels were based on directories no more than 3 years distant from the specified year.

The second measure reflected the number of innovations that the firm chose to patent in the United States. A large number of publications may simply indicate that a high level of research productivity allowed the firm to develop many distinct innovations. The number of U.S. patent awards provides an indication of the number of distinct technologies that the firm has developed that meet some minimal threshold of utility (Griliches, 1990). In addition, cross-national differences in firms' patenting behaviors may arise (Maskus and McDaniel, 1999), and even within one country firms may vary on the percentage of their innovations that they choose to patent. U.S. patent awards, therefore, are included to control for these differences in propensity to patent. Since innovative performance is measured as the value of a firm's German patent portfolio, the inclusion of U.S. patent awards creates a conservative test for all hypotheses. All regressions were checked for multicollinearity, and no problems arose.

Size and nationality

It is possible that large multinational firms had slack resources to renew patents of questionable commercial value, or enjoyed a greater ability to apply for patents in foreign countries. Size and multinationality proved to be highly correlated. Therefore, I included only the size variable in this analysis. A 'large' firm dummy included in each regression equation identifies firms with more than 1000 employees. Finally, since firms based in some countries or regions may systematically outperform other firms, I included dummy variables identifying Japanese, North American, and European firms.[5]

Time effects

The value of FPD patents may well have changed over the course of industry emergence. Earlier patents may have been renewed for longer periods of time, since the industry environment remained uncertain for longer periods of time after these patents were awarded. Therefore, the precommercial period was divided into four equal time periods, and dummy variables were included in regression equations to control for time effects.

Data collection

German patent awards and renewals for all FPD firms came from microfilm and computer files at the German patent office in Munich, Germany. The bibliographic database INSPEC archived firms' publications and conference papers from 1969 to 1989. Articles on FPD technologies were identified using Boolean searches of keywords derived from interviews with engineers and managers of FPD companies. Because not all journals and technical conferences were consistently indexed in the database as far back as 1969, I manually entered information about articles that were cited by previously retrieved articles, but that had not, themselves, been listed in INSPEC. The full database, which included papers written by researchers in industry and academia, included papers that had been published in 39 countries and 19 different languages. 3448 articles were written by researchers in FPD firms, and these constituted the database used to measure the knowledge-sharing variables. Citations of one industrial researcher by another (34,802 in total) were entered manually from the physical articles themselves, and aggregated to the firm level for the analysis.

DATA AND RESULTS

The fundamental argument articulated above suggests that by sharing knowledge with its innovation system a firm can increase the chances that its technology will win out as the dominant design in an emerging industry. Table 2 reports results from an analysis of the knowledge-sharing networks of the primary technological approaches

Table 2. Valued densities in three major FPD technological networks

	1982–86	1977–81	1972–76
LCD	0.32	0.57	0.52
PDP	0.17	0.50	0.29
EL	0.17	0.00	0.00

[5] All Asian firms in the dataset were Japanese.

to FPD design: plasma, electroluminescent, and liquid crystal. Firms pursuing the same technological approach were grouped together into discrete networks, and all interfirm citation ties were identified. The density score of a given technology indicates the average number of citation ties between all possible participants in that technology's knowledge-sharing network. In order to exclude the possibility that a given technological network would display high density as a result of firms' tendencies to cluster around an established dominant technology, I have provided data across three 5-year time periods, and have excluded data from the last 2 years before the dominant design emerged in the industry.[6] Table 2 shows that the technology that eventually won out as the dominant design in the industry, the liquid crystal display, was more interconnected via citation relationships than either of its major technological rivals across all three time periods.[7] Similarly, a t-test showed that the mean values for both volume and relevance of shared knowledge between 1969 and 1986 were significantly higher for LCD firms than firms pursuing other technologies ($p < 0.03$ and $p < 0.01$, respectively). Although neither network analysis nor a t-test can show causality, these results are consistent with the notion that knowledge-sharing strategies can strengthen a firm's technological trajectory and increase the chances that the firm's technology will emerge as the dominant design.

Figures 1 and 2 show patenting and publication trends throughout the precommercial time period, and Table 3 provides descriptive statistics and correlations among all variables used in the regression analyses. Table 4 provides results from four regressions used to test Hypotheses 1–4.

Control variables generally held the same levels of significance across all four models. Dummy variables identifying the earliest two time periods were significantly and positively associated with the dependent variable, indicating that the earliest patent portfolios were renewed for longer periods of time than later portfolios. The dummy variable for North American firms was a significant, negative predictor of innovative performance, while the dummy variable for Asian firms did not emerge as significant. This suggests that Japanese FPD firms achieved higher innovative performance than firms from the United States, even when including their knowledge-sharing activities and measures of research effort in the analysis. Firm size was not a significant contributor to innovative performance.

[6] Technological networks containing fewer than four firms were excluded from the analysis, resulting in three primary technological networks. Firms were considered to be active in a given time period when they published at least one patent across that 5-year period.

[7] The number of firms in each technology varied across time, with the LCD technology having the largest number of firms in each period.

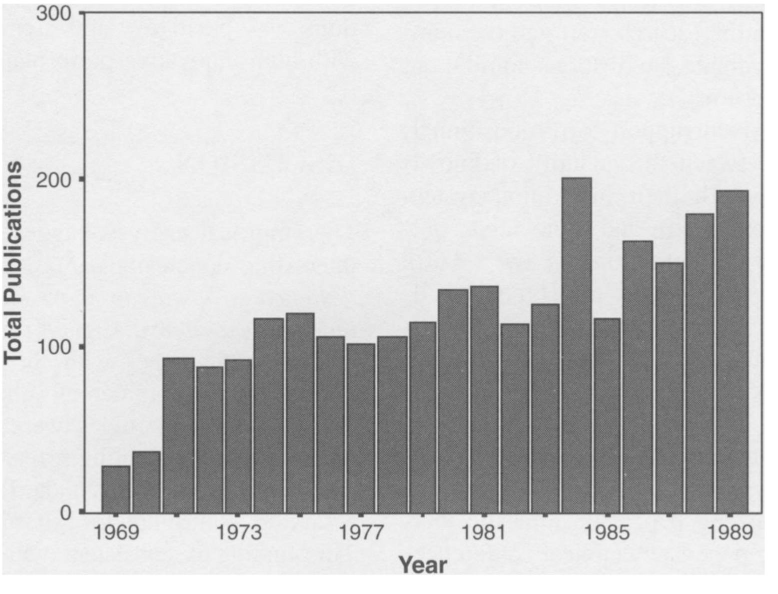

Figure 1. Total publications

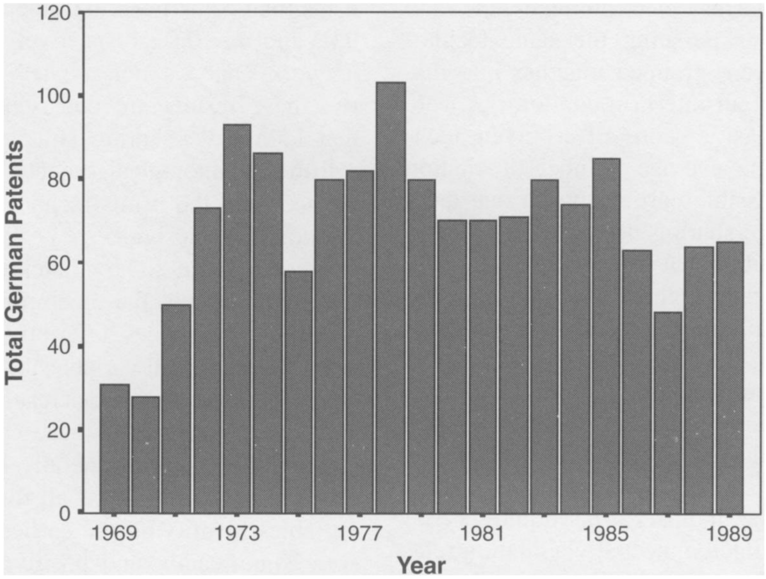

Figure 2. German patent awards

As expected, the two measures of research effort were strong predictors of innovative performance. Specifically, a large number of employees holding SID membership associated positively with high innovative performance. Similarly, the number of U.S. patents that the firm was awarded for FPD technologies was a strong predictor of high innovative performance. Together, these indicate a strong relationship between a firm's research effort and the value of its patent portfolio. Each knowledge-sharing variable, then, was tested after controlling for the size of a firm's research staff and the number of distinct, patentable, innovations coming out of the firm's laboratories.

Table 4 shows mixed support for Proposition 1. The relationship between the quantity of knowledge firms shared with their innovation system (NIS and GIS combined) and innovative performance was marginally significant ($p < 0.06$), offering only marginal support for Hypothesis 1. The relationship between the relevance of knowledge shared and innovative performance was significant at $p < 0.05$, offering support for Hypothesis 2.

Table 4 shows support for Proposition 2. Firms that shared a large quantity of knowledge with their NIS by publishing papers in domestic journals and presenting papers at technical conferences within their home country did not achieve higher innovative performance than firms that published little in their NIS. In contrast, firms that shared a large quantity of knowledge with their GIS by publishing papers in foreign journals and presenting papers at conferences outside their home country did see correspondingly higher innovative performance ($p < 0.05$). Similar results emerged when considering the relevance of knowledge shared with the NIS and GIS. Firms that had their research cited frequently by other domestic firms did not see increased innovative performance. However, citation of a firm's research by foreign organizations was positively and significantly associated with high innovative performance ($p < 0.05$).

DISCUSSION

The empirical analysis suggests three particularly interesting conclusions. *First, some firms actively designed strategies to share knowledge with their innovation systems.* Eighty firms shared at least one scientific paper with the innovation system during the precommercial phase of innovation. These published articles were regularly cited by researchers in competing firms, suggesting that the publications met the standard of relevance necessary to contribute to external research efforts. This finding is consistent with prior results suggesting that industrial researchers share technological knowledge with their innovation system

Table 3. Means, standard deviations, and correlations

	Mean	S.D.	Period 1	Period 2	Period 3	N. Amer. firms	Asian firms	Large firms	SID members	U.S. patents	Quantity (total)	Quantity in NIS	Quantity in GIS	Relevance (total)	Relevance (NIS)	Relevance (GIS)	Innov. perform.
Period 1	0.17	0.38	1.00														
Period 2	0.21	0.41	−0.24	1.00													
Period 3	0.27	0.44	−0.28	−0.32	1.00												
N. Amer. firms	0.53	0.50	0.09	0.01	−0.04	1.00											
Asian firms	0.33	0.47	−0.08	0.00	0.02	−0.75	1.00										
Large firms	0.78	0.41	0.12	0.07	−0.03	−0.14	0.00	1.00									
SID members	7.91	12.46	0.00	−0.07	−0.01	0.37	−0.29	0.26	1.00								
U.S. patents	0.96	2.29	−0.08	0.05	−0.05	−0.07	0.12	0.13	0.10	1.00							
Quantity (total)	2.17	3.54	−0.06	0.01	−0.03	0.04	−0.02	0.14	0.33	0.16	1.00						
Quantity in NIS	1.29	2.95	−0.02	−0.01	0.00	0.09	−0.08	0.15	0.43	0.11	0.87	1.00					
Quantity in GIS	0.88	1.73	−0.09	0.03	−0.07	−0.08	0.09	0.04	−0.05	0.13	0.56	0.08	1.00				
Relevance (total)	0.00	1.00	−0.06	0.05	−0.01	−0.12	−0.05	0.12	0.09	0.08	0.30	0.30	0.11	1.00			
Relevance in NIS	0.00	1.00	−0.03	0.05	−0.02	−0.09	−0.11	0.09	0.04	0.02	0.17	0.17	0.08	0.96	1.00		
Relevance in GIS	0.00	1.00	−0.11	0.03	0.00	−0.15	0.19	0.14	0.18	0.21	0.51	0.52	0.15	0.53	0.27	1.00	
Innov. perform.	35,789	105,299	0.12	0.16	−0.09	−0.18	0.15	0.14	0.03	0.18	0.09	0.06	0.08	0.10	0.06	0.15	1.00

All values above 0.06 significant at $p < 0.05$; $n = 1154$

Table 4. Regression analyses

Control variables	Quantity	Relevance	Quantity in NIS and GIS	Relevance in NIS and GIS
(Constant)	(0.85)	(0.63)	(0.74)	(1.20)
Period 1	0.22 (7.05)***	0.22 (7.00)***	0.23 (7.17)***	0.23 (7.17)***
Period 2	0.22 (7.10)***	0.22 (7.00)***	0.23 (7.17)***	0.22 (7.06)***
Period 3	0.05 (1.48)	0.05 (1.42)	0.05 (1.61)	0.05 (1.45)
N. Amer. firms	−0.20 (−4.45)***	−0.18 (−3.91)***	−0.20 (−4.52)***	−0.19 (−4.12)***
Asian firms	0.03 (0.73)	0.05 (1.14)	0.03 (0.66)	0.02 (0.51)
Large firms	0.02 (0.60)	0.02 (0.62)	0.02 (0.53)	0.02 (0.50)
SID members	0.09 (2.77)**	0.10 (3.22)***	0.11 (3.09)**	0.09 (2.78)**
U.S. patents	0.15 (5.41)***	0.16 (5.51)***	0.15 (5.32)***	0.15 (5.14)***
Quantity (total)	0.06 (1.88)†			
Relevance (total)		0.06 (2.00)*		
Quantity in NIS			0.02 (0.60)	
Quantity in GIS			0.06 (2.26)*	
Relevance in NIS				0.01 (0.45)
Relevance in GIS				0.08 (2.73)**
F	20.44***	20.50***	18.64***	19.03***
Adjusted R^2	0.13	0.13	0.13	0.14

Standardized coefficient (t-value); $n = 1154$
$^{\dagger}p < 0.10$; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

(Rappa and Debackere, 1992a; Henderson and Cockburn, 1994).

Second, firms that shared relevant knowledge with their innovation system earned higher innovative performance than firms that did not share knowledge. There was considerable variation in FPD firms' strategies to share or protect their technological knowledge. Some firms developed reputations for being very secretive, while others were seen as fairly open. This empirical study found that among FPD firms knowledge might have conveyed more value when it was shared with the innovation system than when it was kept secret. Many managers and researchers have contended that a firm's best interest lies in exploiting proprietary technological knowledge without attracting imitators to its technological trajectory (Scherer, 1980, 1992). However, these results are consistent with the argument that under some circumstances firms may be better off sharing their knowledge than protecting it from rivals.

The empirical results also distinguish between firms' strategies to share knowledge in their national and global innovation systems. These results are consistent with the argument that firms' strategies to share knowledge with the national innovation system are not sufficient to enhance a firm's innovative performance. Innovators that share knowledge only with firms in their own country do little to influence the emergence of the *global* dominant design, or even identify the trends emerging in that global industrial community. In contrast, by actively participating in its global innovation system, a firm lies ready to both observe and influence the standards that emerge in the global industry community. This active participation in the global innovation system is associated with higher innovative performance.

Prior research has suggested that firms may allow their researchers to publish academic papers in order to recruit and motivate their research staff (Henderson and Cockburn, 1994). This paper suggests that the effects of a firm's knowledge-sharing strategy extend beyond these internal productivity effects. For instance, Table 2 shows that the technological network that showed the densest pattern of knowledge sharing emerged as the dominant design in the FPD industry. In addition, if the relationship between a firm's knowledge-sharing strategy and performance were due to an increase in internal productivity alone, then one would expect similar effects from strategies to share knowledge with the NIS and the GIS. Indeed, since firms are most likely to recruit domestic scientists and to monitor their research staff's reputation within their national scientific community, one would expect knowledge sharing in the NIS to hold greater predictive ability than knowledge sharing in the GIS. In contrast, the logic presented in this paper suggests that within this globally integrated industry sharing knowledge with the GIS should have a stronger effect than sharing knowledge in the NIS. Future research should identify the relative importance of these complementary productivity and industry-shaping effects more explicitly.

It is possible that the empirical analysis presented here reflects a spurious correlation in which firms that employ the best scientists are likely to have both extensive numbers of foreign publications and high innovative performance. The findings suggest conclusions that extend beyond this simple correlation, however. First, one would expect highly effective scientists to publish more and be cited more in both their NIS and the GIS. Second, including U.S. patent awards as a control variable sets up a relatively conservative test reducing the possibility that both independent and dependent variables simply captured the volume of innovation taking place in a firm's R&D labs. Nevertheless, it is important to recognize that the analysis presented here does not establish a causal relationship between a firm's decision to share knowledge with the GIS and innovative performance.

Current literature on firms' standard-setting activities acknowledges that in networked industries firms may achieve higher performance by licensing their technology and introducing open architectures. For instance, the VHS design to video recorders may well have beat out its competitor, Betamax, because several firms licensed and produced VHS systems (Cusumano, Mylonadis, and Rosenbloom, 1992). Similarly, software developers commonly give away versions of their product for free in order to speed market acceptance of their design.

This paper suggests that the importance of having a critical mass of competitors on the same technological trajectory extends beyond firms operating in networked industries. The primary argument in this paper does not rest on the role of the common interface standards that are critical for success in networks. Instead, it highlights the importance of developing evaluation standards that favor the firm's product design and building a strong industry infrastructure.

Further, unlike previous research that focused on licensing and subassembly strategies, this paper focused on sharing technological knowledge as it was developed, with the possibility, and even intent, of having competitors internalize that knowledge. From the first publication to the last, each firm took the risk that its knowledge would provide its competitors with critical strategic resources. The finding that firms achieved higher innovative performance when they shared knowledge with the GIS is a much stronger conclusion in favor of this perspective than a finding that firms achieved higher performance by licensing out their patented technology.

Allen, Tushman, and Lee (1979) found that the most appropriate type of external communication varied with the nature of a firm's research project. More basic research projects tended to benefit when a wide range of researchers maintained extensive external communication, while more applied development projects succeeded most when a few researchers monopolized external communication. Further research should strive to identify the specific attributes of industries that reward knowledge-sharing strategies, as well as the best way of structuring employees' participation in a firm's knowledge-sharing activities.

Finally, the results from this paper suggest that in this globally integrated industry firms must develop strategies to participate in their global innovation system. Kobrin (1991) emphasized the roles of economies of scale and high investment requirements in determining whether or not an industry would become globally integrated. Zaheer and Zaheer (1997) expanded these criteria for identifying globally integrated industries by suggesting that in some sectors firms not only deal in identical products but also actively interact with one another in the same global marketplace and serve the same set of customers.

The FPD industry is also globally integrated in yet a third manner. Firms from all countries rely on a common institutional environment of technological and evaluation standards and on a common body of technological knowledge. The criteria that are used to evaluate the merits and tradeoffs between firms' product designs are themselves global. In this context, in order to achieve high innovative performance in FPDs, firms need to implement strategies to influence not only their national institutional environment but also the institutions emerging in their global innovation system. Further research should extend this finding to identify other ways in which firms' strategies are embedded in both national and global innovation systems.

In the meantime, in industries characterized by the emergence of a dominant design, managers should consider viewing their scientists' desires to publish in the scientific literature as an opportunity to influence the activities of competing firms, and should encourage their scientists to become active in their global, and not just national, research community. In the early phases of innovation in some industries, knowledge sharing may be one way that a firm can increase its innovative performance for the long run.

ACKNOWLEDGEMENTS

I extend thanks for suggestions and assistance on earlier drafts of this paper to Carolina Gomez, Stefanie Lenway, Sue McEvily, Thomas Murtha, Dennis Polla, Srilata Zaheer, Andrew H. Van de Ven, and two anonymous reviewers. All mistakes, of course, remain my own responsibility. I gratefully acknowledge funding from the Carnegie Bosch Institute, the Alfred P. Sloan Foundation, and George Washington University's Institute for Global Management Research.

REFERENCES

Abernathy WJ, Clark KB. 1985. Innovation: mapping the winds of creative destruction. *Research Policy* **14**: 3–22.

Allen TJ, Tushman ML, Lee DMS. 1979. Technology transfer as a function of position in the spectrum from research through development to technical services. *Academy of Management Journal* **22**(4): 694–709.

Almeida P, Kogut B. 1999. Localization of knowledge and the mobility of engineers in regional networks. *Management Science* **45**: 905–917.

Anderson P, Tushman ML. 1990. Technological discontinuities and dominant designs: a cyclical model of technological change. *Administrative Science Quarterly* **35**: 604–633.

Anderson P, Tushman ML. 1991. Managing through cycles of technological change. *Research in Technology Management* **34**: 26–31.

Arthur WB. 1988. Competing technologies: an overview. In *Technical Change and Economic Theory*, Dosi G, Freeman C, Nelson R, Silverberg G, Soete L (eds). Pinter: London; 590–607.

Barber B. 1990. *Social Studies of Science*. Transaction Publishers: London.

Barney JB. 1991. Firm resources and sustained competitive advantage. *Journal of Management* **17**: 99–120.

Bijker WE, Hughes TP, Pinch TJ. 1987. *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*. MIT Press: Cambridge, MA.

Cockburn IM, Henderson RM. 1998. Absorptive capacity, coauthoring behavior, and the organization of research in drug discovery. *Journal of Industrial Economics* **46**(2): 157–183.

Cockburn IM, Henderson RM, Stern S. 1999. Balancing incentives: the tension between basic and applied research. NBER working paper # W6882.

Cohen WM, Levinthal DA. 1990. Absorptive capacity: a new perspective on learning and innovation. *Administrative Science Quarterly* **35**: 128–152.

Cohen WM, Nelson RR, Walsh JP. 2000. Protecting their intellectual assets: appropriability conditions and why U.S. manufacturing firms patent (or not). NBER working paper #7522.

Collis DJ, Montgomery CA. 1995. Competing on resources. *Harvard Business Review* **73**(4): 118–128.

Constant EW. 1980. *The Origins of the Turbojet Revolution*. Johns Hopkins University Press: Baltimore, MD.

Crane D. 1969. Fashion in science: does it exist? *Social Problems* **16**: 433–441.

Cusumano MA, Mylonadis Y, Rosenbloom RS. 1992. Strategic maneuvering and mass-market dynamics: the triumph of VHS over beta. *Business History Review* **66**: 51–94.

Das SS. 1994. Constructing dominant designs: strategies of firms for technological competition. Doctoral dissertation, University of Minnesota.

David PA. 1985. Clio and the economics of QWERTY. *Economic History* **75**: 332–337.

Debackere K, Rappa MA. 1994. Technological communities and the diffusion of knowledge: a replication and validation. *R&D Management* **24**(4): 355–371.

Garud R, Kumaraswamy A. 1993. Changing competitive dynamics in network industries: an exploration of Sun Microsystems' open systems strategy. *Strategic Management Journal* **14**(5): 351–369.

Garud R, Rappa M. 1994. A socio-cognitive model of technology evolution. *Organization Science* **5**: 344–362.

Gomory RE. 1989. From the ladder of science to the product development cycle. *Harvard Business Review* **67**(6): 99–106.

Griliches Z. 1990. Patent statistics as economic indicators: a survey. *Journal of Economic Literature* **28**: 1661–1707.

Hall BH, Ziedonis RH. 2001. The patent paradox revisited: an empirical study of patenting in the U.S. semiconductor industry, 1979–1995. *RAND Journal of Economics* **32**(1): 101–128.

Henderson R, Cockburn IM. 1994. Measuring competence? Exploring firm effects in pharmaceutical research. *Strategic Management Journal*, Winter Special Issue **15**: 63–84.

Jaffe AB, Trajtenberg M, Henderson R. 1993. Geographic localization of knowledge spillovers as evidenced by patent citations. *Quarterly Journal of Economics* **108**: 577–598.

Kobrin SJ. 1991. An empirical analysis of the determinants of global integration. *Strategic Management Journal*, Summer Special Issue **12**: 17–32.

Lanjouw JO. 1993. Patent protection: of what value and for how long? NBER working paper #4475.

Lanjouw JO. 1992. Under threat: potential competition, litigation, and the private value of patent protection. Economics of Industry Group working paper no. EI/6, STICERD, London School of Economics.

Liebeskind JP. 1996. Knowledge, strategy and the theory of the firm. *Strategic Management Journal*, Winter Special Issue **17**: 93–107.

Liebeskind JP. 1997. Keeping organizational secrets: protective institutional mechanisms and their costs. *Industrial and Corporate Change* **3**: 623–663.

Lievrouw LA. 1989. The invisible college reconsidered: bibliometrics and the development of scientific communication theory. *Communication Research* **16**: 615–628.

Lundvall BA (ed.). 1992. *National Systems of Innovation*. Pinter: London.

Maskus KE, McDaniel C. 1999. Impacts of the Japanese patent system on productivity growth. *Japan and the World Economy* **11**(4): 557–574.

Merton RK. 1938. *Science, Technology and Society in Seventeenth-Century England*. Harper & Row: New York (reprinted 1970; and Humanities Press: Atlantic Highlands, NJ, 1978).

Merton RK. 1968. The Matthew effect in science. *Science* **159**: 56–63.

Murtha TP, Spencer JW, Lenway SA. 1996. Moving targets: national industrial strategies and embedded innovation in the global flat panel display industry. In *Advances in Strategic Management*, Vol. 13, Baum JAC, Dutton JE (eds). JAI Press: Greenwich, CT; 247–282.

Murtha TP, Lenway SA, Hart JA. 2001. *Managing New Industry Creation: Global Knowledge Formation and Entrepreneurship in High Technology*. Stanford University Press: Stanford, CA.

Nelson RR, Rosenberg N. 1993. Technical innovation and national systems. In *National Innovation Systems*, Nelson RR (ed.). Oxford University Press: New York; 3–22.

Nelson RR, Winter SG. 1982. *An Evolutionary Theory of Economic Change*. Belknap Press: Cambridge, MA.

North DC. 1990. *Institutions, Institutional Change and Economic Performance*. Cambridge University Press: London.

Pakes A, Schankerman M. 1984. The rate of obsolescence of patents: research gestation lags and the private rate of return to research resources. In *R&D Patents and Productivity*, Griliches Z (ed.). University of Chicago Press: Chicago; 73–88.

Podolny JM, Stuart TE. 1995. A role-based ecology of technological change. *American Journal of Sociology* **100**(5): 1224–1260.

Polanyi M. 1962. *Personal Knowledge: Toward a Post-Critical Philosophy*. Harper Torchbooks: New York.

Rappa M, Debackere K. 1992a. Pioneering scientists: an analysis of entry and persistence in a field. MIT working paper.

Rappa M, Debackere K. 1992b. Technological communities and the diffusion of knowledge. *R&D Management* **22**: 209–220.

Rappa MA, Garud R. 1992. Modeling contribution-spans of scientists in a field: the case of cochlear implants. *R&D Management* **22**(4): 337–348.

Ruttan V, Hayami Y. 1984. Toward a theory of induced institutional innovation. *Journal of Development Studies* **20**: 203–223.

Sahal D. 1981. *Patterns of Technological Innovation*. Addison-Wesley: Reading, MA.

Schankerman M, Pakes A. 1986. Estimates of the value of patent rights in European countries during the post-1950 period. *Economic Journal* **96**: 1052–1076.

Scherer FM. 1980. *Industrial Market Structure and Economic Performance* (2nd edn). Houghton Mifflin: Boston, MA.

Scherer FM. 1992. *International High Technology Competition*. Harvard University Press: Cambridge, MA.

Schilling MA. 1998. Technological lockout: an integrative model of the economic and strategic factors driving technology success and failure. *Academy of Management Review* **23**: 267–284.

Schott T. 1988. International influence in science: beyond center and periphery. *Social Science Research* **17**: 219–238.

Teece D. 1987. Profiting from technological innovation: implications for integration, collaboration, licensing and public policy. In *Competitive Challenge*, Teece D (ed.). Ballinger: New York; 185–219.

Tushman M, Rosenkopf L. 1992. Organizational determinants of technological change: toward a sociology of technological evolution. In *Research in Organizational Behavior*, Vol. 14, Staw B, Cummings L (eds). JAI Press: Greenwich, CT; 311–347.

Usher AP. 1954. *A History of Mechanical Inventions*. Harvard University Press: Cambridge, MA.

Utterback JM, Suarez FF. 1993. Innovation, competition and industry structure. *Research Policy* **22**: 1–21.

Van de Ven AH. 1993. A community perspective on the emergence of innovations. *Journal of Engineering and Technology Management* **10**: 23–51.

Van de Ven AH, Garud R. 1989. A framework for understanding the emergence of new industries. In *Research on Technological Innovation, Management and Policy*, Vol. 4, Rosenbloom RS, Burgelman RA (eds). JAI Press: Greenwich, CT; 195–225.

Van de Ven AH, Garud R. 1993. Innovation and industry development: the case of cochlear implants. In *Research on Technological Innovation, Management and Policy*, Vol. 5, Rosenbloom RS, Burgelman RA (eds). JAI Press: Greenwich, CT; 1–46.

Winter SG. 1987. Knowledge and competence as strategic assets. In *The Competitive Challenge: Strategies for Industrial Innovation and Renewal*, Teece DJ (ed.). Ballinger: Cambridge, MA; 159–184.

Zaheer S, Zaheer A. 1997. Country effects on information seeking in global electronic networks. *Journal of International Business Studies* **28**(1): 77–100.

Zuckerman H. 1978. Theory choice and problem choice in science. *Sociological Inquiry* **48**(3–4): 65–95.