Strategic Management Journal, Vol. 17(Winter Special Issue), 137–154 (1996)

HOW DOES KNOWLEDGE FLOW? INTERFIRM PATTERNS IN THE SEMICONDUCTOR INDUSTRY

MELISSA M. APPLEYARD
Department of Economics, University of California at Berkeley, Berkeley, California, U.S.A.

Although knowledge spillovers between firms play a critical role in the evolution of technology, we know little about such spillovers. How does knowledge flow across company boundaries? How do industry characteristics and national institutions shape knowledge diffusion? To what extent do companies direct knowledge flows? This study seeks answers to these questions by examining knowledge sharing patterns in the semiconductor industry. The research shows that public sources of technical data play a larger role in knowledge diffusion in Japan than in the United States and in semiconductors relative to steel. By understanding the mechanisms and determinants of knowledge flows, company managers and public policy makers can influence knowledge diffusion more effectively.

INTRODUCTION

This paper examines interfirm information flows in a knowledge-intensive industry. The study looks beyond assumptions that knowledge simply 'spills' across company boundaries to identify and examine the mechanisms by which technical knowledge is disseminated. Survey data on interfirm knowledge transfers in the semiconductor industry are used to explore why patterns of knowledge exchange are different both across industries and across countries. The findings offer a rare account of the primary knowledge sharing vehicles in the semiconductor industry, both in the United States and Japan, and provide a grounding for optimal strategies of knowledge management.

The paper is organized as follows:

- The next section presents a framework for analyzing knowledge sharing decisions by firms. Distinguishing between access to knowledge and its use, the determinants of the costs and benefits from knowledge sharing are identified.
- The third section outlines the primary hypothesis regarding patterns of knowledge sharing in semiconductors compared to steel, based upon the different characteristics of the two industries.
- The fourth section outlines the primary hypothesis concerning international differences in knowledge sharing, based upon different employment systems and intellectual property regimes found in the United States and Japan.
- The fifth section presents evidence on knowledge sharing drawn from surveys of employees in the semiconductor industry. In contrast to findings from empirical studies of the steel industry, *public* channels of communication play a *central* role in the transfer of knowledge in the semiconductor industry. The survey also finds international differences. Semiconductor employees in the United States are approached more frequently for technical information and are more likely to fulfill at least one request per year. However, Japanese workers are more likely to fulfill the majority of requests that they receive. The fieldwork provides a rare

Key words: knowledge sharing and spillovers, knowledge management, semiconductor industry

CCC 0143–2095/96/S20137–18

account of the primary knowledge sharing mechanisms in the semiconductor industry.
- The conclusions section draws implications from the study for the strategic management of knowledge sharing and for public policy.

WHY WOULD RIVALS SHARE?

This section provides a framework for thinking about the costs and benefits derived from knowledge sharing. Knowledge sharing is defined as the transfer of useful know-how or information across company lines. Knowledge sharing decisions are made by firms which process the knowledge on the basis of anticipated costs and benefits. Figure 1 depicts the knowledge sharing decision faced by a firm.[1] If the firm decides to share a piece of technical knowledge, it can do so publicly or privately, and either place legal restrictions on its use or permit unrestricted use. If the firm determines that the gains to exclusive use of the technical information outweigh the gains to sharing, then the firm can resort to secrecy.[2]

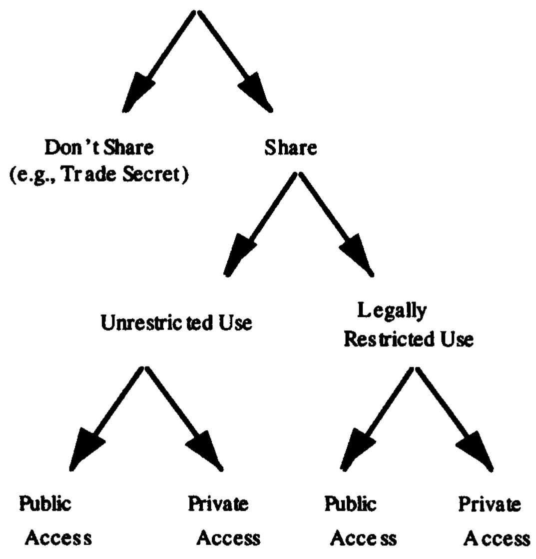

Figure 1. Knowledge sharing decision

The primary mechanisms of interfirm knowledge exchange are arranged in Figure 2 in terms of *access to* and *use of* the shared knowledge. Access to knowledge can occur either through *public* channels:[3] patents, reverse engineering, newsletters, popular press, trade journals, and conference presentations; or through *private* channels: e-mail, the telephone, face-to-face meetings, visits to other companies' fabrication plants (fabs), consortia or benchmarking studies.[4] Even if access to knowledge is public, its use may be *restricted* by legal constructs such as patents or nondisclosure agreements.

Figure 2 assumes that the use and dissemination of knowledge obtained by visiting other companies' fabs or participating in a consortium or benchmarking study face greater legal restrictions than do 'informal' interactions via e-mail, the telephone or face-to-face conversations. Private-unrestricted knowledge sharing is similar to private-restricted knowledge sharing in that costs are incurred to search for appropriate partners and forge relationships. The two modes, though, differ in important ways. First, there is limited legal recourse if the private-unrestricted sharing relationship faces a problem such as opportunism.[5] Second, private-unrestricted transfers incur minimal transactions costs when compared to the costs of drafting a formal agreement; this transaction cost reduction may more than offset the costs of intermittent opportunism.

From the viewpoint of the firm, the decision whether or not to share knowledge with another company depends on whether the expected benefits from relinquishing the monopoly over the knowledge outweigh the expected costs.[6] Unique,

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[1] Throughout this paper, it is assumed that employees' incentives are aligned with their firms', i.e., agency problems do not exist.

[2] Secrecy can be achieved in a number of ways. Instead of patenting, the firm often can create a trade secret. If the knowledge is publishable, the firm can refrain from publishing details that would permit exact duplication of the research results (Hicks, 1995: 408).

[3] Particular channels of knowledge diffusion may conduct certain *types* of knowledge more efficiently. Zander (1991) analyzes the influence of knowledge type on mode of diffusion selected by multinational companies. In a study of knowledge transmission in the United States, Machlup (1962) documents the level of transmission of five types of knowledge—practical, intellectual, pastime, spiritual, unwanted—through four channels: periodicals, newspapers, radio and television.

[4] Although not the focus of this study, legally enforceable, contractual agreements such as joint development and licensing agreements are common in the semiconductor industry (Kogut and Kim, 1991; National Research Council, 1992; Okimoto and Nishi, 1994).

[5] To some degree, negative reputation effects can substitute for legal actions against people who leak valuable information contrary to the wishes of their firms or knowledge sharing partners (von Hippel, 1988: 91).

[6] From the viewpoint of the policy-maker, the net benefit calculation includes the effects on the consumer surplus. See

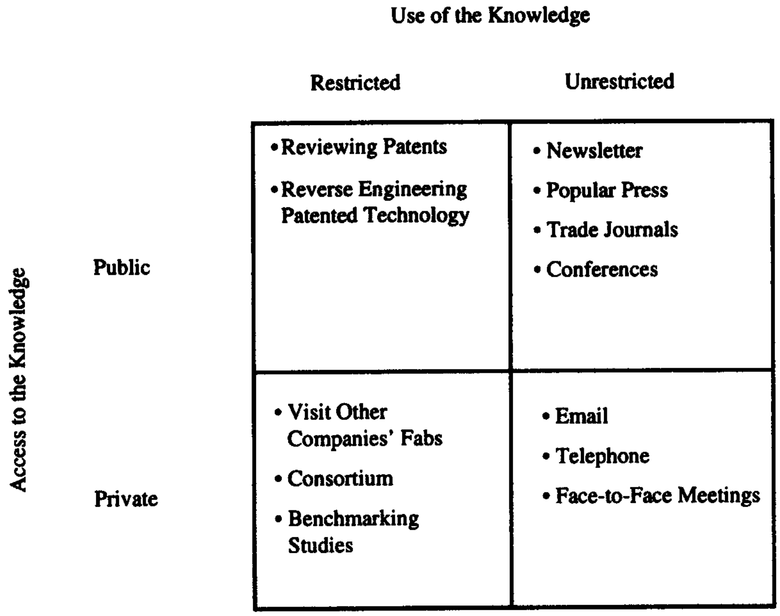

Figure 2. Knowledge sharing mechanisms

useful knowledge confers monopoly rights upon the possessor allowing the firm to charge premium prices or experience lower costs than its rivals. When the firm divulges its knowledge to a competitor, it gives up the monopoly over the knowledge and must share the rents, suffering 'competitive backlash' (Carter, 1989: 156). As long as the firm expects its sharing partner to reciprocate with useful knowledge or some other form of compensation, such as a licensing fee, it can justify interfirm disclosure.

For firm i at time t, the cost and benefit comparison can be represented by the following:

$$E_{it}[B(L, R, A)] \geq E_{it}[C(D, T)]$$

The firm's expected benefit from sharing the piece of knowledge, $E_{it}B$, is an increasing function of the following: revenue from licensing, L, legal rights to use the recipient company's technology, R, and/or knowledge from the recipient company, A.[7] Firm i's expected cost of knowledge sharing at time t, $E_{it}C$, increases with the decline in profitability, D, and the transaction costs, T, associated with the knowledge transfer.

Drawing on previous empirical studies, Table 1 presents cases of knowledge sharing and associated benefits.

In addition to the benefits, firms also must consider the costs. For example, when the knowledge owner patents and licenses knowledge to a market rival, Case III, L increases while the sharer's cost advantage may fall, since the rival can legally use the knowledge.[8] Depending on pricing conditions, erosion of the sharer's cost advantage may precipitate a decline in its profit-

Katz and Ordover (1990) for an exposition of the influence of interfirm R&D cooperation on social surplus and the role of government sanctioned consortia on knowledge diffusion patterns in the semiconductor industry.

[7] Another potential benefit from sharing knowledge is the fostering of relationships with other companies. Hicks (1995) emphasizes the role of publication in building a firm's credibility and entry into professional networks. Furthermore, repeated knowledge sharing between two companies might serve as a testing ground for more extensive relationships like a joint venture. (See Watson, 1996, for a game theoretic treatment of this concept.) When asked about the importance of a history of knowledge sharing when selecting a partner for joint development, however, a senior U.S. semiconductor development engineer replied that technical prowess far outweighs a favorable past history.

[8] The patent-license case subsumes know-how licensing. For a discussion distinguishing these two cases, see Arora (1995).

Table 1. Options for knowledge sharing

	Case	Nature of use	Knowledge owner's reward
I.	Trade secret	Private	Monopoly rents
II.	Patent no license	Private	Monopoly rents
III.	Patent and license	Private, bilateral	Duopoly rents + license fee (*L*)
IV.	Patent and cross-license	Private, bilateral	Duopoly rents + rights (*R*)
V.	Know-how trading (von Hippel, 1988; Schrader, 1991)	Private, bilateral	Oligopoly rents + knowledge (*A*)
VI.	Collective invention (Allen, 1983)	Private, network	Oligopoly rents + knowledge (*A*)
VII.	Message-based tech transfer (Allen, Hyman, and Pickney, 1983)	Private, network	Oligopoly rents + knowledge (*A*)
VIII.	Presenting at conferences or publishing	Public	Variable

ability, an increase in *D*, which will partially offset the benefits of *L*.[9] A similar outcome obtains when the knowledge owner patents and cross-licenses the knowledge, Case IV. Instead of licensing revenue the sharer receives rights of use, *R*, or, as many people in the semiconductor industry claim, a promise not to be sued. Finally, in the know-how trading case, Case V, the knowledge owner benefits from acquiring new knowledge, *A*, but must give up the monopoly rents associated with the knowledge that it shares. As for the transaction costs associated with the three cases, the cost of undertaking know-how trading is, in general, much lower than the other two especially in the presence of legal fees charged to draft and maintain licensing agreements.

CROSS-INDUSTRY COMPARISON OF KNOWLEDGE SHARING: SEMICONDUCTORS VS. STEEL

Previous studies of knowledge sharing behavior have focused largely on manufacturing intensive industries with a slow pace of technological change, in particular, the steel industry. However, the net benefits from knowledge sharing in an R&D intensive industry exhibit much higher variances. In the semiconductor industry, uncertainty surrounds the pay-off to a particular piece of knowledge due to difficulties in predicting: its useful life;[10] the breadth of its applicability across the industry; the ease with which it an be incorporated into another company's process flow; and whether it can be reverse engineered. Imperfect information may lead a knowledge owner to share its knowledge externally when, in fact, the *ex post* net benefit is negative. For example, if firm *i* licenses a processing technique to a rival, it earns *L*. But if the rival incorporates the technique much more quickly into its production process than firm *i* had anticipated, firm *i* may face a steeper decline in its profits, *D*, than initially anticipated.

The pace and nature of technological change in different industries can help explain why distinctive patterns of knowledge sharing coexist.

Hypothesis 1: If an industry experiences a rapid pace of technological change, reflected by the average time between new product or process introductions, private knowledge sharing in that industry will be less likely than in a slower paced industry.[11]

[9] Schrader (1991) provides a thorough analysis of the competitive factors that knowledge traders in the specialty steel and minimill industry consider prior to sharing information. Such factors include the degree to which the their companies compete and whether the knowledge falls into a highly competitive domain like product quality.

[10] Although a product's lifecycle may only last 2 years, process technology used in its manufacture may endure decades. For example, process chemistries used in performing anisotropic, or vertical, etches developed over a decade ago are still in use.

[11] Allen *et al.* (1983: 203) propose a related hypothesis: 'firms from industries with a more advanced degree of technological development (e.g., electrical and electronics; chemicals and

In support of the above hypothesis, von Hippel (1988) finds ample evidence that private-unrestricted know-how trading occurs in the U.S. steel minimill industry, an industry with a slow pace of technological change. He finds such activity almost nonexistent within industries that exhibit more rapid technological change such as powdered metals and biotechnology (von Hippel, 1988: 83), although von Hippel also observes private trading in the research-intensive U.S. aerospace industry. This phenomenon may appear: (1) because much of the research is 'basic,' and thus falls in the bottom category of Table 1; or (2) because of the nature of demand, which is primarily fueled by U.S. government procurement. As von Hippel observes (1988: 87), the aerospace companies curtail communications when government contracts come up for bid. After contracts are granted, however, informal knowledge sharing resumes. That is, when significant profits are at stake, private knowledge exchanges taper off, but recommence after the spike in demand dissipates.

Inventive activity in a development-intensive industry, such as the semiconductor industry, will occur in the top range of Table 1. New innovations often qualify for patent protection and the associated monopoly rents. In slower-paced industries, such as the steel industry, technological change is characterized by the accumulation of numerous incremental improvements over a long time horizon, thus limiting profitable patenting opportunities. Patents grant firms an enforceable claim to rents that accrue to innovations.[12] Patents also give the patent owners defined 'bargaining chips'[13] for technology swapping, e.g., cross-licensing, represented by R in the expected benefits function above. Also, if an industry exhibits rapid technological change, firms in that industry may opt to share little with their competitors to maximize the size of the 'technical cushion' between them. Technical cushions provide protection from a marked decline in profits, captured by a sharp rise in D in the expected costs function.

pharmaceuticals) will have a higher proportion than other industries of internally generated ideas.'

[12] Past studies have documented, however, that patent protection is considered a weak barrier against imitation (Levin *et al.*, 1987; Zander, 1991).

[13] Almeida and Kogut (1994: 23) observe that semiconductor firms often bargain with portfolio of patents.

Hypothesis 1 is tested by comparing knowledge sharing in the semiconductor industry with that in steel. There is an abundance of evidence of the faster pace of technological change in semiconductors. Table 2 shows relative patenting activity by pairs of similarly sized steel and semiconductor companies. R&D expenditure to sales was almost 8 percent in semiconductors in 1994, compared with 0.5 percent in steel (*Business Week*, 3 July 1995). This emphasis translates into a higher incidence of patenting and a higher degree of secrecy in the semiconductor industry relative to the steel industry. A consequence of rapid product and process innovation is rapidly declining product prices, especially in memory chips (see Figure 3). When the 16 megabit DRAM chips were introduced in late 1991, they ran nearly $300 per chip. By mid-1994, their price had plummeted to just under $50. Their current price is under $20 (*The Economist*, 4 May 1996: 66). Since the penalty of late entry into a product market is extremely high, semiconductor developers often are reluctant to provide specific technical information to their peers at competing firms.

Other industry characteristics, such as the nature of product markets, also distinguish the two industries. In a few major semiconductor product markets, such as microprocessors, where standards are based on firm-specific architectures, one would predict a higher level of secrecy. This is consistent with Rogers' findings in his study of microprocessor producers in Silicon Valley (Rogers, 1982).

These characteristics of the semiconductor industry—active patenting, large R&D expenditures, rapid price declines—reflect the frequent introduction of new production processes and products. Given this high frequency, the hypothesis proposed above would suggest that private knowledge sharing would be *less* likely in the semiconductor industry than in the steel industry.

KNOWLEDGE-SHARING IN DIFFERENT INSTITUTIONAL CONTEXTS: JAPAN VS. THE UNITED STATES

The net expected benefits to a firm from knowledge sharing depend not only on industry characteristics, but also on the institutional environment.

Table 2. Patenting behavior in the U.S. steel and semiconductor industries: Selected companies

Company	Type	1992 sales ($ mill)	1992 employment (000)	Total patents (1969–92)	Patents 1990	Patents 1991	Patents 1992	Average (1990–92)
USX	Integrated Steel	5465	21.6	1367	1	3	4	3
Bethlehem Steel	Integrated Steel	4899	29.6	647	13	11	13	12
Intel	Semiconductor	3921	23.9	473	45	56	73	58
Nucor	Steel Minimill	1482	5.5	5	na	na	na	na
LSI Logic	Semiconductor	656	4.4	52	5	10	20	12
Chaparral	Steel Minimill	404	1.0	<5	na	na	na	na
Raritan River Steel	Steel Minimill	270	0.6	<5	na	na	na	na
Cirrus Logic	Semiconductor	142	0.5	8	na	na	na	na

Note: 'na' represents 'less than five'.
Sources: Darnay (1993); U.S. Patent and Trademark Office (1993).

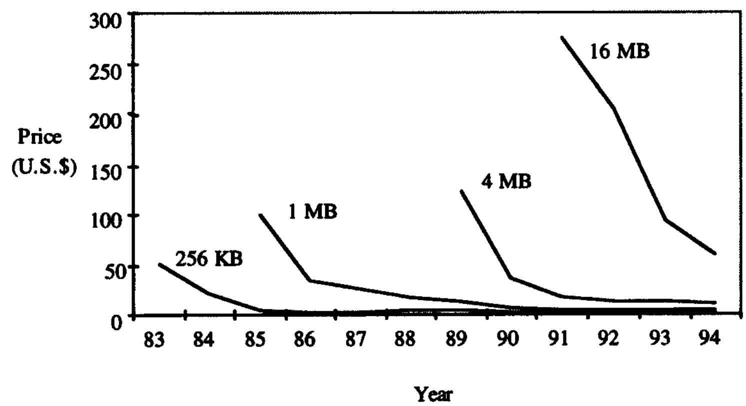

Figure 3. Price trends for DRAM products. Source: Appleyard, Hatch, and Mowery (1996)

The previous section discussed the impact of industry factors on interfirm knowledge sharing. This section extends the analysis by examining the following question: Do knowledge sharing patterns in a given industry differ across countries? Knowledge sharing among semiconductor firms in the United States and Japan is examined.

Two institutions, the intellectual property (IP) right regime and the employment system, differ markedly in the two countries, influencing the net benefit calculation. The institutional distinctions lead to the following hypothesis.

Hypothesis 2: Employees in the U.S. semiconductor industry are more likely to rely on private channels of communication than their Japanese counterparts.

Among the many differences in the IP regimes in the United States and Japan, perhaps foremost are the differences in their patenting systems. First, Japan follows a first-to-file system, whereas the United States follows a first-to-invent doctrine. Second, the patent breadth in Japan is, in general, narrower, where the 'patenting of individual applications' is possible (Katz and Ordover, 1990: 180 fn. 72). In contrast, the U.S. patent authorities generally require a broader range of application. Finally, in Japan, the system of *Kokai*, or 'laying open,' requires that all patent applications be published in the patent gazette by 18 months from the date of filing (Helfand, 1991: 186). In the United States, only patents that issue are made accessible to the public.[14]

When considering the variables influencing the net benefits from knowledge sharing, Japan's first-to-file patent system would likely discourage private, interfirm knowledge sharing to a greater degree than the U.S. system.[15] For example, semiconductor engineers in Japan may be reluctant to discuss ideas in early stages with competitors for fear that the competitors might try to patent the idea. If the originator of the idea is beaten to the patent office, the originator loses the patent and the expected benefits to licensing or cross-licensing, L and R respectively. Under the first-to-invent system in the United States, however, if the originator adequately documents his or her ideas prior to sharing them, the originator can secure property rights over the ideas when they are incorporated into useful applications. Furthermore, since patent breadth in the United States is broader, it is unlikely that talking about a 'small' idea related to a larger invention would disclose enough to jeopardize the originator's rights over the invention.

Both the first-to-invent provision and the broader breadth of the U.S. patent system lead to the prediction that U.S. semiconductor employees are *more* likely to share knowledge privately across company lines than their peers in Japan. The Japanese procedure of 'laying open' all patent applications reinforces this conjecture, since instead of privately sharing 'small' innovations, i.e., ones that would not qualify for patent protection in the United States, the public has access to patent applications.

The principal difference in labor market characteristics in the two countries that may shape knowledge sharing behavior is the level of turnover. Given that turnover of personnel in the semiconductor industry is higher in the United States than in Japan, it is more likely, *ceteris paribus*, that U.S. workers would have relationships with people at other companies, leading to a higher incidence of cross-company communication. To some degree, attending conferences could substitute for turnover in Japan as a way of establishing cross-company relationships. However, semiconductor engineers from both countries actively engage in professional conferences.[16]

In the cost and benefit framework above, turnover would likely influence the transaction cost, T, and the estimation of the decline in profits, D. Turnover decreases transaction costs associated with knowledge sharing, since it reduces the time to develop contacts at other firms. Departed employees often feel comfortable calling on previous co-workers for technical advice. Furthermore, a departed employee often can estimate how easily his or her former company could incorporate a piece of technical knowledge, thus leading to a more accurate estimate of D. Given this ability, it seems *unlikely* that the departed employee would receive requests from former co-workers for technical knowledge that would result in 'competitive backlash'. Such requests would be futile under the assumptions of this paper.[17] Therefore, the level of private knowledge exchange is predicted to be higher in the United States, since former co-workers are better able to share bits of technical knowledge without jeopardizing their employers' competitive positions.

SURVEY DATA

To determine whether knowledge sharing in the semiconductor industry differs both from patterns in the steel industry and across countries, we distributed a Learning and Communication Survey

[14] In August 1994, representatives from the United States and Japan announced a 'framework' for reconciling some of the differences in their patenting systems (Riordan, 1994).

[15] Note that the ensuing discussion focuses on knowledge sharing within a country. Given the global nature of the semiconductor industry, U.S. and Japanese companies patent in both countries and send their engineers to many of the same conferences, but it is assumed that intranational knowledge sharing is more common than international.

[16] Given the differences in the employment systems, an individual engineer's motivation to attend conferences may be very different in the two countries. U.S. engineers may be networking for a new job whereas Japanese engineers are more likely promoting the research feats of their firms (Nishi and Kobayashi, 1993). In the computer industry, Westney (1994) reports that Japanese firms encourage their employees to publish research results and participate in professional activities to a greater degree than U.S. firms.

[17] Such requests would be futile unless they were accompanied by side payments to individuals, but side payments are disallowed by the paper's assumption that agency problems do not exist.

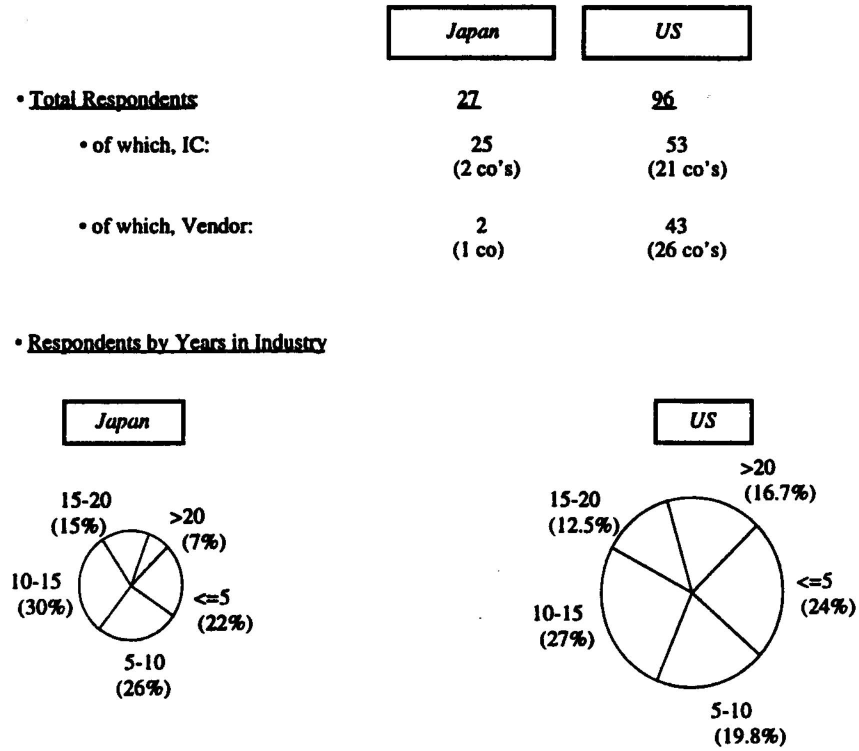

Figure 4. The sample

during 1994 and 1995.[18] The sample comprises questionnaire results from 134 employees of semiconductor and semiconductor equipment companies. The response rate was 40 percent. A total of 333 surveys were distributed to members of the following groups: engineers at participating firms in the University of California Berkeley's Sloan Competitive Semiconductor Manufacturing (CSM) Program that either recently joined the program or participated in a focus study of new process introduction; participants in the SEMICON West equipment trade show; participants in the Plasma Etch Users' Group meetings in Mountain View, California; IC and equipment vendor staff involved with the Quality and Organizational Systems group at Semiconductor Equipment and Materials International. The sample included circuit designers, development engineers, manufacturing engineers, technical sales staff, and quality control personnel.

Of the 134 respondents, 96 worked for U.S. companies, and 27 worked for Japanese companies.[19] Figure 4 shows that they principally worked for IC companies, and over 70 percent of the respondents from both countries have less than 15 years of industry experience.

The sample was not random, and there are some grounds for believing that the respondents were biased towards knowledge sharing. The majority of respondents had either previously agreed to participate in the benchmarking exercises of the CSM study or were attending an industry-related meeting when they were handed the survey. Even if the findings below overstate knowledge sharing activity in the semiconductor industry, they provide a useful reference point for both the primary mechanisms of knowledge sharing and its intensity.

[18] Appleyard wrote the survey with Clair Brown. They received useful input from Thomas J. Allen, Adriana Kugler, and Stephan Schrader. John Schuler was very helpful in distributing the questionnaire.

[19] The remaining respondents are employed by materials suppliers, national laboratories, or universities. Of the total respondents, 104 are located in the United States, 27 in Japan, 2 in Europe, and 1 in Singapore.

RESULTS

Knowledge sharing in semiconductors vs. steel

Given the greater degree of technological change in semiconductors relative to steel, Hypothesis 1 posits that private, cross-company communication would be *less* likely in the semiconductor industry. A comparison of semiconductor survey results with results from a study of the U.S. specialty steel and minimill industry reported in Schrader (1991) supports this hypothesis, but only to a limited degree. The findings highlight that *public* sources of knowledge sharing are much more prevalent in the semiconductor industry than found by previous studies of the steel industry.

A few questions in the Learning and Communication Survey were matched to questions contained in the MIT Steel Industry Communication Survey in order to determine industry-specific communication patterns.[20] In both industries, engineers valued colleagues at other companies. The Learning and Communication Survey asked respondents to rate nine possible sources of technical information on a 7-point scale, where 1 represented 'not at all important' and 7 represented 'very important'. For comparison with the steel study, the semiconductor sample was limited to the 53 respondents from 21 U.S. IC companies. The majority of these respondents were engineers who worked on circuit design, semiconductor process development or equipment development and modification, although a number worked in materials procurement and manufacturing operations. The steel study drew on a much larger sample, 294 respondents, comprised of middle-level managers and engineers. In the semiconductor sample, 57 percent rated technologists at other companies as an important source of technical information, meaning that they scored this source 5 or above on the 7-point scale. This compares with 61 percent of respondents from the steel study (Schrader, 1991: 154). This finding provides only marginal evidence for the hypothesis that knowledge sharing is *less* common in semiconductors than in steel.

Although colleagues at other companies were found to be valuable in both industries, the importance of this source relative to other sources reveals a more striking difference. On average, in the semiconductor industry, technologists at other companies ranked *fourth* behind colleagues within the respondent's company, journals, books, etc. and presentations at conferences (Table 3). In contrast, the steel study found that colleagues at other companies ranked *second*, on average, behind colleagues within the same company. This difference highlights the important role that public sources of technical information play in the semiconductor industry, a very development-intensive industry.

When comparing the frequency with which the respondents answered outside requests for specific technical information, the respondents from the semiconductor industry were less likely to engage in knowledge sharing. A smaller percentage of the semiconductor respondents were approached by someone outside of their company for technical advice or for technological information during the year prior to the survey year: 79 percent of the semiconductor respondents had been approached at least once vs. 85 percent in the steel industry (Schrader, 1991: 155). Not only were the semiconductor respondents less likely to be approached, but a higher percentage of those approached fulfilled none of the requests for specific technical information: 10 percent vs. only 2 percent in the steel study (Schrader, 1991: 155). One interesting finding to note, however, is that 23 percent of the semiconductor respondents reported being approached 11 or more times,

Table 3. Important sources of technical information for IC respondents (1 = highest average score)

	Japan (n = 25)	United States (n = 53)
Private sources		
Colleagues in company	1	1
Technologists at other companies		4
Equipment vendors		
Materials suppliers		
Customers		
Benchmarking studies		
Public sources		
Presentations at conferences	3	3
Journals, books, etc.	2	2
Patents	4	

[20] The author would like to thank Stephan Schrader for providing a copy of the MIT survey.

whereas 19 percent of the steel respondents were approached 10 or more times. This may suggest that semiconductor engineers who have established their reputations through journal articles and conference presentations receive a higher number of requests per year relative to 'gurus' in the steel industry who do not receive as much public exposure.

Overall, 71 percent of the U.S. semiconductor respondents had participated in cross-company knowledge sharing compared with 83 percent of the respondents from the steel study. Although this difference is not dramatic, the survey results do suggest that engineers in the U.S. semiconductor industry rely less on private contacts in other companies for technical advice than in steel.

Table 4. Preferred knowledge sharing vehicles linking IC respondent with another IC company (1 = highest average score)

	Japan (n = 25)	United States (n = 51)
Private vehicles		
E-mail		
Telephone		4
Face-to-face meeting		3
Visit to other company's fab		
Consortium		
Benchmarking studies		
Public vehicles		
Newsletter		
Popular press	2	
Trade journals	4	1
Conferences	1	2
Reviewing patents	3	
Reverse engineering		

Knowledge sharing in Japan vs. the United States

This section extends the analysis of knowledge sharing patterns by examining cross-country differences within the same industry. After limiting the sample to respondents who worked for IC companies in the United States and Japan, the findings suggest a distinctive pattern of knowledge sharing in the two countries, supporting Hypothesis 2: the Japanese respondents relied on *public* channels for external knowledge acquisition, whereas the respondents from U.S. companies gave a higher rank to *private* channels. This is supported by a similar finding reported by Almeida and Kogut (1994: 18): relative to semiconductor engineers in the United States, Japanese engineers possess fewer 'informal contacts' at competitors. Semiconductor workers in the United States were approached more often for technical advice and were more apt to fulfill at least one request per year. According to ordered logit estimates, however, home country does not play a statistically significant role in determining participation in knowledge sharing.

On average, respondents from both countries scored colleagues in company, journals, books, etc. and presentations at conferences as the three most important sources of technical information. The U.S. respondents, though, relied on technologists at other companies and the Japanese respondents relied on patents to a greater degree (Table 3). In terms of finding out useful technical information from 'horizontal' sources, i.e., from fabrication plants at other semiconductor companies, the IC respondents from Japan rated public vehicles as the most important (Table 4). In contrast, the U.S. respondents scored personal channels of communication, namely face-to-face meetings and telephone, in their top four.

A similar pattern was found for how IC workers find out useful technical information from equipment vendors, or 'vertical' sources (Table 5). Although their most important vehicles of knowledge sharing overlapped to some degree, the Japanese respondents were more reliant on public sources than their U.S. counterparts.

Figures 5 and 6 present the opportunities for and the incidence of knowledge sharing involving the IC respondents from the United States and Japan. Consistent with the hypothesis that U.S. workers rely more heavily on private knowledge sharing, nearly 80 percent of the U.S. respondents vs. 64 percent of the Japanese respondents were approached at least once in a given year by someone from another company in the industry for technical information (Figure 5).

Approximately 90 percent of the respondents from both countries fulfilled at least one request (Figure 6).

Although the Japanese respondents were less likely to be asked and slightly less likely to answer at least one request, those respondents who *did* fulfill requests were more likely to fulfill

Table 5. Preferred knowledge sharing vehicles linking IC respondent with vendor (1 = highest average score)

	Japan (n = 20)	United States (n = 48)
Private vehicles		
E-mail		
Telephone		2
Face-to-face meeting		1
Use vendor's facilities		
Consortium		
Benchmarking studies		
Public vehicles		
Newsletter		
Popular press	1	
Trade journals	2	4
Conferences	4	
Reviewing patents		
Trade shows	3	3

over half the requests. This appears to counter Hypothesis 2 that workers in a labor market with higher turnover (the United States) would be more likely to fulfill requests, since they have more information with which to value the costs of knowledge sharing.[21] In the sample, the turnover rate is slightly higher in the United States: None of the Japanese respondents from IC companies had ever changed companies, whereas the U.S. respondents had worked for, on average, 1.1 other semiconductor companies and 0.3 equipment vendors.[22] In addition to turnover, conferences are another way to learn about competitors, but the attendance rate is similar across the sample: on average, the respondents from both coun-

[21] The Learning and Communication Survey, however, does not ask whether the requesters are former coworkers or not.
[22] However, Almeida and Kogut (1994:17) find that interfirm mobility of authors of major semiconductor patents is nearly as high in Japan as in the United States.

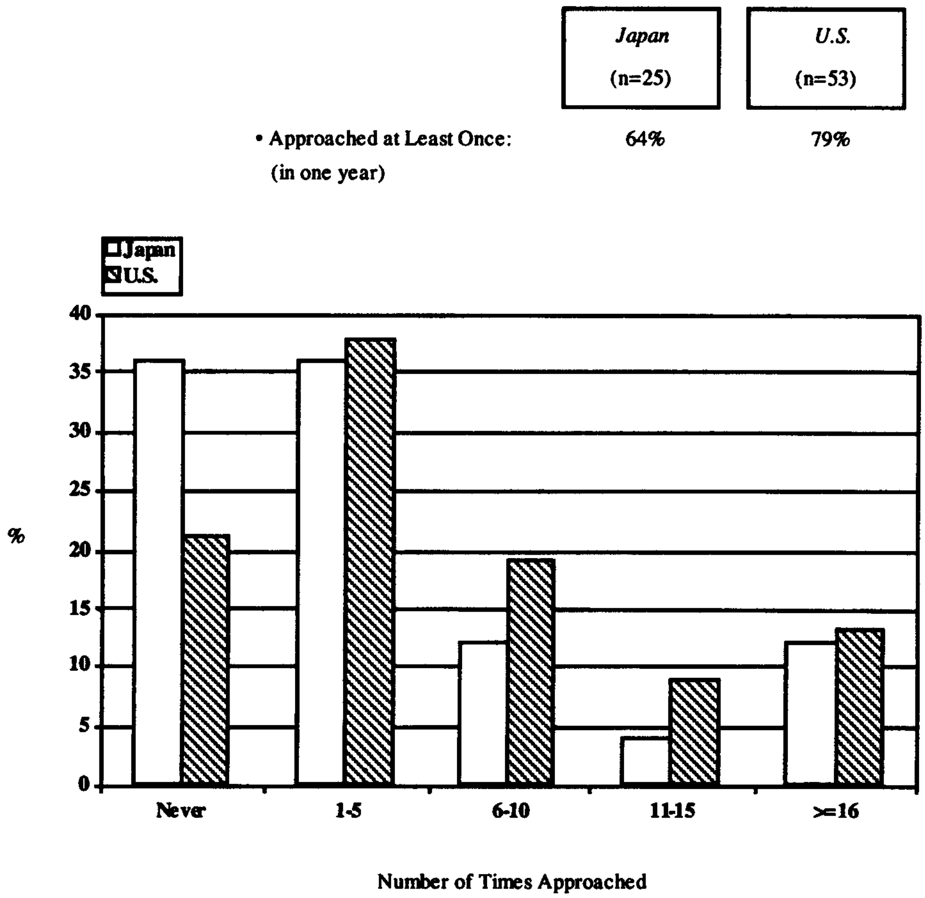

Figure 5. Opportunities for knowledge sharing

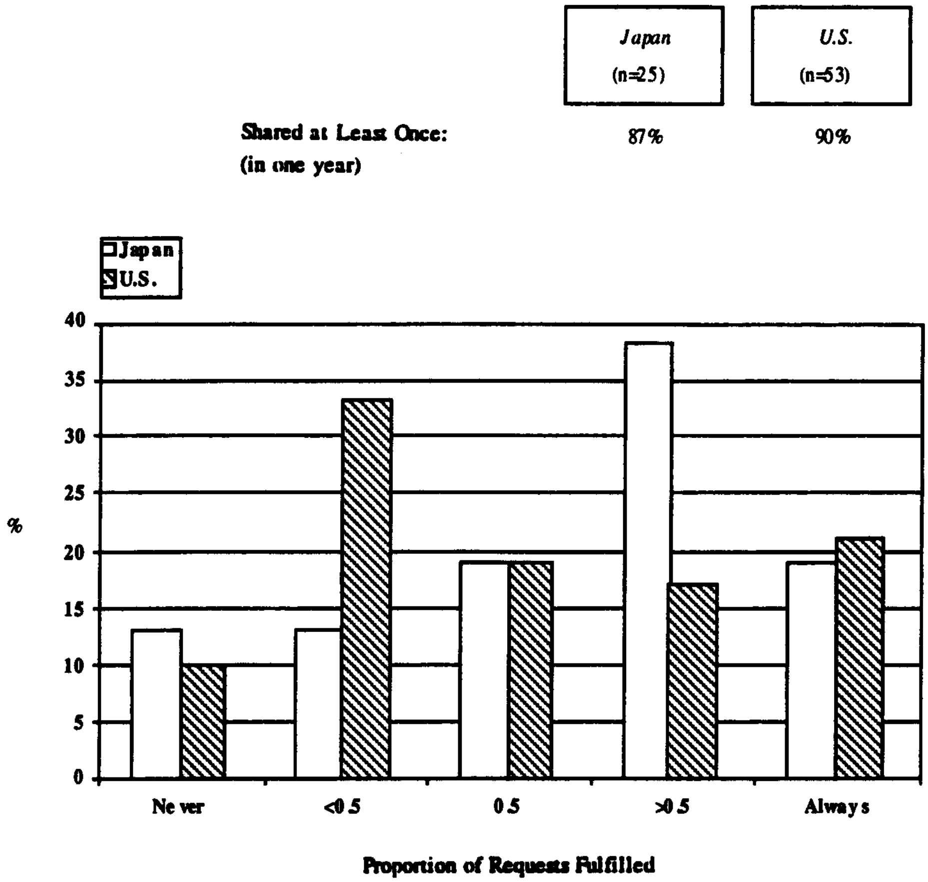

Figure 6. Incidence of knowledge sharing

tries attend approximately 1.5 conferences per year. Instead of refuting Hypothesis 2, the high level of request fulfillment in Japan may reflect business etiquette, whereby one would rarely request knowledge unless the knowledge owner would feel comfortable providing it (Kato and Kato, 1992: 18).

The profile of a knowledge-sharer

Using the larger sample of 123 respondents from Japanese and U.S. companies, the determinants of participating in knowledge sharing are tested using logit analysis. The characteristics of the respondents included in the ordered logit estimations are presented in Table 6, along with their predicted signs.

In addition to testing whether the respondent's home country influenced knowledge sharing behavior, the remaining independent variables fell into two general categories: the respondent's personal characteristics, and components of his or her firm's knowledge management system. First, because of institutional differences, home country is predicted to influence the likelihood of knowledge sharing, with U.S. residents exhibiting a *higher* likelihood of sharing. Second, respondents with the following characteristics were expected to engage in knowledge sharing more frequently: those who worked for equipment vendors, had a high level of education, had a long tenure in the industry, had higher levels of interfirm turnover, were members of professional societies, consulted people outside of their company when solving technical problems, and worked on technical issues common to other companies or universities. These characteristics were predicted to heighten the potential for interaction with outsiders.

Finally, the components of a firm's knowledge management system can influence an employee's participation in interfirm communications. Two components considered are: training in infor-

Table 6. The explanatory variables for the ordered logit analysis

Independent variables	Values	Included in ordered logit with dep. variable 'Approached'?	Included in ordered logit with dep. variable 'Provided'?	Hypothesized sign
U.S. resident	1 = United States 0 = Japan	Yes	Yes	+
IC Company	1 = IC 0 = Eq. vendor	Yes	Yes	–
Level of education	1 ≤ College 2 = College 3 = Masters 4 = Ph.D	Yes	Yes	+
Industry tenure	Continuous	Yes	Yes	+
Turnover	Continuous	Yes	Yes	+
Member of a professional society	1 = YES 0 = NO	Yes	Yes	+
Consulted outsider	1 = YES 0 = NO	Yes	Yes	+
Paper presentations for pay or promotion	1 = YES 0 = NO	Yes	Yes	+
Common technical issues	1 = YES 0 = NO	Yes		+
Sensitive information training	1 = YES 0 = NO		Yes	–

mation control, and rewards for presenting papers at professional conferences. If the respondent's company provided training on how to control sensitive information, it is predicted that the respondent would be more hesitant to provide requested information. If the respondent's company included paper presentations at professional conferences in pay or promotion decisions, then the company actively encouraged external knowledge diffusion.

After eliminating respondents with missing values, 95 respondents were used in the ordered logit analyses. The categories for the first dependent variable *approached*—the number of times the respondent was approached for technical information in the year previous to the survey year—are found at the bottom of Figure 5: *Never, 1–5, 6–10, 11–15*, or ≥ *16* times. The categories for *provided*—the number of times the respondent provided the requested information—are located at the bottom of Figure 6: *Never, Less than Half, About Half, More than Half*, or *Always*. The estimated coefficients are reported in Table 7.

Home country and turnover are predicted to influence the likelihood of being approached for technical information and providing such information. The results in Table 7, show, however, that neither working in the United States nor the level of turnover confer a statistically significant effect. Consistent with these results, Lynn, Piehler, and Kieler (1993: 68) found that U.S. engineers *do* have a greater number of interfirm contacts on average, but they found 'no statistically significant difference (at the 0.05 level) in the frequency with which Japanese and U.S. engineers used personal contacts at other companies for information.'[23]

The only two variables that are statistically significant with the predicted sign are whether the respondent worked for an IC company and the respondent's tenure in the industry. The estimates reported in Table 7 indicate that IC respondents

[23] Their sample consisted of engineers who graduated from Carnegie Mellon and Tohoku University in electrical engineering and metallurgical engineering/materials science.

Table 7. Ordered logit results

Independent variable	Estimate	Standard error
Results for 'Approached for specific technical information'		
U.S. resident	0.278	0.531
IC company	−1.899***	0.432
Level of education	0.246	0.229
Industry tenure	0.045*	0.025
Turnover	0.034	0.069
Member of a professional society	0.524	0.413
Consulted outsider	−0.130	0.388
Paper presentations for pay or promotion	−0.253	0.357
Common technical issues	−0.563	0.417
Results for 'Provided the requested technical information'		
U.S. resident	−0.145	0.660
IC company	−1.222***	0.460
Level of education	0.025	0.229
Industry tenure	0.056**	0.027
Turnover	−0.042	0.045
Member of a professional society	−0.060	0.477
Consulted outsider	−0.984**	0.414
Paper presentations for pay or promotion	−0.264	0.407
Sensitive information training	0.047	0.450

*Significant at the 10% level.
**Significant at the 5% level.
***Significant at the 1% level.

are more likely to fall in the *Never* categories of both dependent variables, whereas people with long tenure in the industry are more likely to fall in highest categories. The results are consistent with the predictions.

A surprising finding is the negative and significant coefficient on 'consulted outsider' reported in the second set of results in Table 7. The negative coefficient suggests that those who asked colleagues at other companies for assistance when problem solving were *less* likely to provide technical information when *they* were asked. This appears to counter the intuition that reciprocity drives knowledge sharing. However, the respondents were not asked to disclose whether they had established relationships with people who approached them.[24]

To understand the rules of thumb followed by respondents when deciding whether to provide requested technical information, the questionnaire asks: 'If you did not [fulfill all requests], how did you decide which requests to answer?' Grouping the answers into broad categories, the respondents replied that they share information across company lines when: (1) the information is of a general sort; that is, nonconfidential or nonproprietary; (2) the information does not confer a competitive advantage; or (3) according to guidelines of the employer or a supervisor's assessment, the information may be shared. Two respondents shared information only if they anticipated reciprocation in the future, implying the existence of trading relationships and countering the negative coefficient on the 'consulted outsider' variable.

DISCUSSION AND CONCLUSIONS

Knowledge creation is essential for growth in industries where the augmentation of knowledge increases at a rapid pace. The management of knowledge in an industry like semiconductors

[24] Schrader (1991) analyzes the role of previous relationships in shaping knowledge trading. He finds that ties of friendship do not play a significant role in heightening the likelihood that requested information would be provided.

becomes a key competitive variable. Successful knowledge management hinges on optimal cross-company sharing directed by net benefit calculations. Based on survey data, this research has shown that even in a fiercely competitive industry, both public and private mechanisms are used for interfirm knowledge sharing. In Japan, semiconductor employees rely on public mechanisms. In the U.S. semiconductor industry, private channels are used to a greater extent but less so than in steel. Many of the mechanisms place limited restrictions on the use of the shared knowledge. Even when knowledge is shared through channels with limited legal recourse, e.g., through face-to-face communication *not* covered by a legal contract, the benefits can have long-run pay-offs both for the firms involved and for the broader economy. As discussed below, the primary benefits accruing to firms that share include: the ability to refine strategic plans, inclusion in professional networks, and coordination on industry standards. Knowledge sharing also fuels growth in regional and national economies by fostering communities of innovators and ensuring knowledge diffusion.

Implications for firms

Input into strategic plan

Firms that share knowledge often receive knowledge in the process (recall A in the net benefit calculus). Knowledge gathering through public and private channels is an integral part of a firm's 'competitor intelligence system' (Porter, 1980: 71).

Through private communication channels, a development engineer often can learn about the technical problems encountered by a competitor. This information can be used by the engineer's company to alter the allocation of resources and to update expectations for future revenue streams. Depending on the progress of their competitors, technology managers may need to revise their projections for licensing revenues or cross-licensing opportunities (L and R, respectively, in the net benefit calculation). Product managers may need to release products earlier than initially planned which may compress future product planning cycles.

As companies expand their product portfolios, they benefit from learning about organizational systems, as well as technical feats. For example, as Japanese semiconductor producers increasingly turn towards architecture-based products, such as microprocessors, and away from commodity products, such as DRAMs, they are experimenting with employment systems that increase rewards to individual creativity. They have learned about options for structuring individual rewards by talking to their U.S. counterparts.

Access to professional networks

Many view knowledge sharing as an 'admission ticket' to the 'back room' discussions of professional groups. By encouraging their engineers to gain admission to these sharing blocs, companies can access private knowledge that may not be patented or published (Hicks, 1995), thus increasing the domain of their knowledge variable, A, in their net benefit calculation. For example, the results of failed experiments are rarely published in journal articles, but learning about them can prevent a firm from duplicating failures. Reflecting the importance of professional ties, over 70 percent of both the Japanese and American respondents to the survey discussed in this paper noted that either they are members of professional societies or that their companies are members of an industry association.

Formation of industry standards

Interfirm knowledge sharing also permits the emergence of industry-wide standards. Semiconductor producers have benefited from agreeing on issues such as wafer diameter and chemical purity requirements. Since these issues are precompetitive in nature, they avoid 'antitrust concern' (Teece, 1993: 15). Coordination can occur in a variety of forums—industry association meetings, industry consortia, etc.—and often requires private, informal communications to circulate technical information and build consensus.

Industry-wide coordination on input standards can increase profitability. It decreases uncertainty about the quality of the knowledge variable, A, in the net benefit calculation, permitting tighter process specifications. Precise process specifications facilitate new process transfer from development to high-volume production and improve production control, thereby attracting customers with stringent reliability requirements.

Few companies adequately prepare their engineers for knowledge sharing, and even fewer internalize the technical and organizational information that their engineers gather. As discussed below, efficient knowledge sharing requires companies to train their engineers and develop information arteries through which externally gathered knowledge can circulate to strategists throughout the organization.

Preparing the knowledge-sharer

The important public and private knowledge sharing vehicles discussed in this paper differ in terms of the intensity of human interaction. For example, the use of trade journals can be characterized by a low intensity of interaction relative to face-to-face meetings. Although a number of the respondents *did* receive company training in paper writing and communication skills, the training was not universally provided.

In order to protect their most strategic knowledge assets, firms must work with their employees to determine which domains of knowledge are off-limits to outsiders and which vehicles of knowledge sharing are preferred. Many semiconductor companies conduct thorough internal reviews of papers prior to submission and screen conference presentations to control knowledge diffusion. But by encouraging employees to estimate the net benefit from sharing knowledge and by hiring legal counsel to help select appropriate sharing vehicles, companies can assist their employees more explicitly. In the absence of guidance, employees will often choose knowledge sharing vehicles with very low transaction costs (T in the net benefit calculation), since they are reluctant to draw up lengthy agreements detailing permitted uses of the knowledge.

Throughout this paper, it was assumed that agency problems do not exist. However, to ensure that the incentives of individuals align with their firms' objectives, changes to employment systems may be necessary. Rewards that emphasize certain sharing mechanisms play an important role in the knowledge management system. Based on data from the Learning and Communication Survey, Japanese engineers are more likely to rely on patents and journal articles for useful technical information than their U.S. counterparts. Their companies encourage participation in these public arenas to a greater degree: The Japanese respondents gave a higher rank to patent awards, conference presentations, and published journal articles as determinants of their pay and promotions than the U.S. respondents. Because turnover is more prevalent in the United States, it is not surprising that many U.S. companies in the sample rely more heavily on individual bonuses, profit sharing, and stock options to help align their employees' incentives.

Constructing a circulation system

Firms can bolster their knowledge stock by actively internalizing information that their employees acquire during knowledge sharing. However, engineers are notorious for their reluctance to document their work outside of their personal lab books. Therefore, firms may need to dedicate people to track engineers' externally gathered knowledge. This 'knowledge tracker' also can function as a resource by scanning journal articles and patents to augment the engineers' own searches. Many of the respondents noted that their companies employ people for the latter function, but the internalization of externally gathered knowledge often is neglected. Finally, after the knowledge is culled from the engineers, it must be distilled and circulated to other strategic groups within the firm in a timely fashion.

Implications for the economy

Not only is it important for firms to understand knowledge flows, but public policy-makers should also consider the implications of knowledge sharing patterns for regional and national growth.

Regional buoyancy

Local officials may wish to encourage active professional networks to ensure the long-term vitality of a geographic region. When comparing the success of California's Silicon Valley with the relative stagnation of Route 128 outside of Boston, Saxenian (1994) finds that the tradition of interorganizational knowledge sharing in Silicon Valley has spurred the entrepreneurial activity of the region, whereas the tradition of secrecy along Route 128 has stifled such activity. Silicon Valley's regional flexibility has permitted its technical community to adapt to changing market conditions through strong professional ties. These ties link technical experts across company lines and extend across institutional boundaries to the academic communities of Stanford and the University of California at Berkeley and the investor community of local venture capitalists.

Economy-wide growth

At a national level, a country's growth potential relies on idea creation and dissemination (Romer, 1990: S72), and government policy that shapes knowledge sharing can have enduring effects. For example, the creation of a national consortium may strengthen some lines of communication but weaken others. Engineers who work for consortium members may talk face-to-face more frequently, thus strengthening their private channels of communication. However, members of the consortium may be restricted to sharing research findings only among consortium members, thus restricting knowledge diffusion.

As this research demonstrates, interfirm knowledge sharing along private and public channels is an important phenomenon in the semiconductor industry with profound implications not only for a firm's vitality but for an economy's growth. The survey data presented show that public sources of technical information play a larger role in knowledge diffusion in Japan relative to the United States and in the semiconductor industry relative to the steel industry. Only by understanding the net benefits from knowledge sharing, which are influenced by the institutional context and the characteristics of the industry under analysis, can managers and public policy-makers pursue optimal knowledge management systems.

ACKNOWLEDGEMENTS

I am indebted to Sarah Bales, Clair Brown, Bronwyn Hall, David Mowery, Paul Romer, Stephan Schrader, the SMJ reviewers, my dissertation group, the participants in the University of California at Berkeley's Institutions and Labor seminars, the participants in the ADRES Strasbourg Conference on Innovation and many people associated with the semiconductor industry, including Tony Alvarez, Jose Arreola, Neil Berglund, Dan Flamm, Jim Nulty, John Schuler, and the late Vinay Sohoni for useful comments and insights. I gratefully acknowledge the Alfred P. Sloan Foundation for funding.

REFERENCES

Allen R. C. (1983). 'Collective invention', *Journal of Economic Behavior and Organization*, **4**(1), pp. 1–24.

Allen, T. J., D. B. Hyman and D. L. Pinckney (1983). 'Transferring technology to the small manufacturing firm: A study of technology transfer in three countries', *Research Policy*, **12**(4), pp. 199–211.

Almeida, P. and B. Kogut (1994). 'Technology and geography: The localization of knowledge and the mobility of patent holders', working paper, The Wharton School, University of Pennsylvania.

Appleyard, M. M., N. W. Hatch and D. C. Mowery (1996). 'Managing the development and transfer of new manufacturing processes in the global semiconductor industry', working paper, University of California, Berkeley, CA.

Arora, A. (1995). 'Licensing tacit knowledge: Intellectual property rights and the market for know-how', *Economics of Innovation and New Technology*, **4**, pp. 41–59.

Business Week (3 July 1995). 'R&D scoreboard', pp. 1–18.

Carter, A. P. (1989). 'Knowhow trading as economic exchange', *Research Policy*, **18**(3), pp. 155–163.

Darnay, A. J. (ed.) (1993). *Manufacturing U.S.A.* Gale Research Inc., Detroit, MI.

The Economist (4 May 1996). 'Japanese semiconductors: Flat as a pancake', pp. 66.

Helfand, M. T. (1991). 'How valid are U.S. criticisms of the Japanese patent system?', working paper, Stanford University.

Hicks, D. (1995). 'Published papers, tacit competencies and corporate management of the public/private character of knowledge', *Industrial and Corporate Change*, **4**(2), pp. 401–424.

Kato, H. and J. Kato (1992). *Understanding and Working with the Japanese Business World*. Prentice-Hall, Englewood Cliffs, NJ.

Katz, M. L. and J. A. Ordover (1990). 'R&D cooperation and competition', *Brookings Papers on Economic Activity*, pp. 137–203.

Kogut, B. and D.-J. Kim (1991). 'Strategic alliances of semiconductor firms', working paper, 'The Wharton School, University of Pennsylvania.

Levin, R. C., A. K. Klevorick, R. R. Nelson and S. G. Winter (1987). 'Appropriating the returns from industrial research and development', *Brookings Papers on Economic Activity*, **3**, pp. 783–831.

Lynn, L. H., H. R. Piehler and M. Kieler (1993). 'Engineering careers, job rotation, and gatekeepers in Japan and the United States', *Journal of Engineering and Technology Management*, **10**(1–2), pp. 53–72.

Machlup, F. (1962). *The Production and Distribution of Knowledge in the United States*. Princeton University Press, Princeton, NJ.

National Research Council (1992). *U.S.–Japan Strategic Alliances in the Semiconductor Industry: Technology Transfer, Competition, and Public Policy*. National Academy Press, Washington, DC.

Nishi, Y. and H. Kobayashi (1993). 'A comparison between Japanese and American technology management practices'. In R. S. Cutler (ed.), *Technology Management in Japan*. Westview Press, Boulder, CO, pp. 31–53.

Okimoto, D. and Y. Nishi (1994). 'R&D organization in Japanese and American semiconductor firms'. In M. Aoki and R. Dore (eds.), *The Japanese Firm*. Oxford University Press, New York, pp. 178–208.

Porter, M. E. (1980). *Competitive Strategy*. Free Press, New York.

Riordan, T. (17 August 1994). 'U.S., Japan in accord on patents', *The New York Times*, pp. C1–2.

Rogers, E. M. (1982). 'Information exchange and technological innovation', In D. Sahal (ed.), *The Transfer and Utilization of Technical Knowledge*, Lexington Books, D. C. Heath, Lexington, MA, pp. 105–123.

Romer, P. (1990). 'Endogenous technological change', *Journal of Political Economy*, **98**(5 part 2), pp. S71–S102.

Saxenian, A. (1994). *Regional Advantage*. Harvard University Press, Cambridge, MA.

Schrader, S. (1991). 'Informal technology transfer between firms: Cooperation through information trading', *Research Policy*, **20**(2), pp. 153–170.

Teece, D. J. (1993). 'Information sharing, innovation, and antitrust', working paper, University of California, Berkeley, CA.

U.S. Patent and Trademark Office (1993). *Industrial Patent Activity in the U.S.* GPO, Washington, DC.

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

Watson, J. (1996). 'Building a relationship', working paper, University of California, San Diego, CA.

Westney, D. E. (1994). 'The evolution of Japan's industrial research and development'. In M. Aoki and R. Dore (eds.), *The Japanese Firm*. Oxford University Press, New York, pp. 154–177.

Zander, U. (1991). *Exploiting a Technological Edge: Voluntary and Involuntary Dissemination of Technology*. Institute of International Business, Stockholm.