Knowledge Search and its Effects on the International Diffusion of Knowledge: Evidence from Information Storage Technology Patents

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ABSTRACT

While research has shown that knowledge spillovers are geographically localized, the globalization of R&D is making international knowledge diffusion increasingly important. We propose that the propensity and speed with which technological knowledge diffuses across national borders is influenced by signals and cues during the search for new knowledge. In the context of the global information storage technology, we show that patented knowledge with high technological impact has higher propensity and speed of international diffusion than low impact knowledge. Moreover, an organization's technological strength increases the likelihood and speed of international citation of its innovations, while internal appropriation efforts reduce diffusion.

(100 words)

Key Words: knowledge diffusion, innovation, patenting, information storage.

1. INTRODUCTION

Knowledge spillovers have long been a focus of both the economics and management literatures (Schumpeter, 1942; Kuznets, 1966; Griliches, 1984; Grossman and Helpman, 1991). Scholars have explored patterns of knowledge flows within and across firms, geographic regions, and nations. They conclude that knowledge flows are constrained by legal barriers, coordination and communications costs, as well as geographic boundaries (Teece, 1977; Jaffe et al. 1993; Cohen et al. 2000). However, the increasing globalization of R&D activities in recent years suggests that greater attention should be paid to the diffusion of knowledge across national boundaries.

In this paper, we focus on why certain types of knowledge diffuse faster across national boundaries than other types of knowledge. The literature has largely focused on the causes and consequences of knowledge localization (Almeida and Kogut, 1999; Rosenkopf and Almeida, 2003; Singh, 2006), and few studies have explored the underlying heterogeneity of knowledge. While some types of knowledge are highly constrained by geographic boundaries, other types diffuse broadly and rapidly. Building upon the innovation literature as well as institutional theory, we propose that the knowledge search process is guided by signals and cues, and this shapes the patterns of knowledge diffusion. We show that a patented invention is likely to exhibit greater international diffusion if it has greater perceived technological importance, if the originating organization is seen to have greater competitive relevance, and if the originating organization has invested less effort to internally appropriate the returns from innovation.

Besides the propensity of knowledge spillovers, the speed with which spillovers occur is also important (Mansfield, 1985). Firms compete not just on the basis of their ability to create knowledge, but also on the speed of knowledge transfer and imitation (Zander and Kogut, 1995). The rate of knowledge transfer is one of the issues at the core of evolutionary theory (Nelson and Winter, 1982). But with rare exceptions (e.g., Zander and Kogut, 1995), the literature has neglected the temporal dimension of knowledge spillovers. We show that the perceived technological importance, competitive relevance and appropriability of an innovation affect the speed of international knowledge diffusion.

The context of our study is the information storage industry, which has experienced very rapid technological change and globalization over the last three decades. It is an arena of intense innovation-based competition (Christensen, 1997; McKendrick et al, 2000; McKendrick, 1998; Rosenkopf and Nerkar, 2001). As described by McKendrick (1998), the industry is both internationally dispersed and regionally concentrated. The geographic distribution of innovation and manufacturing activities makes this an excellent context to study cross-country knowledge diffusion. Figure 1 shows the rapidly increase in the number of information storage-related patents awarded by the US Patent office since 1976. The high incidence of patenting in this context is consistent with a rapid pace of technological change, and the importance of innovation. For example, Seagate Technology, a leader in the industry, was issued over 2 500 patents by the USPTO during 1976-2004.

Insert Figure 1 about here

Our analysis draws upon a sample of 6,077 utility patents issued in five separate years between 1976 and 2004 by the US Patent and Trademark Office (USPTO). Consistent with our hypotheses, we find that a patent's technological importance and its originating organization's technological strength are positively related to the subsequent propensity and speed of international diffusion. The patent owner's efforts at internal appropriation (by developing follow-on inventions that build upon the focal patent) have a negative impact on international knowledge diffusion.

Our research helps to tie together the literature on international knowledge flows with that on knowledge search. In doing so, we move the debate beyond the well-established fact that knowledge is geographically localized. While this is true for the ‘average’ patent in our sample, there is tremendous heterogeneity in the degree to which a patent diffuses abroad. We contribute empirical evidence, showing that diffusion is driven by key elements of the knowledge search process, such as the quality of knowledge embodied in a patent, and signals about the knowledge owner’s technical reputation and appropriation intent. Thus we offer evidence that organizational and institutional forces are important determinants to international knowledge diffusion.

In the next section, we review the prior literature and develop hypotheses. Section 3 describes the dataset and methodology for our empirical analysis. The results are presented in Section 4. Section 5 discusses our results and presents our conclusions.

2. LITERATURE AND HYPOTHESES

2.1 The Geographic Localization of International Knowledge Flows

The literature on international knowledge diffusion has focused mainly on its effects and spatial distribution. One stream of research examines how international R&D flows relate to patterns of cross-border trade (e.g. Coe and Helpman, 1993; Branstetter, 1998, 2001). These studies suggest that country-level productivity is shaped by cross-border flows of technical knowledge (Rosenberg, 1981). Moreover, technological proximity is an important factor that facilitates international knowledge spillovers (Griliches, 1979, 1984; Jaffe, 1986).

A second stream of research examines the spatial pattern of spillovers, and finds a high degree of geographic localization. In early work, Marshall (1920) identified knowledge spillovers as one of three factors that favor the geographic agglomeration of firms within an industry. Using US patent data, Jaffe et al. (1993) provided systematic empirical evidence of technological knowledge localization at the country, the state as well as metropolitan levels, after controlling for the pre-existing concentration of technology activities. They also found that localization fades with time. Subsequent research incorporated geographic distance as a key element of innovation production (Jaffe, 1989; Krugman, 1991; Feldman, 2000; Audretsch and Feldman, 1996), and found a tendency of innovative activities to cluster in regions where knowledge-generating inputs are most highly concentrated and where knowledge spillovers are the most prevalent (Porter, 1990; Saxenian, 1990). In recent work, Thompson and Fox-Kean (2005) refined the methodology used by Jaffe et al., and found that national borders remain a significant constraint to knowledge spillovers, while localization effects at the state and metropolitan levels diminished.

Complementing the above literature, management scholars have examined the underlying mechanisms of knowledge spillovers at the firm level. Building upon the concept of tacit knowledge (Polany, 1966), various management scholars have highlighted the lack of codification of knowledge as the prime deterrent to its diffusion within and across organizations (e.g. Nelson and Winter, 1982; Kogut and Zander, 1993, 1995; Von Hippel, 1994; Szulanski, 1996). When knowledge is less codified and embodied in persons, face-to-face communication becomes necessary in knowledge transfer. Consequently, engineer mobility (Saxenian, 1990; Almeida and Kogut, 1999; Rosenkopf and Almeida, 2003; Song et al., 2003) and interpersonal networks (Granovetter, 1973; Dahl and Pedersen, 2004; Singh, 2005) have been found to significantly influence the transfer of knowledge. Such mechanisms are typically constrained by geographic proximity. As pointed out by Sorenson and Fleming (2004): "absent publication, much of the knowledge gained from research remains private and must diffuse through interpersonal networks. Since these social networks typically remain localized in both physical and social space, transmission occurs most frequently among those in close proximity, and only slowly reaches more distant parties."

While knowledge appears to be geographically localized, scholars have begun to question the extent to which heterogeneity exists along this dimension. While finding evidence that the social distance between inventors helps to account for the geographic localization of knowledge, Singh (2005:769) also speculates that such networks may be useful for overcoming the constraints of distance. Sorenson and Fleming (2004) observe that when knowledge is made public (as is the case with patents), this "accelerates the flow of information by releasing the diffusion process from the limited set of contacts available through social networks". Cowan and Jonard (2004) model the structure of network interactions and show that knowledge diffuses much more completely in specific regions ("small worlds") than elsewhere. They caution that while it is currently popular for governments to pursue a policy of promoting industrial clusters, it is possible to have too much clustering, and that it is preferable to build strong links outside a cluster.

Unfortunately, few studies have examined the heterogeneity of knowledge diffusion. It remains a question whether some types of knowledge have a greater tendency to diffuse across national borders, and with greater speed. We propose that the search process used by organizations in exploring new ideas affect the propensity and rate of knowledge diffusion across national borders.

2.2 Knowledge Search and the International Diffusion of Knowledge

Prior research shows that a significant proportion of innovative activities by firms are incremental improvement built upon past inventions, both their own as well as others', i.e. inventions are built by "standing on the shoulders of giants", rather than as de novo discoveries that are a complete break from prior knowledge (Scotchmer, 1991). A key question for firms engaging in R&D is to decide which prior technological innovations to base their future innovative efforts on. While many factors are likely to influence such decisions, the literature on technological competition suggests that three attributes of a particular technological innovation are likely to affect the propensity and speed with which other inventors will develop future innovations based upon it: *perceived technological importance*, *competitive* *relevance*, and *appropriability*.

a) Perceived Technological Importance

While firms can in principle allocate R&D resources between the pursuit of both explorative and exploitative innovative activities, it is likely that a significant proportion of the R&D of incumbent firms is in fact devoted to the latter category, i.e. incremental improvements on a set of technologies that form the basis of the firm's core products or processes. Consequently, technologies that are perceived to be of greater importance to the foundation of the existing industry are likely to receive greater attention by firms competing within the industry, and they are more likely to base their future innovative efforts around such technologies than around other technologies of minor importance.

In an ideal world where information search and evaluation is costless, firms can exhaustively search all available prior knowledge and independently evaluate their value to judge which prior knowledge is of greater importance. However, in reality information search and evaluation cost is significant, as succinctly stated by Greenberger (1971):

> "What information consumes is rather obvious: it consumes the attention of its recipients. Hence a wealth of information creates a poverty of attention, and a need to allocate that attention efficiently among the overabundance of information sources that might consume it."

Consequently, bounded rationality (Simon, 1957; March, 1994) suggests that firms will resort to heuristic rules or signals to filter information to determine which prior technological innovation is likely to be important, and which is not. While the ideal indicator of the technological importance of an invention is the potential stream of economic values it commands ex-post, this information is not available ex-ante to firms other than the owner of the patent, and even the latter's estimation is likely to be highly uncertain (Hall, Jaffe and Trajtenberg, 2005). Faced with such uncertainty, inventors follow signals and cues from the trajectory of the technology, with a number of ideas emerging to become important inducement mechanisms that focus their efforts and search direction (Rosenberg, 1969).

The literature provides evidence that the number of citations received by a patented invention represents a useful signal of its technological importance to other firms engaged in the similar field, i.e. the more highly cited a patent, the more likely it is to be perceived as important by others (see e.g. Trajtenberg, 1990; Albert et al., 1991; Narin, Noma and Perry, 1987; Carpenter et al, 1981; Harhoff et al, 1999). But while this idea has been verified empirically at the patent and firm level, its impact on cross-border knowledge flows has not been empirically validated. We therefore hypothesize the following:

Hypothesis 1-1: The propensity of a patent to diffuse across national boundaries is positively associated with its perceived technological importance, as measured by the patent's prior citation count.

Hypothesis 1-2: The speed with which a patent diffuses across national boundaries is positively associated with its perceived technological importance, as measured by the patent's prior citation count.

b) Competitive Relevance

In addition to assessing the general technological importance of prior technological inventions, firms also need to assess the competitive relevance of their inventions. To be successful, firms have to invest in acquiring business-sensitive information about external scientific or technological developments, with some firms even relying on dedicated technology intelligence teams and sophisticated science-mapping tools (Norling, et. al, 2000). The literature on competitive intelligence (see e.g. McGonagle & Vella, 1990) suggests that the identity of the inventing organization is likely to represent an important signal of its competitive relevance, with more attention being assigned to knowledge generated by organizations that have a higher reputation in terms of competitive standing in the industry. This is consistent with institutional theory, which posits that organizations face strong pressures to mimic each other, or "mimetic isomorphism".[1] According to DiMaggio and Powell (1983: 152), "organizations tend to model themselves after similar organizations in their field that they perceive to be more legitimate or successful". Thus, all else being equal, firms are likely to pay more attention to the inventions of technological leaders in their industry, rather than to minor competitors. As a result, innovations by organizations with greater technological capability in a particular technology are more likely to attract follow-on innovations by other firms.[2] We thus hypothesize:

Hypothesis 2-1: The propensity of a patent to diffuse across national boundaries is positively associated with the originating organization's technological strength in that area.

Hypothesis 2-2: The speed with which a patent diffuses across national boundaries is positively associated with the originating organization's technological strength in that area.

c) Internal Appropriation

A key concern for innovators is the ability to appropriate the returns to their inventive effort. In principle, a patent provides the owner with the ability to appropriate rents either via licensing fees, or by internal exploitation of the knowledge through the firm's own products and services (Teece, 1986). In practice, however, other firms may create derivative innovations that build upon the invention covered by the original patent, and such derivative innovations, when patented, may block

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[1] Apart from mimetic isomorphism, the other two forms are coercive and normative isomorphism. Coercive isomorphism is not applicable in this case, since the process of R&D is generally voluntary. Normative isomorphism is driven by professional (inventor) networks and mobility, which have been explored in the literature as discussed in Section 2.1.

[2] Similar use of heuristics for filtering information has been documented in other research. For example, Merton (1968) described the Matthew effect in which scientists confronted with the growing task of identifying significant work published in their field rely upon the professional reputation of authors as cues. Also important is the reputation of the institution to which the authors are affiliated.

subsequent commercial exploitation of the original patent. For this reason, cross-licensing practices are widespread in many industries as they allow the original patent owners and derivative patent owners to exchange rights to freely operate.

To ensure appropriation of returns from a patented invention in a competitive industry, the owner of a patent therefore has an incentive to invest in pursuing derivative inventions before others do so. Prior research has highlighted the importance of self-citations as an indicator of the intention and efforts made by the patent owner to appropriate the returns from it (see e.g. Trajtenberg et al., 1997; Hall et al. 2001, 2005). The higher the extent to which a firm's patents cites its own prior patents, the more aggressive it is in appropriating the returns to the cited patents. According to Somaya (2003), self-citations indicate the patentee's level of strategic interest in the associated commercial space, and patentees with a high level of self-citation are more aggressive, and thus less likely to settle during patent litigation.

From the perspective of competitor firms trying to assess whether to invest in developing derivative innovations, the aggressiveness of the original patent owner in investing in internal appropriation is likely to be an important deterrent signal. Derivative patents are often complementary technologies, which are a form of complementary assets (Teece, 1986) that raise the barriers to imitation (Reed and DeFillippi, 1990; Zhao, 2006) and heighten the appropriability of the original invention. The strategy of building a "patent wall" or "ring-fencing" is an important strategy used by patent owners, and one that competitors try hard to avoid (Ziedonis, forthcoming). We therefore propose:

Hypothesis 3-1: The propensity of a patent to diffuse across national boundaries is *negatively* associated with the extent of internal appropriation efforts by the patent owner, as measured by the degree of patent self-citations.

Hypothesis 3-2: The speed with which a patent diffuses across national boundaries is *negatively* associated with the extent of internal appropriation efforts by the patent owner, as measured by the degree of patent self-citations.

3. DATA AND METHODOLOGY

Our study focuses on the information storage technology industry. We chose this setting for three reasons. Firstly, patenting activity in this area grew rapidly over the twenty-year period 1976-1996 (Figure 1). Secondly, the internationalization of the R&D activity and patents in this industry has been significant. Figure 1 shows that although most of the patents were invented in the US and Japan, patents invented in other countries increased around 2.5 times from 146 patents in 1976 to 358 patents in 1996. The third reason we chose the information storage industry is because the number of cross-country citations has increased over time, suggesting a growth in international knowledge flows. Figure 2 presents the average number of foreign citations each patent received. It shows a steady increase of cross-country knowledge diffusion in information storage technology during this period. The slightly decrease in 1996 is probably due to the right-censoring of citations. Patents issued in 1991 to inventors outside of USA and Japan received an average of 7.2 foreign citations. This represents a high frequency of cross-country knowledge diffusion; by comparison, patents invented in US or Japan (locations with highly concentrated clusters of information storage R&D) have on average only 3.4 foreign citations per patent.

Insert Figure 2 about here

Before discussing the construction of our sample and measures, we present a brief history to illustrate the importance of knowledge flows and characterize the spread of inventive activity in this industry. In 1898, Danish engineer Valdemar Poulsen invented the first magnetic recording device, a telephone answering machine. Subsequently, improvements were made by researchers in the United States, with IBM taking the leadership in this technology. In 1957, IBM shipped the world's first computer to incorporate a magnetic hard disk drive for data storage. From 1960s to 1980, the computer industry began to use magnetic disk-based systems extensively. During this period, IBM dominated the industry, with its hard disk drives sold as "integrated" devices as part of its computer systems. The number of participant companies in the disk drive industry grew to include other companies in the United States (Bryant Computer, Burroughs, Caelus Memories, Century Data Systems, Control Data, ISS/Univac, Marshall, Memorex, NCR, Potter Instruments), and eventually those in Japan (Fujitsu, Hitachi, NEC and Toshiba). Between 1966 and 1973, IBM introduced many innovations including the first floppy disk drive and the Winchester hard disk. In 1978, Sony introduced the first digital recorders and in 1980, Seagate Technology introduced the first hard disk drive for microcomputers.

From 1980s to 2000, the personal computer became a mass-produced consumer product, driving the emergence of small magnetic disk storage devices. Many start-up companies emerged that attempted to develop and introduce innovations in magnetic disk drive technologies. In the 1970s, the hard disk industry grew rapidly in Japan and Korea due to the dedication of its workforce and lower labor costs. Ultimately, no fewer than 136 companies entered the industry, so that by the mid-1980s activity had spread beyond the US and Japan to include Europe, Korea, Singapore and other Asian countries.

The breadth and scope of this activity makes it a challenge to identify the key innovators and trace knowledge spillovers in the information storage industry. Much of the prior literature on knowledge localization relies upon case studies, perceptual constructs (derived from survey respondents) or indirect inferences (e.g. using international trade data). A growing stream of research utilizes patent citation data, which offers an objective measure of knowledge flows, and one that is publicly available. Despite well-known limitations, patent citations have been found to be a useful means for tracing knowledge flows (see Jaffe and Trajtenberg, 1999, 2002; Hall, Jaffe and Trajtenberg, 2001). Building upon this approach, we use patent data to characterize the boundaries around information storage technology, and we use patent citations to trace knowledge flows across organizational and national boundaries within this technological area. Without patent citation data, it would be difficult to trace knowledge flows in this industry, which spans numerous organizations operating across the globe, many of which are private entities.

3.1 Constructing the Sample

Our dataset consists of patents granted by the US Patent and Trademark Office (USPTO) in the five years: 1976, 1981, 1986, 1991 and 1996. We include a patent if it falls within one of the following primary patent classes: 360 (Dynamic magnetic information storage or retrieval), 365 (Static information storage and retrieval), 369 (Dynamic information storage or retrieval) and 711 (Electrical computers and digital processing systems: memory).[3] These patent classes are representative of information storage technology.[4] For each patent, we determine the number of forward citations it receives from subsequent patents. Forward citation counts are subject to right-censoring, especially for recent patents. Thus, although our patent database contains patents granted up to 2004, we adopt 1996 as the final year in our analysis, giving us a time window of eight years between 1996 and 2004 for capturing forward citations. According to Jaffe et al. (1993), recent patents get cited faster than old patents. Their analysis of 1975- and 1980-vintage patents show that the average time lag between the originating application year and the application year of the citing patent is 6.5 to 8 years for the 1975 cohort, and a little over 4 years for the 1980 cohort. We therefore include year fixed effects regression models with year dummies to account for these cohort effects.

For each patent in our sample, we obtained its patent number, issue date, technology class, inventor information, assignee information (the organization which

[3] Source: http://www.uspto.gov/web/patents/classification/selectnumwithtitle.htm

[4] See Jaffe and Trajtenberg (2002). Based on the Patent Classification System as of December 31, 1999, they classified more than 400 patent classes into 6 technological categories and 36 subcategories. Patent classes 360, 365, 369 and 711 represent the information storage subcategory.

owns the patent) and patent citation information. The country in which a patent is invented is identified based on the *address associated with the inventor(s)* of the patent. We do not use the address of the assignee organization because many multinational companies use the address of their headquarters for all patents by inventors within their organization, so the assignee's address does not accurately reflect the locus of inventive activity. A small number of patents have multiple inventors from different countries (comprising 1.6% of all patents in our sample), and to avoid ambiguity these are dropped from the analysis.[5] Our final sample consists of 6 077 utility patents in classes 360, 365, 369 and 711.

3.2 Dependent variables

Our first dependent variable is the *relative risk ratio of a patent being cited by a foreign patent*. A relative risk ratio (RRR) is the ratio of the probability of an event occurring in an experimental group versus a control group. In a comparison between an experimental group and a control group, a relative risk of 1 means there is no difference in risk between the two groups. An RRR of less than 1 means the event is less likely to occur in the experimental group than in the control group, and vice-versa.[6]

We use the RRR to compare the actual propensity versus the potential probability of a patent diffusing across national borders. This can be expressed as:

$$RRR_{itg} = \frac{\sum_{T=t}^{2004} \sum_{j \neq i} x_{jTg}}{\sum_{T=t}^{2004} X_{Tg}} \Bigg/ \frac{\sum_{T=t}^{2004} \sum_{j \neq i} n_{jTg}}{\sum_{T=t}^{2004} N_{Tg}}$$

where i represents the country where the cited patent was invented, j is the country where the citing patent was invented, t is the year when the cited patent was issued,

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[5] Including patents with multiple inventors does not change the results substantially.

[6] See http://www.stata.com/support/faqs/stat/2deltameth.html for the definition and use of RRR.

T refers to the year when the citing patent was issued, and g is the technology class of the cited patent (i.e. class 360, 365, 369 or 711). Thus, for each focal patent in class g, which was invented in country i and issued in year t, x_{jTg} refers to the number of citations in class g, invented in country j (where $j \neq i$) and granted in year T, while X_{Tg} refers to the number of citations the focal patent received from all countries. Consequently, the numerator, $\frac{\sum_{T=t}^{2004}\sum_{j \neq i} x_{jTg}}{\sum_{T=t}^{2004} X_{Tg}}$, indicates the actual observed propensity of the focal patent being cited by foreign patents, while the denominator, $\frac{\sum_{T=t}^{2004}\sum_{j \neq i} n_{jTg}}{\sum_{T=t}^{2004} N_{Tg}}$, measures the potential probability that the focal patent is cited by foreign patents. Note that n_{jTg} is the number of potential citations the focal patent may receive from country j (where $j \neq i$), in class g and in year T, while N_{Tg} represents the number of potential citations from all countries. Hence, RRR_{itg} compares the focal patent's <u>actual propensity</u> of being cited by foreign patents with its <u>potential probability</u> of being cited by foreign patents. If a patent's RRR_{itg} is greater than 1, this means the patent has exhibits a higher propensity of being cited by foreign patents than one might reasonably expect. An increase of RRR_{itg} means a higher likelihood of the knowledge contained in a patent diffusing across national borders. Note that RRR_{itg} is a continuous variable ranging from 0 to infinity. In the Appendix, we present an example of how RRR_{itg} is calculated for an actual patent.

In the above definition of potential citation probability, we made the same assumption as in Jaffe and Trajtenberg's (1996) and He, Lim and Wong (2006) that all patents granted in the same technology field subsequent to a focal patent have the same probability of citing the focal patent. In addition, we only include citations if the citing patent is in one of the technological classes associated with information storage technology (class 360, 365, 369 or 711). The main reason for doing so is to measure knowledge spillovers across national boundaries, but *within a single technological realm*, which in this case is information storage technology. This approach is similar to Rosenkopf and Nerkar (2001), who use patent class data to distinguish between citations from outside optical disk technology versus citations from within the same industry. In any case, most of the forward citations in our sample are by patents within the information storage area, with more than 75% of the forward citations in our sample from patents in the four technology classes associated with information storage technology.

Speed of Citation by foreign patents

In addition to RRR, we constructed two other dependent variables to measure the speed of international diffusion of the technology embodied in a patent:

(a) The minimum citation lag between the issue date of cited patent and its first citation (MIN_FRGN_LAG)

This variable MIN_FRGN_LAG measures the time interval (in days) between the date of issuance of the cited patent and its first foreign citation. Once a patent is issued, the knowledge embodied in that patent becomes public. So the first citation reflects the minimum time lag between the cited patent and the citing patent.

(b) The average citation lag between the issue date of cited patent and all its citations within the next 8 years (AVG_FRGN_LAG)

As MIN_FRGN_LAG only takes into account the time lag till the first citation, it does not capture information on later citations. We therefore employ a second measure, *AVG_FRGN_LAG* that captures the average citation time lag across all citing patents issued in the following eight years. As mentioned earlier, while recognizing the problem of right-censoring for counting forward citations, we believe the eight year time window is adequate based on prior research findings by Jaffe et al. (1993).

3.3 Independent variables

Perceived technological importance of a patent (TTL_CITE)

We measure the total number of forward citations (excluding self-citations) received by each patent in our sample. As mentioned above, we only include citing patents that fall within the four information storage technology classes. This allows us to focus on knowledge spillovers across boundaries but within a single technological area (information storage).

Competitive Relevance (ASSGN_PTNT_STK)

We measure the perceived competitive relevance of a patent by using the technological strength of the patent owner (assignee) in the selected technological field. A firm's technological strength may be measured in other ways, such as the share of the firm's technology embodied in products, or its R&D expenditure. Unfortunately such data is not readily available for all organizations across countries in a consistent form, and is difficult to obtain for private companies. Following Almeida and Phene (2004), we use the number of patents granted to the patent assignee as a percentage of total worldwide information storage patents granted. We calculate patent counts for the same year as the focal patent.

Internal Appropriation (SELF_CITE)

Drawing on the prior literature (Trajtenberg et al., 1997; Hall et al. 2001, 2005; Somaya, 2003; He, Lim and Wong, 2006) that highlights a strong association between self-citation intensity and the investment of resources by the patent owner to appropriate value from a focal patent, we measure the internal appropriation efforts of a patent owner by the ratio of self-citations to the total number of forward citations received by the focal patent.

3.4 Control variables

The patent inventor country's patent stock (INVT_PTNT_STK)

There is a need to control for the size of the country from which a patent originates, since a country with a larger patent stock is more likely to have a larger number of citations generated within its national boundary, all else being equal. In contrast, a country with a small pool of patents in the same technology field is likely to have a higher foreign citation probability. To control for this size effect, we calculate the patent inventor country's cumulative patent stock in information storage technology until year $t-1$, where t is the issue year of the focal patent.

University & public research institute patent (UNIV_PRI)

This is a dummy variable and is set to 1 if the patent assignee is a university or public research institute. Studies have shown that patents owned by a university or public research institute have different diffusion patterns than patents owned by firms or individuals (Jaffe and Trajtenberg, 1996; Sorenson and Fleming, 2004).

Year dummy (D_81, D_86, D_91, D_96)

To control for possible year-specific effects, we include dummy variables corresponding to patent issue dates in 1981, 1986, 1991 and 1996 respectively, with 1976 being used as the baseline.

3.5 Regression Models

We use Tobit regressions to test hypotheses H1-1, H2-1 and H3-1, due to the fact that the dependent variable *RRR* is a non-negative continuous variable. To test our hypotheses on the speed of knowledge diffusion, we use Cox regression models, since our dependent variables *MIN_FRGN_LAG* and *AVG_FRGN_LAG* represent time-to-event constructs, in which there are right-censored observations. For example, a patent issued in 1996 may not have been cited by foreign patents until the end of 2004, which is the final year of our database. In this case, the citation lag for this patent is right-censored. These censored “survival” times cannot be properly handled by standard OLS models, but are accounted for in the Cox model.

4. RESULTS

The descriptive statistics along with the Pearson correlations among variables are presented in Table 1. The mean of RRR is below 1, which is consistent with the view that overall, knowledge spillovers are localized within national boundaries. However, the maximum value of this variable is 1.82, which means that some patents are quite broadly diffused across national boundaries—almost twice the expected probability of being cited by foreign patents. Also, while it takes an average of 6.2 years (2 260 days) for a patent to receive its first foreign citation, the shortest time before a foreign citation appears for a patent is only around 4 month (119 days). If we take the number of total forward citations received by a patent from subsequent patents in the same technological field (*TTL_CITE*) as the indicator of its technological importance, Table 1 suggests that information storage patents are very heterogeneous in their technological importance, with many patents receiving a small number of citations (mean=7.7), and a few patents receiving many forward citations (max=149). The average value of *SELF_CITE* is 13%, but ranges all the way from 0 to 100%, so some patents are highly appropriated by their owner, and others not at all. Pairwise correlations are quite low, except those between MIN_FRGN_LAG and AVG_FRGN_LAG, and hence do not pose serious multicollinearity problems.

Insert Table 1 about here

Table 2 presents the results of Tobit regression estimates. Models 1 through 3 each include an explanatory variables for testing hypotheses H1-1, H2-1 and H3-1 respectively. Model 4 presents a full model with all three explanatory variables included simultaneously. In all four models, the explanatory variables’ coefficients are significant and have the expected signs. Consistent with hypothesis H-1, the total number of citations a patent received (excluding self-citations) has a significant and positive effect on a patent's propensity to diffuse across national boundaries.[7] Consistent with Hypothesis H-2, the technological strength of a patent's assignee (as measured by the share of the assignee's patent stock) also has a significant positive impact on the patent's propensity to receive cross-country citations. Lastly, the significant negative coefficient of *SELF_CITE* suggests that the higher a patent owner's efforts at internal appropriation, the less likely it is to diffuse across national boundaries. Hence, hypotheses H1-1, H2-1 and H3-1 are strongly supported.

Insert Table 2 about here

Table 3 presents Cox regression estimates to test hypotheses H1-2, H2-2 and H3-2 regarding the speed of international knowledge diffusion. The dependent variable in Models 1 to 4 is the citation lag between cited patent and its first foreign citation (*MIN_FRGN_LAG*), while in Model 5 through Model 8 it is the average citation lag in an 8-year window (*AVG_FRGN_LAG*). A Cox regression estimates the influence of each independent variable on a baseline survival function or hazard function. A positive coefficient means that the hazard is increased and vice versa. In other words, variables with positive coefficients are associated with decreased survival time. In our model, the survival time refers to the time lag between a focal patent and its citations. Hence, a positive coefficient means a more rapid speed of knowledge diffusion while a negative coefficient indicates longer citation lag. The results show that hypotheses H1-2 and H3-2 are strongly supported. H2-2 is supported in the fully specified models (Model 4 and Model 8). However, in Models 2 and 6, the coefficients for *ASSGN_PTNT_STK* are not significant.

Insert Table 3 about here

Among the control variables, the inventor country's patent stock has a negative and significant effect on a patent's subsequent diffusion across national boundaries. At

[7] The results are similar if we include self-citations in the total forward citation counts.

the same time, it has a significant and positive impact on the time taken by a patent to be cited across countries, i.e. the larger the inventor country's patent stock, the longer it takes for the focal patent to diffuse to foreign countries. Surprisingly, the university/public research institute dummy variable does not show any significant effect in all the models. This is contrary to the hypothesis that science-based innovations diffuse more widely than other innovations (Sorenson and Fleming, 2004; Sorenson and Singh, 2007). However, this non-significant effect is probably due to the small number of such patents in our sample: of the 6 607 patents, only 37 are assigned to universities or public research institutes, which is less than 0.6% of the total.

5. DISCUSSION AND CONCLUSIONS

In this paper we examine how the diffusion of knowledge embodied in a patent is affected by the patent's perceived technological importance, its competitive relevance, and internal appropriation by its owner. These factors influence the propensity and speed at which firms in other countries develop new and patented technologies that build upon the focal patent. Due to uncertainty in the knowledge search process, these factors signal the quality of the focal patent, its commercial viability, and the appropriation risk of producing derivative (or follow-on) innovations.

While past research has emphasized knowledge localization within national boundaries, our findings suggest the need to take into account the heterogeneous nature of knowledge, and the manner in which firms search for information. The patents citations in our sample are on average geographically localized within national boundaries (RRR<1), but exhibit strong heterogeneity. Patents containing high impact knowledge are less constrained by geography, and have a higher propensity to diffuse across national borders. This suggests that the quality of knowledge does matter: good ideas diffuse more readily and at a faster rate than mediocre ideas, even if they originate from a foreign country.

Our findings also suggest the need to consider the signaling effect of the identity and action of the patent owner: on the one hand, a patented innovation by a firm with a strong technological reputation is likely to be considered of greater competitive relevance, leading to higher propensity and time urgency for international competitors to develop derivative innovations that build upon the original patented innovation; on the other hand, when the patent owner exhibits significant internal appropriation efforts with respect to a patent it invented, it is likely to be a deterrent signal discouraging others, particularly its international competitors, from seeking to develop derivative innovations. Thus, while a strong technological leader is likely to attract imitative learning by its competitors, an aggressive strategy emphasizing internal appropriation may deter such derivative innovations. In their study of the mobile communications industry, He, Lim and Wong (2006) find that late entrants to the industry (Nokia, Ericsson and Samsung) targeted the industry's technological leader (Motorola) by pursuing derivative innovations that made extensive citations to the leader's technologies in their initial catch-up phase. A number of late entrants eventually overtook the incumbent, which did not invest aggressively enough in internally appropriating the "crown jewels" of its patent portfolio.

We find that knowledge is more likely to diffuse internationally and at a faster rate if it originates from organizations with a strong technological base (hypotheses 2-1 and 2-2). This lends empirical support to the institutional concept of mimetic isomorphism. Prior research has offered evidence for mimetic isomorphism in terms of diversification (Haveman, 1993) market positioning (Greve, 1996) and non-profit groups (Galaskiewicz and Wasserman, 1989). But evidence of mimetic behavior in innovation-related activities remains scant. In a study on the global diffusion of ISO9000, Guler et al. (2002) find support primarily for coercive isomorphism, but surprisingly limited effects for technological learning through normative or mimetic isomorphism. They acknowledge a likely cause is the weakness of several variables: they used publications as a rough measure of technology, and they were unable to measure knowledge flows. By relying on patent data we are able to obtain proxies for both of these. Moreover we don't just test for the presence of mimetic behavior; hypotheses 2-1 and 2-2 consider the *relative technological strength* of the knowledge-originating organization. This accounts for the extent to which an organization represents a "model of success" to be imitated by others. Thus our paper builds upon the evidence presented by Guler et al. (and others) to clarify and extend the institutional literature.

Another interesting finding from our study is the negative effect of an inventor country's patent stock on the propensity and speed with which a focal patent's knowledge diffuses internationally. Patents invented in countries with strong technological capability are less likely to diffuse internationally, and they take longer to do so. This suggests that knowledge originating from a country with a large cumulative technological base is more "sticky" than knowledge generated in a country with a smaller technological base, and is thus consistent with prior research showing that knowledge tends to become concentrated over time in geographic regions that are better endowed in terms of prior stocks of knowledge to begin with (Acs et al., 2005). A number of factors may contribute to such localization over time. Firstly, a technologically rich country may possess better infrastructure to facilitate knowledge spillovers within national boundaries. Secondly, firms in such a country may have superior capabilities in seeking out and assimilate relevant knowledge spillovers. Finally, to the extent that knowledge diffusion is likely to be facilitated by the mobility of scientists and engineers, barriers to the international mobility of such talent may hinder cross-border knowledge diffusion. These factors may have contributed to the ability of USA to sustain its technological advantage in the information storage technology field, despite the fact that more countries are investing in innovation activities in this technology field in recent years, particular the newly industrialized economies from East Asia.

Our study contributes to the literature on international knowledge diffusion in several ways. Prior researchers have focused on various mechanisms of knowledge diffusion, such as collaborative networks (Singh, 2005; Granovetter, 1973; Rogers, 1995), the mobility of engineers (Saxenian, 1990; Almeida and Kogut, 1999; Rosenkopf and Almeida, 2003; Song et al., 2003) and the linkage between technology and science (Sorenson and Fleming, 2004). We propose that the quality of knowledge transmitted as well as organizational signals (the patent owner's technical reputation as well as its internal appropriation efforts) also play an important role in shaping the patterns of international knowledge diffusion.

By calling attention to the nature of knowledge and to the signaling effects of the knowledge owner's attributes and actions, our findings have clear implications for managers as well as innovation researchers. First, it implies that proprietary knowledge resources represent a key source of competitive advantage for the technological leaders in an industry. While this knowledge resource may be vulnerable to spillovers to foreign competitors, our study suggests that a strategic focus on internal appropriation can reduce spillovers. Second, for the technological followers of an industry, our study suggests that it may be efficacious to pursue a derivative innovation strategy that targets learning from the technological leaders. Finally, our study suggests that the quality of knowledge matters in the dynamics of diffusion. Future research on knowledge diffusion should therefore pay greater attention to this dimension, such as by developing better measures for the quality of knowledge.

Several limitations of our study point to useful directions for future research. Our findings are based on a narrow technological area—information storage technology. Future studies should explore whether our results generalize to other technological fields. Similarly, while universities and public research institutes appear to play a very small role in patenting in the information storage technology field, subsequent research may focus on science-based fields like biotechnology to examine the role of patenting by universities and public research institutes. Due to data limitations, we have used patent citations as a proxy for measuring knowledge diffusion in this study.

However, patent citations represent a limited measure, since not all knowledge is patentable or patented, and citation data itself is noisy. Future studies may consider including other measurements to complement patent citation data, e.g. the role of inventors as the carriers of knowledge and their mobility across national borders as an indicator of inter-country knowledge diffusion.

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Figure 1 Information Storage Patents Issued per Year According to Inventor Country.

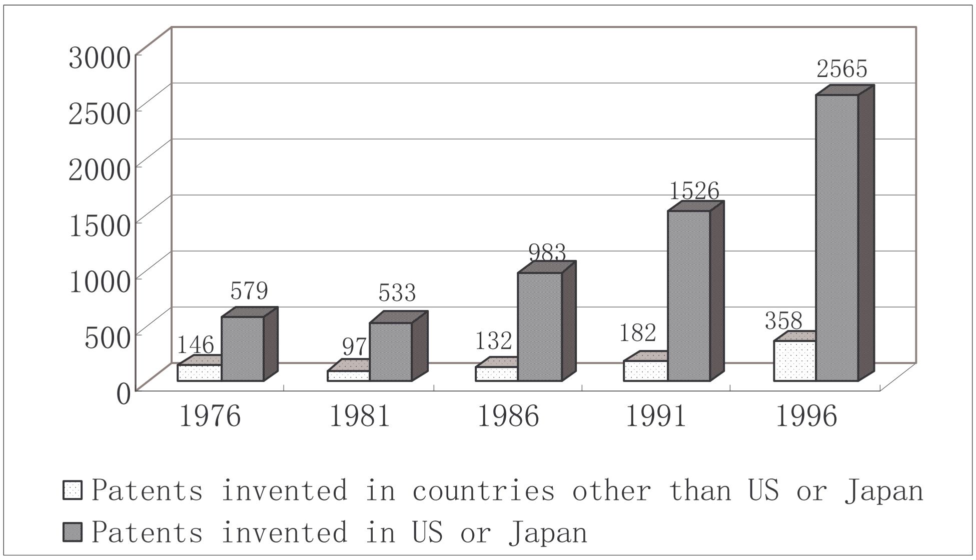
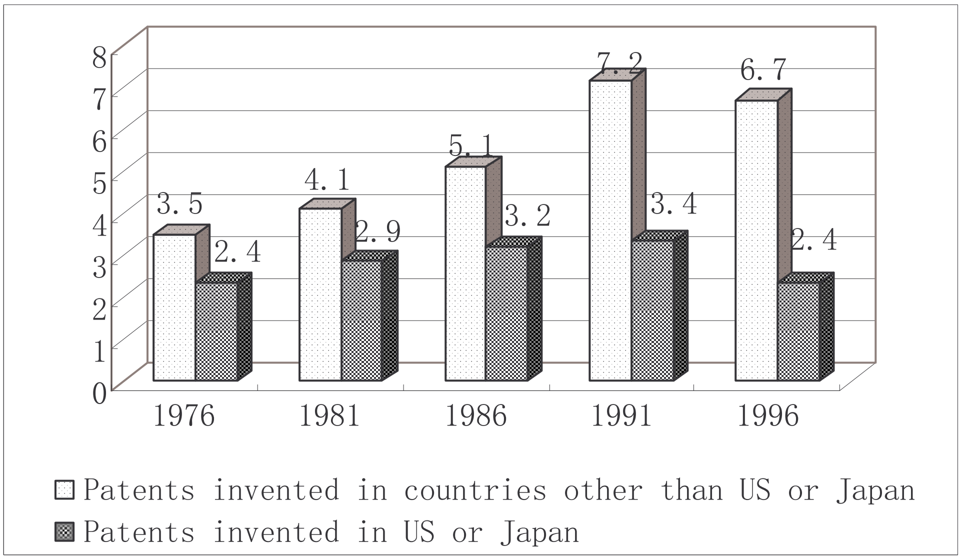


Figure 2 The Average Foreign Citations Received by each Information Storage Patent, according to Inventor Country.



Note: Citing patents issued till end-2004 are used for calculating the citations.

Table 1 Summary Statistics

Variable	Min	Max	Mean	SD	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) RRR	0	1.82	0.763	0.568	1.000							
(2) MIN_FRGN_LAG	119	10 587	2 260	2 132	-0.494**	1.000						
(3) AVG_FRGN_LAG	140	3 286	2 065	816	-0.451**	0.749**	1.000					
(4) TTL_CITE	0	149	7.790	9.466	-0.005	-0.286**	-0.166**	1.000				
(5) ASSGN_PTNT_STK	0	0.11	0.025	0.025	0.032*	0.030*	0.057**	-0.016	1.000			
(6) SELF_CITE	0	1	0.130	2.232	-0.162**	0.152**	0.145**	-0.146**	0.207**	1.000		
(7) INVT_PTNT_STK	0	3.15	2.722	0.538	-0.084**	-0.043**	0.049**	0.029*	0.210**	0.076**	1.000	
(8) UNIV_PRI	0	1	0.006	0.078	-0.003	0.011	- 0.011	- 0.007	- 0.073**	- 0.036**	- 0.068**	1.000

Note: **. Correlation is significant at the 0.01 level (2-tailed)
*. Correlation is significant at the 0.05 level (2-tailed)
N=6 077

Table 2 Tobit Regression for Relative Risk Ratio (RRR) of Being Cited by Foreign Patents [a, b, c]

Variable		Model 1	Model 2	Model 3	Model 4
TTL_CITE	H1-1	0.004***			0.002*
		(0.001)			(0.001)
ASSGN_PTNT_STK	H2-1		1.383***		2.641***
			(0.375)		(0.378)
SELF_CITE	H3-1			-0.630***	-0.676***
				(0.041)	(0.042)
Controls					
INVT_PTNT_STK		-0.154***	-0.166***	-0.136***	-0.166***
		(0.019)	(0.019)	(0.041)	(0.019)
UNIV_PRI		-0.109	-0.086	-0.166	-0.122
		(0.116)	(0.116)	(0.115)	(0.114)
YEAR DUMMY		Yes	Yes	Yes	Yes
LR Chi2		91.22***	85.58***	311.95***	366.05***
Log likelihood		-6 344.41	-6 347.23	-6 234.04	-6 206.99
Pseudo R2		0.007	0.007	0.02	0.03
No. of Observations		6 077	6 077	6 077	6 077

a. DV = Relative Risk Ratio of a patent being cited by foreign patent (RRR).

b. *** p<.001, ** p<.01, *p<.05, standard error in parenthesis.

c. Four year dummies were used: *D_81*, *D_86*, *D_91* and *D_96*.

Table 3 Cox Regression for Patent Citation Rate [a, b]

Variables		DV=MIN_FRGN_LAG				DV= AVG_FRGN_LAG			
		Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Constant									
TTL_CITE	H1-2	0.035***			0.034***	0.021***			0.020***
		(0.001)			(0.001)	(0.001)			(0.001)
ASSGN_PTNT_STK	H2-2		-0.204		2.124***		-0.968		1.069*
			(0.601)		(0.598)		(0.641)		(0.643)
SELF_CITE	H3-2			-1.019***	-0.951***			-0.946***	-0.885***
				(0.068)	(0.071)			(0.072)	(0.075)
Controls									
INVT_PTNT_STK		-0.462***	-0.406***	-0.403***	-0.478***	-0.351***	-0.322***	-0.325***	-0.354***
		(0.028)	(0.028)	(0.027)	(0.028)	(0.029)	(0.029)	(0.028)	(0.029)
UNIV_PRI		-0.134	-0.148	-0.254	-0.192	-0.007	-0.028	-0.093	-0.062
		(0.190)	(0.190)	(0.190)	(0.190)	(0.197)	(0.197)	(0.197)	(0.197)
YEAR DUMMY		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
-2 Log Likelihood		77 139	77 937	77 660	76 928	71 941	72 240	72 035	71 778
Chi-Square (Change)		1130***	332***	608***	1340***	548***	249***	454***	711***
Right Censored		1 217	1 217	1 217	1 217	1 651	1 651	1 651	1 651
No. of Observations		6 077	6 077	6 077	6 077	6 077	6 077	6 077	6 077

a. *** p<.001, ** p<.01, *p<.05, standard error in parenthesis.

b. Four year dummies were used: *D_81*, *D_86*, *D_91* and *D_96*.

Appendix. An example of the calculation of our dependent variable RRR_{itg}

Table A-1. Forward citations received by patent 3932890 (Issued in 1976, invented in Japan and is owned by Pioneer Electronic Corporation)

Patent No.	Issue year	Forward citation assignee name	Inventor country
5150265	1992	Tanashin Denki Co. Ltd.	JP
4017896	1977	-	JP
5781359	1998	Alpine Electronics, Inc.	JP
4214283	1980	Pioneer Electronic Corporation	JP
4224646	1980	Staar, S. A.	BE
4442466	1984	Pioneer Electronic Corporation	JP
4348702	1982	Ford Aerospace and Communications Corporation	US

Patent 3932890 has 7 total citations among which there are 2 self-citations: 4214283 and 4442466. So $\sum_{T=1976}^{2004} X_{Tg} = 5$. Among these 5 non self-citations, 2 are invented outside Japan (patent 4224646 in BE and 4348702 in US). So $\sum_{T=1976}^{2004} \sum_{j \neq JP} x_{jTg}$ =2. The real probability of patent 3932890 being cited by foreign patents is 2/5=0.4.

To calculate patent 3932890's potential probability of being cited by foreign patents, we found that there are totally 65930 patents issued from 1976 (which is the year when 3932890 was issued) in class 360, 365, 369 and 711 from all countries; among which are 37 261 patents invented outside Japan. Thus in our formula: $\sum_{T=1976}^{2004} N_{Tg}$ =65 930 and $\sum_{T=1976}^{2004} \sum_{j \neq Japan} n_{jTg}$ =37 261. The potential probability of being cited by foreign patents is (37 261)/(65 930) = 0.5652. Finally, the *RRR* for patent 3932890 is 0.4/0.5652 = 0.7077.