Death hurts, but it isn't fatal: the postexit diffusion of knowledge created by innovative companies

Glenn Hoetker
University of Illinois at Urbana−Champaign

Rajshree Agarwal
University of Illinois at Urbana−Champaign

Abstract

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DEATH HURTS, BUT IT ISN'T FATAL: THE POSTEXIT DIFFUSION OF KNOWLEDGE CREATED BY INNOVATIVE COMPANIES

GLENN HOETKER
College of Business
University of Illinois at Urbana-Champaign
350 Wohlers Hall, 1206 S. Sixth Street
Champaign, IL 61820
Phone: (217) 265-4081; Fax: (217) 244-7969; E-mail: ghoetker@uiuc.edu

RAJSHREE AGARWAL
College of Business
University of Illinois at Urbana-Champaign
350 Wohlers Hall, 1206 S. Sixth Street
Champaign, IL 61820
Phone: (217) 265-5513; Fax: (217) 244-7969; E-mail: agarwalr@uiuc.edu

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ABSTRACT

The innovative knowledge created by firms that ultimately exit their industries represents a source of technology that existing firms may build on. However, no empirical work has examined if such knowledge dies with an innovating firm or if significant diffusion of knowledge occurs even after a firm exits an industry. We base our theoretical predictions about the differing effects of firm exit on private and public knowledge and discuss implications for interfirm knowledge transfer. Using the disk drive industry as our empirical setting, we investigated the main and moderating effects of firm exit on the rate of knowledge diffusion to other firms. Our findings are consistent with prior work highlighting the importance of location and employee mobility in knowledge transfer. We also found evidence that the ability to use a firm as a template plays a critical role in successfully replicating its knowledge. Absent this template, knowledge "stickiness" reduces knowledge diffusion.

In 1999, despite millions of dollars of investment and a portfolio of innovative technologies, flat panel display manufacturer Optical Information Systems (OIS) shut down operations, unable to achieve commercial success. Although OIS failed, its technology lived on. The firm's former director of advanced technologies wrote this in a letter to the editors of the magazine *Information Display:* "OIS technology continues to make waves. Since the shutdown, 11 more U.S. patents and three more European patents have been issued to OIS." Many of these patents covered processes that were becoming mainstream technology in the flat panel display industry. The letter then continued to cite specific innovations by other firms that had built on OIS breakthroughs. Although the firm had exited the industry in spite of its technological strength, it left a lasting legacy for the industry's technology.

Is the OIS story unusual, or does it highlight a regular occurrence? Since technological expertise is an important determinant of firm success (Teece 1986; Jovanovic and MacDonald 1994), it could be argued that firms that exit an industry are typically lacking in this important area, and thus they have little impact on the technological progress in the industry. This formulation would imply that firms like OIS are outliers and that diffusion of the knowledge they created is generally low, both before and after they exit an industry. However, there is strong evidence that many companies exit despite having developed innovative knowledge (Katz and Shapiro 1985; Golder and Tellis 1993; Podolny and Stuart 1995) and that it is a lack of complementary assets (Teece 1986) that often results in firms' untimely deaths. If this is the case, then firm exit will not be perfectly, negatively correlated with technological superiority and, importantly, other firms may attempt to build on the knowledge created by a departed firm.

The issue of whether other firms subsequently capitalize on knowledge created by companies that exit an industry remains underresearched, but it is important to investigate this issue for several reasons. First, 8 to 10 percent of all companies leave an industry in an average year (Dunne , Roberts, and Samuelson 1988; Agarwal and Gort 1996). Many of these companies may have been technologically innovative and are thus underexploited sources of technological progress and increases in social welfare. Further, in some industries, substantial public investment may have been made in these companies, through either tax incentives or direct funding. Does the value of that investment depend on the commercial success of the firm receiving the funding, or can other firms that remain commercially viable subsequently harness the resulting innovation?

Theoretically, since the issue relates to interfirm knowledge transfer under the most challenging conditions, it offers an opportunity to examine the mechanisms that operate when firms seek to capitalize on other firms' technologies. The traditional view of knowledge highlights the positive externalities inherent in knowledge creation and the nonrival, nonexcludable nature of information, particularly when it is codified through patents (Arrow 1962; Griliches 1979; Jaffe 1986; 1988). In its extreme form, the assumption in this research stream is that all knowledge available in codified form is in the public domain and that firms other than the originators of the knowledge can freely build on it to their advantage (Spence 1984; Jaffe 1986). In contrast, an alternative view emphasizes that technological knowledge may have private aspects in addition to its public aspects (Nelson and Winter 1982). These private aspects (Nelson and Romer 1996) impart knowledge "stickiness" (von Hippel 1994), a consequence (Szulanski 1996) either of the embeddedness of innovations in organizational routines and teams (Nelson and Winter 1982; Martin and Mitchell 1998) or of causal ambiguity (Lippman and Rumelt 1982; Rumelt 1984) Restriction of interfirm knowledge transfer is the outcome. Researchers have found that significant tacit knowledge resides within the social structures of organizations, since innovation is the result of concerted and directed efforts by entire teams of employees.

Our paper builds on the complementarity of the private and public components of knowledge (Nelson 1990) to examine how the absence of private knowledge affects subsequent diffusion of the public knowledge embodied in a firm's patents. Exit means both loss of the private knowledge embodied in a firm and loss of the possibility of using the firm's activities as a template (Winter and Szulanski 2001). Examining the effect of firm exit on knowledge diffusion can thus shed light on the importance of private knowledge as a facilitator of the diffusion of public knowledge. Thus, we contribute to the literature on the extent of knowledge spillovers across firms by discussing how private knowledge may serve as a boundary condition on the public knowledge a firm creates. Our examination of the postexit diffusion of knowledge also complements studies of the importance of geographical location (Agrawal, Cockburn, and McHale 2003) and employee mobility (e.g. Rosenkopf and Almeida 2003) for accessing private knowledge and reducing the tacitness and stickiness of knowledge (von Hippel 1994)

To the best of our knowledge, no study has systematically examined the impact the exit of a firm has on the diffusion of the knowledge it created. The empirical setting of our study is the hard disk drive industry, called the "fruit fly of industries," owing to its rapid technological change (Christensen 1993). We define firm exit as a firm's having ceased operations in the disk drive industry, excluding firms that were acquired. We first address the possibility that firms that have exited had inferior technologies and were thus insignificant in the development of hard drive technology. Using patent citations as a measure of knowledge diffusion, we examine the effects of firm exit not only on the overall patent-citation life cycle, but also on the relationship between characteristics of an innovation and its diffusion to other firms.

THEORY

Private and Public Components of Knowledge

The idea that as firms pursue new knowledge, they create a public good dates back to Arrow (1962). Subsequent work in the area discussed the implications of the nonrival and nonexcludable properties of knowledge for its subsequent diffusion, since both aspects increase the likelihood of another firm benefiting from the knowledge created by a focal firm. Because investments in knowledge-creating activities by a firm also increase the human capital of its employees (Becker 1964), employee mobility has been identified as a key mechanism for knowledge diffusion (Almeida and Kogut 1999), though knowledge diffusion can also occur through other mechanisms, including codification, reverse engineering and scientific reproduction, and formal or informal interpersonal contacts (Arrow 1996).

However, much attention in the last twenty years has also been paid to the tacit aspect of knowledge, particularly that which is team-based and socially embedded in firm routines (Nelson and Winter 1982). Highlighting the fact that not all the innovative knowledge firms create is public, Nelson (1990) argued that firms generate innovative knowledge by combining generic, public knowledge with specific designs and practices that are private to the creators. The success of other firms in replicating and building on the knowledge created by a firm thus depends on their ability to understand the private knowledge within which the public knowledge is embedded (Rosenberg 1982). The private aspect of knowledge results in knowledge stickiness (von Hippel 1994) derived from causal ambiguity and the embeddedness of innovations in organizational or team-based rules and routines (Lippman and Rumelt 1982; Nelson and Winter 1982; von Hippel 1994; Szulanski 1996). For example, causal ambiguity, the "basic ambiguity concerning the nature of the causal connections between actions and results," impedes duplicating and extending another firm's innovative knowledge (Lippman and Rumelt 1982:420). It may be unclear which of the multiple research efforts that a firm engaged in ultimately led to its innovative success. It may also be difficult to judge the potential value of an innovation (Podolny and Stuart 1995). Nor is it always clear under what conditions a technology can be gainfully applied (Nelson and Winter 1982). Greater ambiguity on each of these dimensions limits the degree to which other firms can build on an innovation, even if it may have access to the public component of the relevant knowledge.

Thus, the received literature suggests that private and public knowledge are complementary requisites for the creation of new knowledge; in order to understand the private aspects of another firm's innovative knowledge, a firm must overcome the associated embeddedness and causal ambiguity. It can attempt to do so by undertaking its own research efforts, to build the required understanding internally (Cohen and Levinthal 1990). However, vicarious learning—learning from the experience of others through observation (Cyert and March 1963)—is likely to be less costly than reinventing and learning experientially (Schulz 2003). Since transferring knowledge often requires access to tacit organizing principles that are not easily articulated, the opportunity to consult a working example can be very valuable (Winter 1987). As Winter and Szulanski (2001:742) wrote, "The recreation of a complex, imperfectly understood, productive routine is often a protracted process that involves many references to an existing working model." This statement is consistent with Haunschild and Miner's (1997) finding that firms faced with uncertain technology rely on observing the organization that is the source of the technology for clues on how to organize and act. In essence, a source firm's routines and subsequent actions serve as a template for those wanting to emulate its innovative activities. Interacting with or observing the source firm enables understanding which innovative trajectories were considered important to pursue, and what associated research efforts were subsequently emphasized or dropped. Other firms also gain valuable insights on how to manage roadblocks that arise in advancing the innovation (Almeida and Kogut 1999). Observing what innovations eventually become commercial products provides a way to evaluate the commercial potential of an innovation (Arrow 1996). Thus, observing an innovating firm's subsequent actions helps other firms decide what innovative knowledge is worth replicating and extending and how they should go about replication and extension. The importance of such direct or indirect interaction with an innovative firm has been well established in the vast literatures on learning in alliances (Dyer and Singh 1998; Gulati 1998), social networks (Granovetter 1985; Burt 1992; Gynawali and Madhavan 2001) and knowledge spillovers via geographical proximity (Audretsch and Feldman 1996; Alcácer and Gittelman 2004)

Effect of Firm Exit on Knowledge Diffusion

The preceding discussion emphasizes the importance of the continued existence of innovative firms for the diffusion of their knowledge—the firms themselves serve as templates, because their routines embody the interaction of the private and public components of their knowledge. Thus, much like any artifact, whether hammer or computer, embodies knowledge that new producers of similar artifacts can use (Cowan, David, and Foray 2000), developers of knowledge created by a focal firm can rely on the firm's existence and activity while building on its knowledge. We now argue that the exit of a firm removes the possibility of direct or indirect interaction with the firm as a whole, thus limiting the extent to which other firms can capitalize on its knowledge, even if its employees and the codified knowledge are available.

In developing our hypotheses on the effect of its exit on the diffusion of a firm's knowledge, we deliberately focus on knowledge that is already codified and information available to other firms via patents. Patent data thus provide a more stringent environment within which to test the importance of private knowledge and firm existence. If the private knowledge of a firm is not an important complement to the explicit/codified knowledge available within patents, then firm exit should have no appreciable impact on the rate at which other firms use and cite the patented knowledge.[1] Indeed, the exit of a firm

[1] We note that since our theory compares the pre and post exit diffusion of a knowledge codified in the same patent, the quality of the information is kept constant . Thus, while patents of different quality will have different *levels* of the diffusion of the knowledge, the quality of the inherent information should not change pre and post exit of the firm.

from a focal industry should release many employees who can act as conduits of knowledge transfer in the organizations that subsequently hire them. As Ingram (2002:657) noted, “The experience of a failed organization may be particularly likely to diffuse through employee mobility as participants in the failure go to new jobs.” As a result, even though the firm may have exited, to the extent that its knowledge resided in the human capital of individual employees (Becker 1964), mechanisms for its continued diffusion exist. Thus, the exit of the firm should not negatively affect the availability of the public component of its knowledge to other firms. Nor should the firm’s exit affect the abilities and underlying absorptive capacity (Cohen and Levinthal, 1990) of potential recipient firms, to the extent that these are independent of any need for interaction with or observation of the source firm.

However, exit removes the opportunity to observe and interact with the firm, which, as indicated above, is important for understanding the private aspects of the knowledge created by the firm. While access to the public good aspect of the knowledge remains (via reverse engineering and reliance on codified knowledge),the firm’s activities can no longer serve as a template for other firms seeking to build on its knowledge. It is not possible, postexit, to observe how the innovating firm would have built upon an innovation. Furthermore, since the firm’s commercialization efforts have stopped, other firms cannot use observations about what innovations eventually become commercial products to evaluate the commercial potential of an innovation. The scattering of the firm’s innovative personnel to other firms complicates efforts to use social networks as a way of gathering information on the firm. The complementarity of the private and public components of the knowledge a firm has created lead us to expect that its exit will reduce other firms’ ability to capitalize on its knowledge. Accordingly,

> *H_1: Subsequent citation (use) of a patent by other firms will be negatively impacted by the patenting firm’s exit from the industry.*

Interaction of Firm Exit with Knowledge Characteristics

The importance of the private knowledge held by a firm to the diffusion of its patented knowledge will vary with the characteristics of an innovation. An innovation may embody varying degrees of private and public components, and the greater the private component, the greater will be the effect of firm exit on the subsequent diffusion of knowledge. We examine the interaction of exit with five variables that have been associated with the embeddedness of knowledge in a firm's private routines: the age of the innovating firm, the degree to which the innovation built on the innovating firm's internal knowledge base, whether the firm is of foreign origin, the number of inventors, and the diversity of technologies the innovation drew upon. Each variable influences the importance and/or accessibility of the innovating firm's private knowledge. Since the loss of the innovating firm as a template makes it more difficult to replicate the firm's private knowledge, we expect that exit will have a larger negative impact the more important or inaccessible the private knowledge was for that innovation. We now examine each variable in turn, exploring its relationship to the role of the private knowledge associated with innovations.

It is well established that the embeddedness of innovations in organizational routines increases with a firm's age owing to greater formalization of structures and encoding of lessons in routines (Nelson and Winter 1982; Levitt and March 1988). A firm's core capabilities, particularly those related to technology, are developed through learning and experience, and this "path dependency" implies that older firms have higher stocks of private knowledge. This is because older firms have gone through a longer process of learning and due to the storage of the past learning in behavioral rules and routines (Nelson and Winter 1982; Dosi, Teece, and Winter 1992). Building on an older firm's knowledge thus requires a recipient firm to observe or interact with the older one to learn both its rules and routines and how its subsequent innovations built on its earlier ones. Thus, the older a firm was at the time of a patent, the greater will be the impact of the loss of the firm as a template.

H_2: The older the patenting firm is at the time of a patent application, the more negatively the firm's exit will impact subsequent citation (use) of that patent by other firms

A similar logic applies to innovations that result from a firm building on its prior innovations (Jaffe and Trajtenberg 2002:17). These innovations draw heavily on a firm's internal knowledge base rather than on the knowledge of others and are said to reflect "localized search" (Anderson and Tushman 1990). They will therefore be closely bound within the routines and culture of the innovating firm (Nelson and Winter 1982). Further, they are likely to be couched in the idiosyncratic language of the firm (Arrow 1974).

As such, innovations that draw heavily upon a source firm's internal knowledge base will be highly tacit and be more difficult for others to imitate and extend, particularly after the exit of the source firm. Again, we anticipate a larger postexit drop in the diffusion of an innovation if that innovation drew heavily on a firm's internal knowledge base.

H_3: The more related a patent is to the patenting firm's internal knowledge base, the more negatively the firm's exit will impact subsequent citation (use) of that patent by other firms.

Much research has shown that geographical proximity enhances knowledge spillovers. In our case, the geographical proximity appears relevant particularly for firms that are foreign (relative to others that may use its innovative knowledge). When a source firm is foreign, it is especially challenging to acquire and integrate its knowledge, since language or cultural differences may interfere with the ability to "decode" knowledge about an innovation (Hayek 1945).Because the foreignness of a source firm increases the stickiness of its knowledge, its exit may have a stronger negative effect on the subsequent use of its knowledge than will the exit of a domestic firm. Firms may already be less likely to observe a foreign firm because of "spatial myopia," the fact that learning tends to favor effects that occur near the learner (Rosenkopf and Tushman 1994). This tendency is partially offset by competitive pressures that cause domestic firms to monitor foreign firms' activities, even if doing so is expensive and time consuming. However, when a firm is no longer active as an innovator or competitor, the competitive pressures no longer exist, and such information gathering will likely become a low priority (Hoetker 1996). Also, while there is evidence that employee mobility transfers knowledge as effectively internationally as domestically (Song , Almeida, and Wu 2003), employee mobility will have less effect internationally to the degree that firms are less likely to hire employees from a defunct foreign firm. Thus,

H_4: When the patenting firm is foreign, the negative impact of the firm's exit from an industry on subsequent citation (use) of a patent by other firms will be stronger.

The larger the number of inventors associated with an innovation, the larger the pool of mobile employees upon the industry exit of the firm that has the patent for the innovation. This condition might lead one to argue for greater diffusion of knowledge after the exit. However, many inventors means many interactions between individuals, thus implying a high likelihood that the innovation required private knowledge. That is, as more individuals become involved, an innovation becomes increasingly embedded in a complex web of relationships (Van de Ven 1986).

When a team of inventors is large, the range of specialized skills represented on it is also often large (Valentin and Jensen 2002). Such a large team represents not simply more interactions, but increasingly complex ones. Maintaining effective communication in a group whose members have diverse technical backgrounds is a complex challenge (Pfeffer 1981) , requiring the development of routines and languages that span technical specializations. This requirement increases the importance of the continued existence of the knowledge-creating firm for other firms seeking to build on its innovations. Absent the routines of a departed firm, other firms and their individual inventors will, we believe, have limited ability to replicate the exiter's activities. Overall, we posit that a firm's exit will have a stronger impact on the diffusion of knowledge created by a large team of inventors than it will have on the diffusion of knowledge created by a small team. Accordingly,

H_5: The larger the team of inventors a patent has, the more negatively the patenting firm's exit will impact subsequent citation (use) of that patent by other firms.

Similarly, innovations that draw upon a wide range of underlying technologies (e.g., organic light-emitting diodes, which require expertise in electronics, organic chemistry, and materials science) tend to be stickier than those that are extensions of a narrow field of knowledge. Knowledge that synthesizes divergent knowledge bases tends to be highly original (Trajtenberg, Henderson, and Jaffe 1997), and combinations of multiple fields tend to occur at the technological frontier. Knowledge surrounding such breakthrough research is likely to be highly tacit and therefore hard for outsiders to imitate (Nelson and Winter 1982). Further, just as tacit expertise is vital to the management of products with many interacting components (Chesbrough and Teece 1996), it is also important in the management of research that draws on many interacting technologies.

Thus, direct interaction and vicarious learning should be especially important for diffusion of technologies that draw on a wide range of technologies. This statement implies that firm exit will have a greater detrimental impact on the subsequent use of an innovation that embodies a wide range of technologies.

H_6: The more diverse technologies a patent draws upon, the more negatively the patenting firm's exit will impact subsequent citation (use) of that patent by other firms.

DATA

Context: The Rigid Disk Drive Industry

To address the research questions above, we need to examine knowledge transfer and the mechanisms through which it occurs for the census of corporations within an industry. Since the data requirements of such a study are very high, the industry studied needed to conform to certain boundaries. First off, the industry had to be relatively technologically intensive, because technologically intensive industries have higher rates of knowledge generation, and hence higher rates of knowledge transfer. More importantly, we needed longitudinal data on firms that were successful in an industry and those that ultimately exited it. We selected the hard disk drive industry for our empirical context, since it conformed to both the theoretical and empirical requirements of the study.

Disk drives are magnetic information storage devices used in computers. In 1973, IBM pioneered the 14-inch Winchester, the first completely sealed and removable disk drive, and the disk drive industry has since experienced rapid technological evolution (see Christensen [1993, 1997] for a detailed industry history). The *Disk/Trend Report,* a market research publication, tracked annual productive activity by all firms in the industry from 1977 to 1997, the period studied here. Given the richness and reliability of the data, the industry has been used as the empirical context in numerous prior studies (Christensen 1993; Lerner 1997; King and Tucci 2002; Agarwal, Echambadi, Franco, and Sarkar 2004). The industry experienced significant levels of both entry and exit in the relevant period, during which it went through the "shake-out stage" of the industry life cycle (Gort and Klepper 1982). In addition to the 39 incumbents that entered in or before 1976, there were 153 entries during the period under study. By 1997, 116 of these industry participants had exited the industry, 52 had been acquired, and 24 still existed. Since every productive firm was included in our data, regardless of size, the data do not suffer from a survivor bias.[2] Many of the entering firms represented employee entrepreneurship and, thus, interfirm knowledge

[2] We note that our data does not cover the first three years of the industry. However, industry life cycle studies (Gort and Klepper, 1982; Agarwal and Gort, 1996) indicate that exit is very infrequent during this time, so we do not expect our results to be affected by the non-availability of data during these years.

transfer (Agarwal, Echambadi, Franco, and Sarkar 2004). Additionally, McKendrick, Doner, and Haggard (2000) documented the extensiveness, in the disk drive industry, of both employee mobility and interfirm spillovers that shape new firms' technology and location choices. Thus, the disk drive industry is a particularly appropriate setting for our study.

Data Description

We track the subsequent use of a firm's technology by other firms via patent citations. In doing so, we follow a large body of research that has used the citations a patent receives as an indication of the degree to which subsequent innovations have built upon it (Jaffe and Trajtenberg 1996; Rosenkopf and Almeida 2003). The chief advantage of using patent data for our purposes was that these data reliably capture subsequent use of innovative knowledge by other firms. When an inventor files a patent application, she is required by law to list all "prior art" of which she is aware. Unlike academic citations, these citations to earlier work have the important legal function of limiting the scope of the property right granted to the patent. Further, the patent examiner in charge of the application, who is an expert in the technological area of the patent, can add citations that the inventor may have missed or concealed. This practice reduces the probability that irrelevant patents will be cited or that relevant patents will be omitted. Not every citation represents awareness of the cited patent within an organization filing the citing patent, since the patent examiner could have added the citation (Cockburn Iain M., Kortum, and Stern 2002; Alcácer and Gittelman 2004); however, a variety of studies have confirmed that patent citations are an accurate, though noisy, indicator of actual knowledge flows (Jaffe , Trajtenberg, and Fogarty 2002).

Our data on patents and patent citations were drawn from the NBER Patent-Citations Data Base (Hall, Jaffe, and Trajtenberg 2002) and the MicroPatent U.S. patent database. To ensure that we were capturing innovative activity in the relevant industry, we restricted the pool of patents to U.S. Patent Classification code 360, dynamic magnetic information storage or retrieval. We then matched the information on firms from the *Disk/Trend Report* to the assignee firms in the patent databases and selected all disk-drive-related patents assigned to a firm that had application dates between 1976 and 1997. This process generated a pool of 5,179 patents. Finally, we identified all patent citations for these patents in each year until 1999, the final year in the NBER Citations database.

The final data set consists of 43,161 patent-year observations—for instance, patent 4,933,785 observed one year after its application year (the year in which it was applied for); patent 4,933,785 observed two years after its application year, etc.—in an unbalanced panel that contains all years from the year in which a patent was applied for, through 1999. For every observation, the data contain detailed characteristics regarding both the patent and the firm to which it was assigned.

Variables in the Study

We now turn to a description of the chief variables in the study, which are summarized in Table 1. Our dependent variable, *citations received*, is the number of citations received by the patent from firms other than the one holding a focal patent in each year after its application year. This variable measures interfirm knowledge flows in a manner similar to Song, Almeida, and Wu (Song , Almeida, and Wu 2003) and Rosenkopf and Almeida (2003). We omit self-citations—citations by a firm to its own earlier patents—since we are primarily interested in interorganizational knowledge transfer. Doing so is also conservative, since the mechanisms driving self-citations may differ from those behind citations by other firms (Trajtenberg, Henderson, and Jaffe 1997; Caballero and Jaffe 2002). Further, since self-citation is not possible after a firm exits the industry, including self-citations could falsely magnify the impact of firm exit on knowledge transfer.

[Insert Table 1 here]

Firm exit is defined as the cessation of a firm's operations in the disk drive industry. Since acquisitions represent a change in ownership and differ substantially from exits, we treat acquisition as a censoring event. The indicator variable, e*xited*, is set to one for observations occurring after a patenting firm had exited the industry, and is zero otherwise.

The independent variables remain the same for all observations associated with a given patent and define characteristics of the patent and the patenting firm at the time the firm applied for the patent. *Firm age* at the time of a patent is calculated by subtracting the year of firm entry from the application year of the patent. A patent's *internal focus* is the proportion of citations in it that are to the firm's own prior patents and corresponds to the self-citation ratio calculated in the NBER database.[3] The larger the value of this variable, the more an innovation drew upon the firm's internal knowledge base. *Number of Inventors* is the number of inventors listed on a patent application, used here as an indication of the size of the team involved in the innovative research being patented. The indicator variable, *Foreign*, is set to one for patents filed by firms headquartered outside of the United States, and zero otherwise. *Range of Technologies Combined* corresponds to the Originality score calculated in the NBER data and first suggested by Trajtenberg, Henderson, and Jaffe (1997). By looking at the number of citations a patent makes to each of the three-digit patent classes, this measure captures the degree to which a patent draws upon a wide range of technological areas. It is defined for patent *i* as

$$1-\sum_{k=1}^{K}\left(\frac{NCITED_{ik}}{NCITED_{i}}\right)^{2}, \qquad (1)$$

where *NCITED* represents the number of number of patents cited by the focal patent and *k* indexes three-digit patent classes. Patents based on research that draws upon a wider range of technological roots will have a larger value of this variable.[4]

To estimate the effect of the time since a patent was applied for, we created a set of indicator variables, *Lag_1* to *Lag_24*, setting the appropriate variable to one for observations of the first through the twenty-fourth year after the patent was applied for. By interacting the lagged variables with the *exited* variable, we are able to compare the mean number of citations received by patents of active firms and firms that had exited at any interval after their application dates. To capture the impact of firm exit on the effect of our independent variables, we interact *exited* with each of them except the application year and firm dummy variables.

[3] Several data challenges compelled Hall *et al* to calculate a lower and upper bound for the estimate of self-citations. We use the lower bound, although the differences are small and our results are invariant to the use of either measure. Alcacer and Gittleman (2004) note that large number of self-citations are paradoxically added by examiners, rather than inventors. Fortunately for our purposes, high numbers of self-citations from either source indicate that a given patent is closely related to a firm's prior technological trajectory.

[4] Hall (2002) subsequently suggested a modification of this measure to reflect the fact that patents with few citations will be less likely to cite a broad range of classes. We use the original measure, having confirmed that our results are unchanged by using Hall's modified measure.

Among the control variables, we include firm dummies, to control for unobserved heterogeneity that may affect citations to all of a firm's patents, and application year dummies, to control for potential cohort effects. Additionally, we include two control variables for the quality of an innovation and an innovating firm: *Maturity of Technology* and *Recent Technological Activity*. *Maturity of Technology* is represented by the number of citations to prior patents made by a focal patent, divided by the number of claims the patent made. More citations to prior art per claim indicates a more developed or mature technological field (Lanjouw and Schankerman 2003). While a mature technology may be easier to understand, it may also simply be of less interest to other firms. Further, because there is likely to be a larger stock of innovations for a more mature technology, any given innovation would be, ceteris paribus, less likely to be built upon. *Recent Technological Activity* of a firm is computed as the mean number of disk drive-related patents applied for in the prior three years. For patents in the second and third year of a firm's existence, it is the mean of the number of patents applied for each year since firm entry. We include this measure of a patenting firm's technological activity at the time of a patent because we expect that technologies developed by firms perceived as highly technologically active may draw disproportionate attention from other firms. Because their innovative efforts are more broadly observed, they are more likely to be built upon by others (Podolny and Stuart 1995).[5]

Table 2 provides the descriptive statistics and correlation matrix for the key variables in the study. An inspection of the correlations does not reveal any multicollinearity concerns (mean VIF: 2.31, max VIF: 4.84).

[Insert Table 2 here]

METHODOLOGY

Our dependent variable is the number of citations a patent receives in each year after its application date, so we turned to the family of count data models for estimation (Greene 2000). Our empirical model is similar to that of Song et al (2003) and Rosenkopf and Almeida (2003). While those papers measured the total citations a patent received from a given firm, we model the number received

[5] To avoid potential confusion, we note that our independent variables all relate to information in the focal patent, e.g., the number of the firm's own prior patent that it cites. Our dependent variable relates to the decision by other companies to cite the focal patent subsequent to its granting.

from all firms in each year in order to be able to estimate the effect of firm exit over time. Specifically, the probability of a patent receiving a given number of citations can be modeled as resulting from a Poisson process:

$$\Pr(Y_{it} = y) = \frac{e^{-\mu_i}\mu_i^{y_i}}{y_i!}, \tag{2}$$

where Y_{it} represents the number of citations received by patent *i in* year *t* after the patent application. The mean value μ_i is parameterized in terms of $\boldsymbol{x_i}$, the vector of attributes, and coefficient vector β:

$$\mu_i = \exp(\boldsymbol{x}'_{it}\beta). \tag{3}$$

The Poisson process, however, restricts the mean and variance to be equal, which may not be a reasonable assumption. The negative binomial (NB) regression model extends the Poisson regression model by allowing the variance of the process to exceed the mean (Cameron and Trivedi 1998). The degree by which it does so, the overdispersion parameter, equals the variance of the process divided by its mean. Because we had panel data, we use a random-effects NB model (Hausman, Hall, and Griliches 1984), which specifies that all observations for a given patent *i* share a common overdispersion parameter δ_i in which $1/(1+\delta_i) \sim \text{Beta}(\alpha,\beta)$.

RESULTS

We first investigate the effect of firm exit on patent citation counts to test if diffusion rates differ significantly before and after a firm's exit. For ease of exposition, we depict this effect graphically and note that the results from the negative binomial model presented later are consistent with the graphs in Figure 1. In panel i of Figure 1, we report the average number of citations received by patents in each year after their application dates. The three curves in panel i correspond to three groups of patents: those belonging to firms that do not exit during the study period; those belonging to firms that will exit during the study period, but have not yet done so at the observation point; and those belonging to firms that have already exited at the time of the observation. Like the authors of earlier studies (e.g., Trajtenberg 1990; Jaffe, Trajtenberg, and Henderson 1993; Jaffe and Trajtenberg 2002; Caballero and Jaffe 2002), we find an inverted-U-shaped curve for patent citations that peaks after a lag of four years. Further, prior to their exit, the patents of firms that eventually exited the industry received approximately the same number of citations as firms that remained in existence. Tests of homogeneity confirm the visual impression: the number of citations received is indistinguishable for these first two groups ($p > 0.10$) for lags of up to ten years.[6] Thus, patent citation counts do not differ, *while a firm is still in existence*, for firms known to have survived and firms known to have later exited. Our finding of similar diffusion rates prior to exit for exiting and surviving firms supports earlier studies that indicate that firms may exit this industry despite being technologically innovative (Katz and Shapiro 1985; Golder and Tellis 1993; Podolny and Stuart 1995) It also confirms the anecdotal evidence provided by McKendrick and colleagues (2000:73) that led them to conclude that the industry landscape is "littered with the graves" of firms that were once considered technological leaders.

[Insert Figure 1 here]

Once a firm exits, however, citations to its patents drop precipitously. As the third curve in panel i reveals, the patents of firms that have exited the industry by a focal citation year receive lower citations than either of the other two groups, and this difference is particularly stark shortly after a patent's appearance. For lags of one to eleven years, the difference between citations to patents of firms that do not exit and those that already have ranges from 18 to 40 percent (p[difference > 0] < 0.01). Citations to patents of firms that will exit, but have not already, and to those of firms that have already exited differ at the 0.05 level or better for lags of one to eleven years, with the exception of the five-year lag, with the difference ranging from 16 to 67 percent. In spite of this drop, citations to the patents of exited companies remained significantly above zero for most of the period ($p < 0.10$ for lags of one through twenty years). For later years, the citation count is not significantly different from the citation counts received by the other two groups.

To further clarify the point, we use the same data in panel ii to illustrate the average citation pattern over time for two hypothetical patents, one belonging to firm A, which never exits the industry, and the other belonging to firm B, which exits five years after the patent is applied for. As is seen in panel ii, the two curves are relatively indistinguishable till the year that firm B exits, after which the

[6] The exception is the lag of 2 years, in which patents of firms that will exit, but have not done so yet, receive significantly more citations on average (0.74 versus 0.59, p=0.005).

citations received by firm B's patent are significantly lower than firm A's for the next ten years. The effect of firm exit on citation counts fades to insignificance fifteen years after a patent is granted. Taken together, panels i and ii in Figure 1 indicate that firm exit has a detrimental, but not a fatal, effect on the diffusion of knowledge to other firms. Thus, we find support for Hypothesis 1.

We now turn to the effect of firm exit on the relationships between citation counts and key variables of interest. Table 3 presents the results of a negative binomial estimate of citations received from other firms. Column 1 reports the results for the main effect of our explanatory variables—it does not differentiate between citations received while an innovating firm was active and citations received after its exit from the focal industry. The twenty-four lag variable dummies (not reported owing to space limitations) provide an estimate of the effect of the passage of time since a patent was applied for on the citations it received. Collectively, results for the dummies confirm the pattern observed in Figure 1. The number of citations increases quickly, peaking around four years after a patent was applied for, and then slowly decreases. In column 2, we examine the main and interaction effects of firm exit. The incremental log-likelihood chi-square statistic indicates that consideration of firm exit significantly improves the fit of the model ($\chi^2[29] = 112.4$, $p < 0.001$). The interactions of the *lag* variables with *exited* are negative and significant for lags of one to twenty-one years, indicating that patents received fewer citations once a patenting firm exited the industry.[7] However, as noted above, the mean number of citations received per patent of a company that has exited remains significantly above zero until a lag of twenty-one years. In combination, these findings confirm the above graphical depiction that firm exit reduces the rate of citations to a firm's patents, but not to zero, and they provide additional support for Hypothesis 1.

[Insert Table 3 here]

Our test of the first two hypotheses, related to *firm age* and *internal focus,* yield similar results. Neither variable is significant when a firm is active, and both have a significant, negative interaction with firm exit. Both variables are associated with more embedded innovative routines: an innovation that

[7] Interacting *exited* with all *lag* dummies, rather than including a main effect for exit and omitting a single year to create the excluded category, allows us to interpret our results as relative to the citations expected for non-exited firms with those characteristics that many years post-patent application, rather than the much less informative comparison to the number of citations expected in the excluded year. See Kennedy (1998:223-4).

draws upon a firm's own knowledge base is naturally stickier than other innovations, and older firms have more established innovative routines. Our results indicate that, *when an innovating firm is active,* other firms are able to overcome these barriers through opportunities for learning from the innovating firm's activities. However, absent this template, upon firm exit, other firms find it harder to build on an initial innovation. Thus, we find support for hypotheses 2 and 3.

The coefficient of *number of inventors* is positive and significant in both models, indicating that patents involving more inventors receive more citations. However, there is a significant, negative interaction with *exited*, implying that after a firm's exit, other firms find it very difficult to build on knowledge that required many inventors and many interactions among them to be generated. In particular, since a high number of inventors implies a large pool of mobile employees, the large and significant coefficient of the interaction term in column 2 underscores the need for the innovating firm to continue to exist so that other firms may observe its routines and management of innovation. This finding supports our hypothesis 4.

Patents belonging to *Foreign* firms receive the same number of citations as those of domestic firms while a firm is active. The interaction of *Foreign* and *exited* is negative and significant, indicating that the postexit drop in citations to the patents of foreign firms is larger than the drop experienced by patents of domestic firms. It appears that the stickiness of knowledge created in foreign firms that is due to distance, language difficulties, and differences in engineering and measurement standards makes the availability of a template even more important. Thus, hypothesis 5 is supported.

Finally, we find no effect for the *range of technologies combined* or its interaction with firm exit. Thus, hypothesis 6 is not supported. This absence of support suggests that the combination of technologies that occurs in this industry poses little challenge for imitation. Once a firm has successfully combined multiple technologies, other firms do not find it difficult to build on the resulting combined technology, with or without access to the firm as a template. We note, though, that this result may reflect the relatively low value of this variable in our sample; this value was 0.236 in a range of 0–1. By comparison, the average across all sectors was approximately 0.30 in 1975, and it rose to approximately

0.40 in the 1990s (Hall et al 2002:430, Figure 15). The range of technologies combined in the hard drive industry may not have been diverse enough to pose a barrier to knowledge replication.

Among the control variables, we find that *Maturity of Technology* is negative and significant, and that *Recent Technological Activity* is positive and significant. This pattern of findings accords with our expectations that patents building on mature technologies are less likely to be cited and that patents belonging to more technologically active firms are cited more heavily.

ALTERNATIVE EXPLANATIONS

Our hypotheses regarding the main and moderating effects of the exit of a firm from a technologically intensive industry on the diffusion of its knowledge centered around the importance of the private knowledge contained in the firm's routines. There may, however, be alternative explanations for the observed effects. For example, it could be argued that differences in technological prowess caused firm exit and also manifested themselves in lower citation rates. We do not believe that this is the case for the following reasons. First, our data do not indicate that firms that exited the industry differed significantly in their patenting behavior from firms that were still in existence in 1999. The tests for homogeneity revealed no statistically significant differences between firms that exited during the period of our study and those that did not on the following: the number of patents received (either total or per year), the tendency to self-cite, the range of technologies drawn upon, the number of claims per patent, and the number of inventors per patent. Second, as indicated above, there was no significant difference in the citation rates observed for years in which firms existed between firms that remained in existence over the study period and those that eventually exited the industry.[8] More importantly, although differences in technological capabilities may result in differences in the overall number of patents a firm receives or in the overall *level* of citations those patents receive, our hypotheses centered around the *change in the slope* of the citation trend of a given patent associated with firm exit. The quality of the knowledge underlying patents plays no role in our model; rather, we ask to what degree other companies build on a patent, contingent on the status of the inventing firm (surviving vs. defunct). Since we look at citations received

[8] Further, while not during the period under investigation, the fountainhead of knowledge and creator of the industry, IBM, subsequently ceased operations in disk-drives, indicating the importance of factors beyond technological capabilities.

by a *given* patent over time, conditional on the current status of the inventing firm, the quality of the original innovation is not affected by the eventual fate of the innovating firm. The empirical evidence is clear: firms build to varying degrees on the patents of surviving firms and nonsurviving firms.

Another alternative explanation for the observed results could be that firms may take the exit of a company as a signal that its technology is no longer relevant,[9] an assumption that would lead them to pay less attention to the innovations the firm generated while active. Though we control for these issues to some degree by including *Maturity of Technology* and *Recent Technological Activity*, we cannot rule out this explanation altogether for the main effect of firm exit (hypothesis 1), since it may drive a portion of the overall drop in citations a patent receives after the exit of the firm that holds it. However, the signaling effect cannot explain the effects of the interaction of firm exit with variables associated with varying degrees of private knowledge (Hypotheses 2–6). The evidence still points strongly to the loss of private knowledge having an important effect. A firm's exit would taint all of its patents as inferior or irrelevant to the same degree, yet we find that the postexit reduction in citations received for a given firm's patents is highly conditional on the characteristics of each patent—characteristics that are closely tied to the importance and inaccessibility of the private knowledge associated with that patent. Indeed, the support that we find for the interaction hypotheses, coupled with the cross-patent variation in citations of patents belonging to the same exited firm helps rules out a wide-range of alternative explanations.

DISCUSSION AND CONCLUSION

The fate of innovative knowledge created by firms that subsequently exit an industry is of practical and theoretical importance. To the degree that knowledge languishes after the exit of an innovating firm, other industry participants and society at large lose a potential source of technological progress. If, however, knowledge that a defunct firm created is significantly diffused, these positive externalities result in some social benefit from the investments made when the firm was alive. Theoretically, the fate of innovative knowledge after firm exit illuminates the impact of private

[9] The signal may be based either on an accurate or inaccurate perception of the event, it may be that an exogenous event caused the firm's technology to become less relevant, or that firms assume it to be so due to the change in status.

knowledge on the diffusion of knowledge that is in the explicit/codified domain and the extent to which the continued existence of a firm enhances spillovers of its knowledge.

There is anecdotal evidence that a firm's innovative knowledge can outlast its existence. The introduction to this study cited OIS as an example of a firm whose knowledge has had considerable impact on the flat panel display industry after its demise. Another such firm is Prairietek. This company was active in the disk drive industry for only five years, but one of its patents was cited one hundred six times in the eight years between its death and 1999. Our study sought to systematically study this issue and provide empirical evidence on whether OIS and Prairietek are merely exceptions to the rule or examples of a regular pattern of postexit diffusion.

Our study provides several insights. First, death clearly hurts knowledge diffusion. Examining the patent citation trends before and after the exit of a firm, we found a significant decline in the citation rate that was attributable to firm exit, even after controlling for firm and patent characteristics. Our results show that, in addition to the features identified in prior research as the characteristics of a firm that is the source of knowledge, another important determinant of continued knowledge diffusion is the continued existence of the firm. Thus, our evidence points to the fact that it is not only the quality of knowledge that matters in its ultimate citation; the fate of the firm that originated the knowledge is also important.

However, death is not fatal to knowledge diffusion. OIS and Prairietek are not just anecdotal exceptions. There is clear evidence of significant postexit diffusion of knowledge. Thus, while citation rates did decline after firm exit here, firms that exited still received a significant proportion of the citations that they could have expected to receive were they still in existence. Further, death may also not have a permanent impact on diffusion, since we found that differences in the diffusion of active and defunct firms' knowledge faded over time.

Our study also sheds light on the mechanisms underlying knowledge transfer. In particular, we note that the extent of employee mobility in the disk drive industry is so high that disk drive designers have said that "workers remain the same, they just shift periodically from company to company" (McKendrick et al 2000:44). That disk drive production is an art rather than a science appears in part to be the source of this high mobility. The nature of the industry results in a need for industry-specific skills and highly specialized human capital and an accompanying premium on industry experience. (McKendrick et al 2000). Employee mobility and reverse engineering allow for continued diffusion of a firm's technology after its exit; however, these mechanisms are tempered by the inability to access private knowledge that was embedded within the firm's organizational structure after firm death. Even though the possibility of knowledge transfer to other firms through employee mobility is highest at the time of firm exit, we found no evidence of increased citation by other firms after firm exit. This absence of evidence implies that knowledge transfer through employee mobility is more effective when a source firm remains active. Recipient firms, even when they hire employees from the source firm, may still need to either interact with, or at least observe, its rules and routines in order to fully benefit from the knowledge transfer. We find that knowledge stickiness owing to embeddedness is a major impediment to diffusion of the knowledge, and our study highlights the importance of using a firm's activities as a template for successfully replicating and extending its innovative knowledge. This finding is also consistent with the observed geographical clustering of firms engaged in both innovation and operational activities in the hard drive industry.

The results from our study point to several intriguing questions for future research. The study highlights the impact of firm exit on innovative knowledge that is explicit and codified in patents. It is also important to assess the impact of firm exit on other types of knowledge, particularly those with high tacitness. We suspect that firm exit will have an even more detrimental impact in these cases, resulting not just in a decline in diffusion, but also in an actual *loss* of knowledge. For instance, MacKenzie and Spinardi (1995) presented evidence on the "uninvention" of tacit knowledge in the nuclear weapons industry that was due to cessation of design and operations. On a more optimistic note, since significant knowledge diffusion occurs even after firm exit, future research could examine the characteristics of the firms that are the most likely to harness a defunct firm's technology. In view of our findings, we expect that absorptive capabilities (Cohen and Levinthal 1990) will play an especially important role. In the absence of an observable template, firms with a greater ability to dissect and absorb innovative knowledge on their own will have an advantage in building on a departed firm's knowledge. Further, are there differences in the mechanisms that underlie knowledge transfer from existing and defunct firms? If there are such differences, firms need to employ different technology strategies depending on whether a source firm is active or defunct. In addition to learning vicariously and forming collaborative networks, three other mechanisms for transferring technology from other firms that the literature often mentions are hiring technical employees (Rosenkopf and Almeida 2003), hiring managers (Boeker 1997), and buying intellectual property (Arora, Fosfuri, and Gambardella 2001). Intellectual property, while useful, transfers only formal, public knowledge, omitting associated private, tacit know-how that may be critical. Technical employees bring both explicit and tacit knowledge to a new firm, but they are removed from the routines and culture of their previous employer. Managerial employees bring important organizational knowledge that can help in the re-creation of team dynamics and routines. Are these mechanisms more or less effective when a firm that is the source of knowledge is still in existence or when it has exited an industry? Should the technology strategy for harnessing knowledge created by a departed firm focus on one more than the others, or is it more effective to combine multiple mechanisms? Future research in this direction will provide additional insights into the factors affecting knowledge diffusion. Finally, it would be useful to replicate the results of this single-industry study in another industry, as is always the case. Industries that lack the hard disk drive industry's high employee mobility or that draw on a wider range of technologies than the disk drive industry would be especially interesting contexts, since they would allow researchers to identify additional industry conditions that may affect the postexit diffusion of knowledge.

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Table 1: Variable definitions

Variable name	Variable definition
Dependent variable	
Citations received	Number of citations received in a given year from other firms
Independent variables	
Firm exit	0/1 variable set to 1 if the firm had exited at the time of an observation
Firm age at time of patent	Application year of focal patent minus year of firm founding
Internal focus	Percent of citations in the focal patent that were to other patents of the same company (*selfctlb* variable in the NBER Patent-Citations Data File)
Number of inventors	Number of inventors listed on focal patent
Range of technologies combined	Heterogeneity of patent classes cited by focal patent (*original* variable in the NBER Patent-Citations Data File)
Foreign firm	0/1 variable set to 1 if the patenting firm was from outside of the U.S.
Control variables	
Maturity of technology	Number of citations made by focal patent divided by the number of claims it contained
Recent technological activity	Average number of patents by the firm over the three years prior to patent application

Table 2: Summary statistics and correlations

		Mean	S.D.	Min	Max	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1)	**Citations by other firms**	0.578	1.264	0.000	28.000	1.00								
(2)	**Firm has exited**	0.215	0.411	0.000	1.000	-0.04	1.00							
(3)	**Firm age at time of patent**	13.670	10.216	0.000	41.000	0.03	-0.37	1.00						
(4)	**Internal focus**	0.158	0.249	0.000	1.000	0.01	0.00	0.26	1.00					
(5)	**Number of inventors**	2.447	1.784	1.000	20.000	0.05	-0.13	0.12	0.03	1.00				
(6)	**Range of technologies combined**	0.231	0.249	0.000	0.867	-0.00	0.04	0.08	-0.03	0.01	1.00			
(7)	**Maturity of technology**	0.872	1.368	0.016	26.333	-0.03	0.03	0.01	-0.04	-0.02	0.14	1.00		
(8)	**Foreign firm**	0.514	0.500	0.000	1.000	-0.11	0.13	-0.46	-0.13	0.12	-0.07	-0.00	1.00	
(9)	**Recent technological activity of firm**	35.196	31.523	0.000	128.000	0.05	0.01	0.45	0.27	0.09	0.08	0.03	-0.06	1.00

N=45644. Because of the large N, every correlation is uninformatively significant at the 10% level or better.

Table 3: Negative binomial estimation of citations received

	(1)	(2)
	Citations by other	**Citations by other**
Firm age at time of patent	0.028 (0.043)	0.032 (0.043)
Firm age at times of patent * Exited		-0.064** (0.008)
Internal focus	0.011 (0.064)	0.095 (0.071)
Internal focus * Exited		-0.313* (0.123)
Number of inventors	0.028** (0.009)	0.033** (0.009)
Number of inventors* Exited		-0.045* (0.021)
Foreign firm	1.577 (1.535)	1.653 (1.536)
Foreign firm * Exited		-0.381** (0.090)
Range of technologies combined	-0.045 (0.059)	-0.024 (0.063)
Range of technologies * Exited		-0.072 (0.116)
Maturity of technology	-0.029** (0.010)	-0.033** (0.011)
Recent technological activity of firm	0.017** (0.000)	0.017** (0.000)
LAG1 – LAG 24 (joint significance)	$p<0.001$	$p<0.001$
Exited * LAG dummies (joint significance)		$p<0.001$
Firm dummies (joint significance)	$p<0.001$	$p<0.001$
Application year dummies (joint significance)	$p<0.001$	$p<0.001$
Dispersion parameters (α,β)	6.17, 2.24	6.22, 2.24
Average overdispersion	1.364	1.358
Observations	43161	43161
Log-likelihood	-38541.4	-38485.2

Standard errors in parentheses
* significant at 5%; ** significant at 1%

Figure 1: Citations received from other firms over time