

Knowledge Sharing and Value Flow in the Software Industry: Searching the Patent Citation Network

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Abstract

A firm's innovative capabilities depend on its ability to learn from the environment. To learn from the environment a firm must have access to external knowledge, and it must have the absorptive capacity to identify, assimilate and exploit such knowledge. While previous research recognized that firms must invest to acquire absorptive capacity, it assumed that access to knowledge spillovers is free, or a perfectly correlated component of R&D investments. We argue that a firm must also invest in developing organizational routines that search for and acquire access to knowledge spillover. In order to explore the relationship between own-knowledge development and search, we examine the relationship between software firms' R&D investments and their position within the patent citation network and their subsequent knowledge development and financial performance. The results show that a firm's position within the knowledge flow of the industry helps predict knowledge development and financial performance.

1. Overview

1.1. Introduction

A firm's innovative capabilities depend critically on not only its in-house knowledge and expertise, but also its ability to learn from the environment. To learn from the environment, first, a firm must have access to external knowledge; second, it must have the capacity to identify, assimilate and exploit such knowledge.

Neoclassical economics assumes that information is free-flowing, costless, and can be absorbed at negligible cost [4]. Cohen and Levinthal [11] relaxed the third assumption when they modeled the importance of knowledge spillovers between firms and the resulting decisions to invest in own-knowledge creation in order to develop the absorptive capacity to identify, assimilate and exploit spilt knowledge. A firm must know something in order to learn something.

They show that in certain situations firms would invest in R&D even if the resulting knowledge were not fully appropriated by the firm in order to learn from other firms.

Zahra and George [46] refined the definition of absorptive capacity as the routines and capabilities that enable a firm to acquire, assimilate, transform and exploit knowledge. Knowledge acquisition "refers to a firm's capability to identify and acquire externally generated knowledge that is critical to its operations." Assimilation refers to the ability to understand externally sourced knowledge. Transformation refers to the ability to internalize and integrate new knowledge with existing knowledge. Exploitation refers to the ability to leverage new and existing knowledge.

March [28] theorized that firms exploit existing knowledge and explore others' knowledge in order to generate new knowledge. Nonaka and Takeuchi [31] describe learning organizations as those that acquire and integrate internal and external sources of knowledge. The resource-based view of the firm argues that firms have specific competencies that underlie their competitive advantage. Firms have different capabilities to manage learning and imitation of external knowledge [47]. Sustainable competitive advantage depends upon the firm's ability to reconfigure its knowledge [19, 22, 38].

Rosenkopf and Nerkar [33] develop a framework in which knowledge exploration is categorized as either local, technological boundary spanning, organizational boundary spanning, or radical boundary spanning. In local exploration the firm develops its own-knowledge within the same technological domain as its previous knowledge. In technological boundary spanning the firm continues to perform own-knowledge generation, but it does so outside of its existing knowledge domain. In organizational boundary spanning, the firm learns from other firms, but within the same technological domain as its previous knowledge. In radical boundary spanning the firm gains knowledge from other firms in technological areas outside its own knowledge domain.

This paper focuses on the relationship between local-knowledge exploration, which develops the

assimilative, transformational, and exploitative components of absorptive capacity, and the costly search for, and access of, external knowledge, which may or may not cross technological boundaries. We have empirical and observational evidence that firms engage in a variety of costly activities that facilitate joint knowledge production [35]. Knowledge is sticky and does not flow automatically from one place to another [43]. Therefore, we suggest that external knowledge does not spill over to a firm unless it has invested to search and acquire outside knowledge. Firms invest in search and access (S&A) because the information they seek to explore is not freely available, and they engage in such costly activities as attending industry trade-shows, visiting common customers and studying other firms' products.

Each firm's costly S&A activity builds conduits to other firms through which knowledge flows. The collection of firms and their conduits form a network. This research recognizes the importance of networks to firms and studies the impact of a firm's position within the network of its industry's knowledge flow and the firm's investments in own-knowledge generation on firm performance and knowledge generation. Other researchers have also recognized the importance of networks. Gnyawali finds that "Firms are embedded in networks of cooperative relationships that influence the flow of resources among them." [16] Business networks are characterized by lateral and vertical linkages within and among firms [30].

The results of this paper show that investments in network position enhance the innovative and financial performance of the firm. The results suggest firms balance investments in own R&D and S&A to acquire, assimilate, transform and exploit spilt knowledge in order to maximize the present value of future profits.

This paper is organized as follows. Section two reviews and extends the theory of absorptive capacity and develops hypotheses. Section three describes the methodology, including an examination of software patenting as a proxy for firm learning. Section four describes the dataset and variables. Section five describes the analyses and results. Section six concludes the paper with discussion and direction for future research.

2. Theory and Hypotheses

2.1. Outside knowledge

Outside sources of knowledge are critical to innovation in both U.S.-based and international (e.g., Japanese) firms [27, 34]. At the industry level, the ability to exploit external knowledge predicts the decision to locate a new venture [2]. At the organizational level outside knowledge sources are also important and frequently the genesis of innovations

[42]. At the project level, differences in the informal networks of software developers seems to explain differences in project success due to the presence of gatekeepers that are able to monitor external knowledge sources and translate the knowledge to project members [3].

Locating and accessing these outside knowledge sources is not costless. Firms invest in joint ventures, research consortia, and R&D activities. Firms meet with customers, attend trade shows and analyze competitors. Both time and equipment are limited; therefore, the firm must make allocation decisions that ultimately affect firm performance. When there are many sources of outside knowledge, the sources the firm selects are critical to what it learns and how it allocates its resources.

2.2. Formal or Informal Access

Firms learn from each other through formal and informal relationships. The relationships can be cooperative or competitive. Firms can share knowledge, or inadvertently spill knowledge. The literature describes the knowledge one firm inadvertently learns from another as spillover [10].

Firms learn from each other through formal mechanisms such as joint ventures as part of strategic initiatives [14]. Depending upon the nature of the innovation, strategic considerations dictate the form of relationship from informal agreements to acquisitions [37].

As a result of the importance of outside knowledge, firm boundaries may be determined by the demands for knowledge sharing [7, 45]. The knowledge gained from joint ventures is not limited to the specifics of the venture. In addition, overseeing effort and management involvement are channels of learning [39].

March and Simon [29] suggest most innovations result from borrowing rather than invention. Von Hippel [42] suggests that sources of innovation include suppliers, manufacturers, and customers. Von Hippel goes on to state that utilizing knowledge enhances the economic rent firms appropriate, and more can be gained than lost in most knowledge trading environments.

2.3. Network-position

We posit that firms that compete in the same markets or have customers in common also share and spill knowledge. The knowledge that flows from one firm to another may be technical, managerial or market oriented. Industry differences and technological difficulty determine the type and amount of knowledge that flows between firms, and as a result, the mechanisms that firms use to protect valuable intellectual property [24].

Knowledge flows between firms as a result of activities such as attendance at industry trade-shows, visiting common customers, and reading industry publications. Firms also learn by examining each other's products and inventions. The amount firms can learn through observation may be a function of the types of products and innovations they produce, and may lead to different forms of intellectual property protection. Firms that produce easily observed products, such as software, may produce more easily absorbed knowledge spillover. As evidence that software knowledge is both easy to spill and absorb, we offer the prevalence of software patents. Software is relatively easy to describe, and is thus amenable to patent definition. Software is also inexpensively copied; thus, its developers benefit from the protection offered by software patents. Other products or services may be more difficult to replicate, or to protect, and thus use other forms of intellectual property protection.

So far we have argued that two firms can learn from each other by jointly participating in the same technical or market segments. If we make the reasonable assumption that knowledge is heterogeneously distributed across firms, then it matters to the firm which firms it is learning from.

Uzzi [40] finds that "the structure and quality of social ties among firms shape economic action by creating unique opportunities and access to those opportunities" in his studies of Broadway Musicals and the New York Garment industry [40, 41]. Firms that have ongoing, stable relationships with a few customers or suppliers (strong ties) and additional relationships with newer partners (weak ties) learn more than either firms that have exclusively strong ties or weak ties. In their study of investment banking firms, Baum et al. [5] find that firms made strategic decisions in determining who they partnered with in order to improve their network position.

Roskenkopf and Nerkar [33] explored patent citations within the optical disk industry. They found that firms that explore beyond their organizational boundary, but within their technological domain, have the greatest impact on the domain, and that firms that explore beyond their organizational and technological boundaries have the greatest impact outside their technological domain.

External knowledge is important, firms pay to access it independently of their own-knowledge development investments, not all firms know the same thing [36], and because firms are not linked to each other randomly the size and shape of the firm's network are critical components of its knowledge investment decisions. In order to better understand the relationship between these components on a firm's knowledge investment decisions, we have adapted the

model presented by Cohen and Levinthal[11] to incorporate search and access (S&A) costs.

2.4. Network Absorptive Capacity

2.4.1. Model introduction

Cohen and Levinthal define absorptive capacity as the capacity to identify, assimilate and exploit new knowledge[11]. Zahra and George [46] refined the definition of absorptive capacity as the routines and capabilities that enable a firm to acquire, assimilate, transform and exploit knowledge. Cohen and Levinthal suggest that firms build their absorptive capacity as a by-product of their own-knowledge development efforts. Own-knowledge development is that portion of knowledge development not dependent on outside knowledge, but which is a result of independent research effort. Own-knowledge development is the endogenous variable, proxied by R&D expenditure[10]. Absorptive capacity, as stated by Cohen and Levinthal, is a second-order construct.

The absorptive capacity developed through own-knowledge development is then applied to knowledge that originates with other firms (including competitors) in the industry that spills over original, valuable knowledge and from extra-industry sources in order to develop a firm's knowledge stock. Cohen and Levinthal do not explore the explicit search and access of the external knowledge. Zahra and George [46] refine the absorptive capacity construct provided by Cohen and Levinthal to explicitly incorporate the capability to search and access knowledge. We complement this second-order capability with a search and access investment that we incorporate into a knowledge production function.

Firms invest in knowledge development to both generate new knowledge and assimilate and exploit existing information. In order to learn something, firms need to know something. Thus, although a firm can concentrate only on internal knowledge development, it cannot only concentrate on spillovers. What a firm can learn from spillovers is a function of both the absorptive capacity of the firm – developed by investing in knowledge development – and the amount of spillover accessible to be learned. Absorptive capacity is a measure of how well the firm learns. Part of the investment in knowledge development develops the ability to learn. For example, doing in-house research in chemistry enables a firm to better learn from developments in chemistry occurring outside the firm. The amount of spillover to be learned is a function of the barriers to appropriability (trade secrets, patents, etc.), the visibility of the innovations (certain products or processes are easier to replicate than others), and the amount of innovation, which may be limited by opportunity conditions.

In classical economic literature, information in the public domain is assumed to be free, and costlessly absorbed [4]. Cohen and Levinthal [11, 12] effectively argue that if such information is costlessly absorbed, it is only because firms invest in absorptive capacity, which is not costless. Their model is:

$$z = M + \gamma(\theta \sum_{j=1}^J Q_j + T), \text{ in which}$$

- z firm's incremental addition to own-knowledge.
- M firm's investment in own-knowledge development.
- γ absorptive capacity. $0 \leq \gamma \leq 1$.
- θ fraction of intra-industry spillovers. $0 \leq \theta \leq 1$.
- Q_j knowledge stock of other firm, j .
- T the level of extra-industry knowledge.

One implicit assumption of the Cohen-Levinthal model is that information flows freely, or, alternatively, is perfectly correlated with own-knowledge development investments. That is, there is no explicit search cost variable.

2.4.2. Model development

We argue that the assumption of free-flowing information, or that information search and access (S&A) is perfectly correlated with own-knowledge development, does not generally hold and that in order to take advantage of knowledge spillover a firm must invest in S&A. We argue that S&A investments are independent of own-knowledge development investments, and we hypothesize that their effectiveness is dependent on the firm's position within the industry network. The cost of absorbing spillovers is not just the cost of developing the absorptive capacity. Knowledge does not just accrue to the firm once the absorptive capacity has been developed. Rather, there is a cost to locate and access the knowledge held by the other firms.

This brings us to the new model of the firm's knowledge acquisition function. Firms invest in own-knowledge development, which builds absorptive capacity. Firms also invest in S&A, which provides the information that the firm's absorptive capacity acts upon. Formally,

$$z = M + \gamma(\theta \sum_{j=1}^J (\chi_j \cdot Q_j) + T) \text{ in which}$$

- z incremental addition to knowledge.
- M firm's investment in own-knowledge development.
- γ absorptive capacity. $0 \leq \gamma \leq 1$.
- θ fraction of intra-industry spillovers. $0 \leq \theta \leq 1$.
- χ_j focal firm's effectiveness of access to firm j . $0 \leq \chi_j \leq 1$.
- Q_j knowledge stock of other firm, j .
- T the level of extra-industry knowledge.

All variables other than χ are the same as described by Cohen and Levinthal [10]. Absorptive capacity, γ is a function of the investment that the firm makes in its own-knowledge creation, M , and the characteristics of the outside knowledge that makes learning difficult ($\gamma=f(M, \text{Difficulty of learning})$). If the firm faces a technological environment in which all knowledge is tacit, the firm will have to invest considerable sums in its own-knowledge development in order to learn from firms and other outside sources. If the firm faces a technological environment, however, in which all knowledge is codified, the firm will need to invest very little in order to learn from those same sources. The firm cannot exclusively rely upon past investments in knowledge development in order to maintain its absorptive capacity.

Industry spillover, θ , reflects the intellectual property appropriability regimen for the industry. If the industry's technology is unobservable, hard to replicate, and non-transferable, θ will be very low. If the industry's technology is easily observed, replicated, and transferable, and not well protected by patent or other legal safeguards, θ will be very high. θ is assumed exogenous to the firm.

Effectiveness of access, χ_j , represents the access the focal firm has to firm j 's knowledge. It is the result of S&A investments that the firm has made. S&A represents a wide range of activities from attending common trade association meetings, visiting a firm's website or reading its product literature, to reverse engineering products and entering into joint ventures.

Effectiveness of access is an emergent function of what the focal firm invests in S&A to build links to the other firms in the industry, and the links other firms have developed through their own S&A investments. These links are conduits through which knowledge flows[32]. The greater the resources a firm expends in S&A, the greater its effectiveness of access will be.

T is, as described by Cohen and Levinthal, "the quantity of extra-industry technological knowledge." Government, universities, or customers may provide it. It may be made available through journals, conferences, websites, or other mechanisms[10].

z is the addition, in one time period, to the focal firm's stock of knowledge. If $\gamma = 0$, the firm has no absorptive capacity and only learns by doing its own-knowledge development. If $\gamma = 1$, the firm learns everything that is spilt. If $\theta = 0$, no knowledge is spilt. Either other firms perform no knowledge creation, or they have perfect knowledge appropriability. If $\theta = 1$, all the knowledge developed by other firms enters the public domain. If $\sum \chi_j = 0$, the firm has no effectiveness of access to spillovers, limiting the value of absorptive capacity to building on extra-industry knowledge.

If unlinked firms characterize the industry, the cost to develop effectiveness of access to other firm's knowledge may be so prohibitive that firms are protected by anonymity and need not engage in costly efforts to restrict spillovers or develop absorptive capacity.

2.5. Hypotheses

The central thesis of this research is that firms maximize their knowledge development by investing in own-knowledge development and searching and accessing the knowledge of other firms. Own-knowledge development builds the absorptive capacity that enables the firm to utilize the knowledge accessed from external firms to add to its own knowledge stock.

Own-knowledge development has both a direct and indirect contribution to incremental knowledge production. The direct production of knowledge is due to research activities the firm performs without accessing external resources; the indirect contribution is due to the second-order affect of developing the absorptive capacity that enables the firm to acquire, assimilate, transform and exploit external knowledge. This leads us to expect:

H1: Firms that invest more in own-knowledge development produce more knowledge.

Absorptive capacity is increased through investments in own-knowledge development, but at a decreasing rate [11]. This leads us to predict:

H2: Firms that invest more in own-knowledge development will spend more own-knowledge development resources per unit of knowledge.

Effectiveness of access enables the firm to access the knowledge of other firms, whether or not it is shared or spilt. To the extent enabled by the firm's absorptive capacity, this external knowledge is then assimilated by the focal firm and used to increase the firm's knowledge stock.

Effectiveness of access is a function of the specific firms that the focal firm links to, and the links those firms make to other firms, recursively. Although these links are the result of investments in S&A, we do not have an operationalization that measures either the investment in S&A or the effectiveness of access constructs. However, the firms and the links – the knowledge conduits – that connect them can be described as a monopartite network, and analyzed as such. The links that connect the firm to the network give the firm a specific position relative to the network. This position is a component of the firm's effectiveness of access. Other components of effectiveness include, but are not limited to, the types of links and the quality of those links.

Network researchers utilize a variety of constructs to measure network position [1, 5, 8, 15, 17, 32, 40]. Ahuja [1] utilizes direct ties, indirect ties, and

redundant ties (structural holes). The number of direct ties represents the number of firms the focal firm learns from directly. The number of indirect ties represents the number of firms that the direct firm can learn from through its direct ties. Redundant ties represent the degree to which the firms that the focal firm learns from are learning from each other.

We utilize two constructs to measure effectiveness of access: Freeman closeness centrality and redundant ties. Freeman closeness centrality [44] measures the number of direct ties and a weighted measure of indirect ties. A firm with high closeness centrality can access the knowledge of more external firms than can firms with low closeness centrality. Therefore, following Ahuja [1], we predict:

H3: Firms with higher closeness centrality, having higher effectiveness of access to the industry's knowledge, will produce more knowledge.

As a result of the firm's access to external knowledge, it has less reliance on own-knowledge development to generate new knowledge. However, as pointed out earlier, the firm must continue own-knowledge development in order to maintain its absorptive capacity. Therefore:

H4: Firms with higher closeness centrality, having higher effectiveness of access to the industry's knowledge, will spend less own-knowledge development resources per unit of knowledge.

Redundant ties reduce the firm's access to non-overlapping information flows [8]. Given two firms with the same closeness centrality, the firm with fewer redundant ties has access to more unique information. In measuring access to spilt knowledge, the trust fostered by redundant ties is not valuable [1, 13]. Therefore, we predict:

H5: Firms with more redundant ties, having lower effectiveness of access to the industry's knowledge, will produce less knowledge.

As a result of the reduced effectiveness of access due to redundant ties, there will be less knowledge from the industry that the focal firm can integrate. Therefore, we predict:

H6: Firms with more redundant ties, having lower effectiveness of access to the industry's knowledge, will spend more own-knowledge development resources per unit of knowledge.

3. Methodology

3.1. Data

To test our hypotheses, we measure knowledge production, closeness centrality, and redundant ties through patenting activity. We measure knowledge flow through a patent citation network. This approach follows the research efforts of several other scholars who have used patents as a measure of knowledge [9,

18, 20, 21]. Each patent contains information about the invention, inventor, the company to which the patent is assigned, the technological antecedents of the invention, and the technological class to which the expert patent examiner has assigned the patent. Each class represents a unique technical area, and there are 400 such technical areas currently in the patent classification system. The patent examiner also attempts to make sure that the patent references all the prior art that it draws on. Thus, the patent acts as a document-based, fossilized track of knowledge flow.

We know that firms do not, generally, patent all of their inventions. In some cases, this is because patents do not provide good appropriability protection, or because it is too difficult to describe the invention for the patent office [24]. In other cases the benefits of greater appropriability are not worth the cost of obtaining the patent. Thus, the patent record understates the true level of knowledge development for the focal firms.

The basic unit of analysis in this research is the individual patent. The level of analysis is the firm. Within the regression analysis, we look at firm/year performance. We utilized patent data from the United States Patent Office online data base.

We started the data collection by downloading the list of all publicly traded companies with primary SIC code 7372 (Prepackaged Software) from the Compustat IDC database. These firms face the same appropriability regime and market conditions, which allows us to control for industry effects. We then used Compustat to download revenue, employee, and R&D data for the twelve years from 1990 to 2002. For each year in the study, we selected the top 50 firms by revenue. We then collected the list of patents that each of these top firms where issued, the patents that they cite, and the patents that cite them. After we eliminated all firms that didn't patent or report R&D spending, and restricted the years in our study to 1995 through 1999 (in order to minimize right censoring and avoid those years in which our focal firms did little patenting), our list was reduced to 77 firms with 158 firm/years. Over the original twelve-year period, these firms produced 5,027 patents across 78 patent classes. These patents cited 22,958 unique patents from 3,900 firms across 255 classes.

Patent production by software companies is a recent phenomena, and represents a small portion of the total number of software patents [6]. However, we are studying software firms and not software patents. Although software firms represent a small part of software patents, we make the reasonable assumption that patents do represent evidence of a new unit of knowledge[20]. The US Patent Office is a third-party, expert evaluator of novel invention (i.e., of new knowledge). The cost of patenting limits patenting to

those innovations – units of new knowledge – the firm finds cost effective to protect. Since all firms in SIC 7372 confront the same appropriability regimen, the firms in our sample that do patent will make similar decisions regarding when it is cost effective to do so.

Firms may have different motives for patenting. They may patent to protect their intellectual property, to create patent thickets [6], or to measure or reward their engineers. We make the reasonable assumption that regardless of motivation, patenting behavior does represent the firm's otherwise unmeasured knowledge development activities.

Part of each patent is a list of citations to prior art. Both the inventor and the patent examiner identify the patent's antecedents. Because the citations limit the value of the new patent, the firm attempts to minimize the number of citations. However, the patent examiner's job is to identify all relevant antecedents. The larger community of individuals and firms from whom the inventor is seeking protection also seeks to limit the scope of the patent by making sure that all prior art is identified. Therefore, we make the assumption that the citations represent the sources from whom the inventor learned.

3.2. Variables

We display descriptive statistics and correlations for each of the variables described below in Table 1.

3.2.1. Network Analysis

A central feature of this research is the flow of information within the industry defined by SIC 7372. By examining the network of patent citations, we can examine learning between firms. When firm *A*'s patents cite firm *B*'s patents, we assume that firm *A* learns from firm *B*. For each year in our sample, we construct a knowledge flow network consisting of our focal firms and the firms they learn from. Arcs between nodes represent which firms cite which other firms. The values of the directed arcs represent the number of times the source firm cited the target firm. We are uncomfortable using patent citation counts as a measure of the value or quantity of learning between firms, so we dichotomize the arc values in order to measure the structural qualities of the learning network (i.e., the value of all arcs is set to one); we leave measuring the value of the network flows to a future research project. We assume that a continuous stream of knowledge flow will be indicated by a continuous stream of patent cites; thus, we don't preserve arcs across years.

Using network analysis methods, we then calculate closeness centrality and the number of reciprocal ties for each focal firm in our network [44].

Closeness Centrality (CLOSE)

When firm focal firm *A* cites firm *B* it is one step from *B*. If *B* then cites *C*, *A* is two steps from *C*. The value of one firm to another is the inverse of shortest, directed path to the firm. Thus, a direct connection (direct tie) has more value than an indirect tie. Its distance to the focal node weights an indirect tie. The number of other intermediate firms the knowledge must travel through to reach the focal firm attenuates the knowledge from one firm to the focal firm. A firm that cannot be reached following the arcs has no value to the focal firm. The distance to an unconnected firm is infinity; its reciprocal is zero. We interpret this as the focal firm not learning from firms it can't reach.

The raw closeness value for each focal firm is the sum of the reciprocals of the number of arcs between the focal firm and all other firms. In order to normalize this value across years, we divide the raw score by the number of nodes in the network.

Redundant ties (RTIES)

We calculate the percentage of redundant ties for each focal node by counting the number of arcs between the firms cited by the focal firm, and then dividing this sum by the maximum possible number of arcs. This measure is the density of the digraph consisting of the focal firm and the firms it learns from [44].

3.2.2. Firm Characteristics*R&D intensity (R&DINT)*

R&D represents the firm's investment in own-knowledge development. We normalize the investment in own-knowledge development by dividing it by the number of employees in the firm.

Knowledge production productivity (KPROD)

The number of patents filed by a firm in a year represents the innovative output of the firm in that year. We consider this innovative output a measure of knowledge production. We divide the number of patents filed in a year by the number of employees in that year to get a measure of knowledge production productivity.

Own-knowledge cost per unit of knowledge (KCOST)

Since we operationalize knowledge production by counting patents applied for (and subsequently granted), and we operationalize the cost per unit of own-knowledge development as the amount of R&D investment, we operationalize the investment in own-knowledge development per unit of knowledge as the ratio of R&D to patent count.

3.2.3. Controls*Experience (AGE)*

In order to control for competency traps [25, 26], the value of experience, or a changing propensity to patent due to firm age, we calculate the age of the firm at the time the patent was filed.

Knowledge stock (KSTOCK)

Firms vary in the amount of in-house knowledge they have. Existing knowledge is both an input to additional knowledge production and to absorptive capacity. We control existing knowledge stock by counting the number of patents granted to the focal firm that were applied for in the year prior to the panel year.

Technical opportunity (TECHOP)

Firms vary in the areas in which they research. Firms that patent in classes with higher levels of patenting may find research in these areas easier or cheaper. The higher number of patents also implies a higher level of patent citations. In order to control for variance in KPROD, KCOST, CLOSE, and RTIES due to technical opportunity and not the underlying construct, we control for technical opportunity.

We calculate TECHOP by creating an industry vector of patenting activity, the focal firm's vector of patenting productivity, and then calculating the Pearson correlation coefficient between the two vectors. This measures the distance between the firm and the industry. The industry vector is created by counting the number of patents in each patent class for each year. The number of classes in which the focal firms and the firms they cited patented represented the number of dimensions of the vector. The count within each class represents the value of the vector in that dimension. Each firm vector is created in an analogous fashion.

Year dummies

In order to control for differences in patenting levels intensity and right censoring that affects all firms equally, we created year dummy variables.

3.3. Analysis**3.3.1. Regressions**

The regression model has been constructed using a pooled-cross-sectional methodology that combines data for each year into a single block of data for purposes of coefficient estimation. Such a model enables us to examine the hypothesized relationships over different time periods and test for changes due to time. The models' explanatory power and coefficients are estimated using OLS.

3.3.2. Models

We estimated coefficients for the following model formulation using KPROD and KCOST as dependent variables:

$dep_var = \alpha + \beta*(R\&DINT + CLOSE + RTIES + \delta) + \varepsilon$
 where β is a vector of coefficients for the vector of variables, including the vector of dummy variables, δ .

In order to correct for skewness and kurtosis of the variables, the following variables were transformed using natural logs: KCOST, KPROD, KSTOCK, and RTIES.

CLOSE was transformed using $ArcTan(c \cdot \frac{(x_i - \bar{x})}{SD(x)})$, with

a value of 0.4 for the constant c . This angular transformation of CLOSE reduced its kurtosis and the influence of extreme values in the regression[23]. Unfortunately, such a transformation makes the interpretation of the estimated coefficient much more difficult. However, interpreting untransformed closeness measures is difficult anyway; the improved adherence to the assumption of normality is worth the cost.

3.4. Results

Table 1: Descriptives (n=158)

	Min	Max	Mean	Std. Dev	Skewness ^a	Kurtosis ^b
CLOSE ^d	-1.04	1.10	-.01	.31	.79	2.12
KCOST ^c	-.35	6.82	2.66	1.27	.22	.67
KPROD ^c	-2.43	3.92	.85	1.38	-.14	-.36
KSTOCK ^c	.00	7.58	2.61	1.66	.41	-.12
R&DINT	.39	175.23	42.47	27.02	1.45	3.83
RTIES ^c	-4.61	-1.08	-3.37	1.02	.29	-.96

a. Standard Error of Skewness is 0.193.

b. Standard Error of Kurtosis is 0.384.

c. Natural log transformation.

d. Arctangent transformation.

Table 2: Correlation coefficients (n=158)

	CLOSE	KSTOCK	RTIES	KCOST	KPROD
KSTOCK	.537**				
RTIES	.213**	-.062			
KCOST	-.479**	-.333**	.115		
KPROD	.526**	.257**	-.087	-.826**	
R&DINT	.120	-.028	-.026	.148	.347**

** Correlation is significant at the 0.01 level (2-tailed).

Table 3: Model Summary (dv=KPROD)

	Model 1	Model 2	Model 3	Model 4
YEAR DUMMY	ns	ns	Y1999	ns
AGE		-0.105* (0.12)	-9.3E-02* (0.013)	-7.7E-02* (0.13)
TECHOP		2.326 (0.937)	1.988 (0.936)	ns
KSTOCK		0.367* (0.061)	0.359* (0.060)	0.154 (0.072)
R&DINT			7.9E-03* (0.060)	6.9E-03 (0.003)
RTIES				-0.250* (0.094)
CLOSE				1.827* (0.404)
ADJ R ²	0.023	0.428	0.447	0.517
R ² CHANGE		0.405	0.019	0.070
F CHANGE		35.417	5.198	10.677
SIG F CHANGE		0.000	0.024	0.000

* p < 0.01, otherwise p < 0.05

Table 4: Model Summary (dv=KOST)

	Model 1	Model 2	Model 3	Model 4
YEAR DUMMY	Y1999	Y1999	Y1999	ns
AGE		4.2E-02* (0.013)	6.2E-02* (0.013)	4.6E-02* (0.013)
TECHOP		ns	ns	ns
KSTOCK		-0.326* (0.064)	-0.340* (0.062)	ns
R&DINT			1.3E-02* (0.004)	1.4E-02* (0.003)
RTIES				0.262* (0.096)
CLOSE				-1.773* (0.416)
ADJ R ²	0.023	0.210	0.273	0.349
R ² CHANGE		0.197	0.065	0.081
F CHANGE		13.027	14.002	9.737
SIG F CHANGE		0.000	0.000	0.000

* p < 0.01, otherwise p < 0.05

For each dependent variable we ran four models (Tables 3 and 4). Model 1 included year dummies only (years with a significant correlation are noted in the tables). Model 2 added the additional controls. Model 3 tested the significance of R&D intensity. Model 4 tested the significance of the network position constructs, closeness and redundant ties.

The results indicate acceptance of all hypotheses. Own-knowledge development has negative returns to scale. Closeness to the firms containing the industry's knowledge increases knowledge production productivity and decreases the cost per unit of knowledge. Redundant ties decreases knowledge production productivity and increases the cost per unit of knowledge.

Interestingly, older firms produced fewer units of new knowledge at a greater cost. There could be many reasons for this. Older firms could be less exploratory, they could fall into a competency trap, or they could just decide to patent less because they have found more

cost effective ways to protect their intellectual property.

Firms with a larger stock of existing knowledge produced more patents and at less cost than other firms. This finding suggests they have a more developed absorptive capacity, or a greater patenting competency.

4. Conclusions

We have argued that firms invest in own-knowledge development in order to build absorptive capacity. In addition, firms invest in search and access (S&A) to gain access to the industry's knowledge that is then assimilated and exploited through the firm's absorptive capacity to create new knowledge. The result of the firm's investment in S&A, in conjunction with similar investments by other firms, is a knowledge flow network in which firms learn from each other. Due to different levels of S&A investment, different formal and informal learning arrangements between firms, and different learning partners (whether intentional or inadvertent) firms have different positions within the knowledge flow network.

A firm's position within the knowledge flow network can be measured in many ways. We measured the position through closeness centrality, which we argued measures the relative access one firm has to the industry's knowledge compared to other firms, and redundant ties, which measures the degree to which the firm has access to distinct knowledge streams.

As predicted, increasing own-knowledge development investments increases knowledge production levels, but at a diminishing rate and increasing cost. Firms that have a higher closeness measure produce more knowledge at less cost. However, firms that have redundant ties – the firms the focal firm learns from are learning from each other – have lower knowledge production productivity and spend more in own-knowledge development per unit of knowledge.

This research does not explore questions about the aggregate cost of knowledge production. We do not have a construct that measures S&A; we can only measure the results of such investment on the firm's position within the knowledge flow network. In practice, the R&D measures we used to operationalize own-knowledge development most likely involve expenditures on S&A. We can suggest that well managed firms balance their investments in own-knowledge development and S&A in order optimize knowledge production. Moreover, such well-managed firms should strategically consider which firms they will learn from in order to improve access to the industry's knowledge and moderate the redundancy of their knowledge flows.

Much of the economic research considers only industry concentration, size, appropriability

considerations, and technological opportunity in explaining investment decisions. We suggest, however, that this assumes that firms operate as independent entities through the market, and not as interdependent, interrelated entities that form distinct networks. Firms, however, do form networks, and these networks are not random. A firm's position within its network(s) gives it access to information that, were it not in the network, it would not have at the same cost. Free information does not flow freely. Thus, network position is critical to the absorption of external information.

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