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Global gatekeeping, representation, and network structure: a longitudinal analysis of regional and global knowledge-diffusion networks

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Abstract

This paper argues that structural characteristics of knowledge-diffusion networks, such as density levels, centralization levels, and the presence of global knowledge brokers, contribute to the emergence of dominant designs and the competitiveness of countries' firms and industries. It further suggests that national institutional structures and firm-specific attributes influence the development of these knowledge-diffusion networks. Six propositions, developed from examination of one industry's networks and previous scholarly literature, specify these arguments.

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Introduction

New scientific knowledge is rarely appropriated entirely by a single innovator, but instead diffuses to other organizations through formal and informal knowledge-diffusion networks (Jaffe *et al.*, 1993; Almeida and Kogut, 1999). Although these networks act as potentially important sources of competitive advantage for firms, and pose both opportunities and threats for government policy makers, we know remarkably little about them. What patterns of interaction emerge in national, regional, and global knowledge-diffusion networks? Do national or regional differences arise in these networks, and can these different patterns of knowledge diffusion contribute to the competitiveness of particular firms, countries or regions? This exploratory paper tracks changes in the structure of one global network through 20 years and uses these observations to develop propositions concerning patterns of knowledge diffusion in emerging high-technology industries.

Studies of firms' efforts to exploit external knowledge have emphasized firms' embeddedness within socially constructed networks (Granovetter, 1985), and have articulated how firms can leverage these networks for their best advantage. However, research has devoted less attention to the development of these technological networks themselves. In particular, some recent contributions (Chesbrough, 1999; Murmann and Homberg, 2001) have provided

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evidence that patterns of industry evolution vary considerably when viewed at global *vs* national levels. Such differences in knowledge-diffusion networks may well influence the evolution of a country or region's industries and the competitiveness of its innovating firms.

This paper presents a quantitative case study of the earliest phase of competition in the global flat panel display (FPD) industry. FPDs are thin displays used in applications such as flat televisions and portable computers. The paper draws from the citations present in published scientific articles to identify patterns of knowledge diffusion among North American, Japanese, and European FPD firms. Unlike many studies that track industry emergence beginning with the first product introduction, this analysis extends from the earliest published technological breakthroughs until the beginning of large-scale manufacturing for one of the most highly prized FPD applications – portable computers. It then uses these observations, along with current theory, to develop propositions concerning the global diffusion of technological knowledge within national, regional, and global networks. Finally, it explores whether firms with particular characteristics are likely to emerge as global knowledge brokers (global gatekeepers and representatives), influencing the evolution of their network, and contributing to their own performance in the emerging industry.

The global FPD industry

A technology's evolution reflects an interaction of its technical attributes with the strategies of innovating firms (Tushman and Rosenkopf, 1992). Anderson and Tushman (1990) described this evolution as a technological cycle driven by processes of variation, selection, and retention. The cycle begins with a technological discontinuity – a rare, unpredictable product innovation that offers significant cost, performance, or quality advantages over earlier products (Tushman and Rosenkopf, 1992). This innovation inaugurates an 'era of ferment' characterized by competition between old and new product designs and between rival approaches to the new product. The era of ferment results in considerable ambiguity for firms, who must assess both the technical and the commercial feasibility of competing product designs. Commercialization becomes particularly challenging because once a firm devotes resources to one approach, its competences become specialized, and earlier technological choices constrain future options (Arthur, 1988). Thus firms become dispersed along path-dependent technological trajectories, and each firm has an enormous interest in seeing its own product win this early competition.

Most FPD technologies trace their roots back to US laboratories in the 1960s. Some of the most noted early innovations stemmed from a group in RCA Laboratories led by George Heilmeier. RCA began experimenting on FPDs in 1964 (Sanger, 1990), but encountered problems identifying dyes and liquid crystals that were stable when exposed to electric fields for extended stretches, and compounds that exhibited desirable properties at room temperature. RCA kept most of its technical advances secret until the end of the decade, when it announced a series of technical accomplishments that overcame these obstacles, and 'worldwide excitement…surged practically overnight' (Rybak, 1994, 5). This technological discontinuity in the display industry opened a competition between FPDs and traditional cathode ray tubes in large display applications such as computers and airplane cockpits, and between FPDs and light-emitting diodes in more basic applications such as digital watches and calculators.

In the following years, firms attempted to develop displays using a variety of approaches including electroluminescent, plasma, liquid crystal, and several other technologies. Some large firms such as Exxon developed parallel divisions with mandates to pursue different technologies; others, such as IBM, suspended research on one technology and launched development of a different design. However, owing to the enormous cost of R&D, no firms pursued *all* technologies, and most firms placed their bet on a single approach. Therefore each FPD firm had a strong interest in seeing its technology dominate a lucrative end-market.

The years 1973 and 1974 marked a transition in the industry reflecting the first production of simple FPDs, when firms such as Sharp and Seiko began manufacturing FPDs for watches and calculators (Murtha *et al.*, 2001). These investments highlight differences in firms' strategic approaches. Some firms began early manufacturing of basic FPDs and later expanded to production of advanced screens; others focused on R&D, intending to ramp up production once their product had improved sufficiently. Throughout this period there was a raging competition between rival designs.

The period 1983–1984 marked another turning point with the beginning of a gradual convergence on LCDs as the dominant design for use in computers. In 1983 IBM ceased research and began to phase out manufacturing of plasma displays, shifting its attention to LCDs through an alliance with Toshiba. In 1984 Seiko introduced the world's first 'pocket TV' with an LCD screen. This transition also marks the peak of participation in the global FPD industry. From 1984 onward, the total number of FPD firms declined.

The era of ferment for a particular application ends when a single technology emerges as the dominant design (Anderson and Tushman, 1990). The emergence of a dominant design facilitates subsequent progress, sets off an era of incremental change, and opens the door for investments in complementary products, infrastructure, and large-scale manufacturing (Utterback and Suarez, 1993).

The competition for the dominant display design for portable computers ended in approximately 1989, when the LCD emerged as the winner. Essentially 100% of portable computers produced after 1989 contained an LCD, and almost all manufacturing took place in Asia. Firms pursuing some other technologies have persisted in alternative markets, and several other technologies have more or less disappeared.

Experience in other industries suggests that this era of incremental change in the display industry will persist until another technological discontinuity launches a subsequent era of ferment (Anderson and Tushman, 1990). At that time, other display technologies will arise to challenge the LCD's dominance in portable computer applications.

Figures 1 and 2 illustrate industry entries and exits for a 30-year period, from 1965 to 1995.[1] Figure 2 shows that the dynamics of industry emergence varied across regions. North America corresponded most closely to the traditional expectation of an explosion of entries and a later industry shakeout (Utterback, 1994), whereas Japan exhibited a later accumulation of entries and a less pronounced industry exodus.

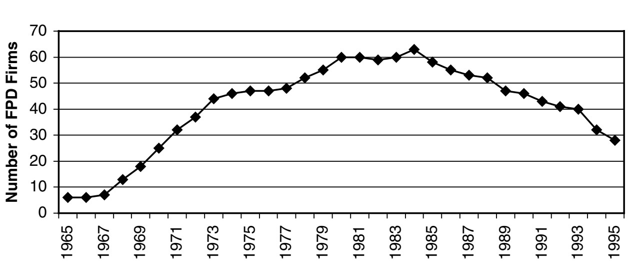

Figure 1 Firms in global FPD industry.

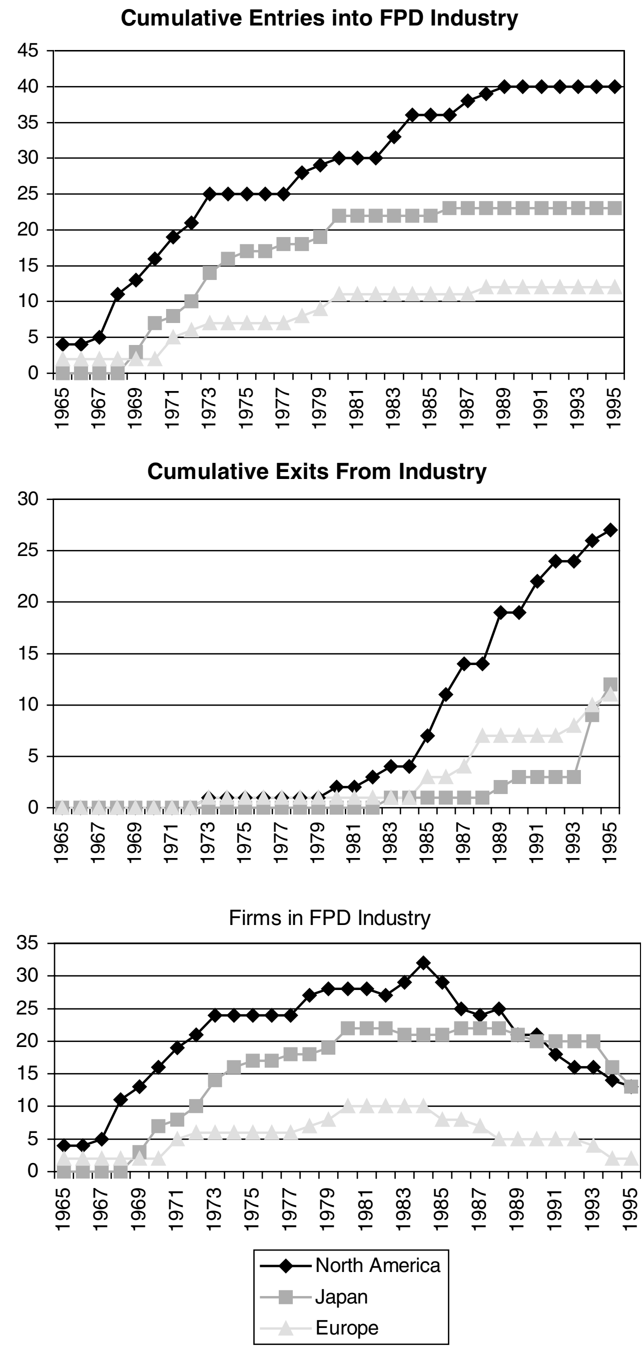

Figure 2 Entries and exits.

These differences appear similar to those found by Murmann and Homberg (2001) in the synthetic dye industry, where a pronounced industry shakeout occurred in France, but not in several other countries. The patterns of entries and exits in the FPD industry are consistent with Ergas's (1987) argument that US high-technology industries display more frequent entries and exits than their counterparts in Japan. Several potential explanations are consistent with these observations. Jovanovic and MacDonald (1994) suggested that firms able to adopt an innovation early on are rewarded with growth, and others are expelled from the industry. Similarly, Gort and Klepper (1982) suggested that industry shakeouts occur when an innovation raises barriers to entry and reduces the profit margins of the least efficient firms. In FPDs, the innovators that commercialized displays in basic applications such as watches and calculators were primarily Japanese firms; North American and European firms tended to keep their efforts in the laboratory. Japanese innovators were thus better able to build process competences, perhaps contributing to ever stronger positions as time progressed.

Second, Chesbrough (1998) observed that architectural changes in the disk drive industry prompted new entry by US firms but strengthened incumbents in Japan. In FPDs, North American firms pursued at least eight different approaches and Japanese firms only four, with most Japanese firms clustering around LCDs (Murtha *et al*., 1996). Therefore, as the industry approached a dominant design, more US firms found themselves in technologies with low probabilities of becoming the industry standard for computer applications.

Finally, Murtha *et al*. (1996) posited that Japan's institutional environment tends to strengthen Japanese firms' abilities to make credible commitments to their investments. By making rapid progress on technological development and committing resources to manufacturing, Japanese firms may have persuaded North American firms to exit the industry (Murtha *et al*., 1996). The trends displayed in Figure 2 are consistent with these arguments. Japanese firms appeared to sustain their investments through the end of the era of ferment; in contrast, North American exits accelerated once several Japanese firms had made commitments to FPDs.

Murtha *et al*. (1996) concluded that the North American industry peaked early on. By the mid-1980s, Japanese firms began to dominate the industry. Supporting this view, Figure 3 shows that North American firms received the most FPD patents per firm during the mid-1970s, with fewer average awards in the 1980s. Japanese firms showed an increase in average patent awards over time. European firms displayed a relative peak in the mid-1970s, and a higher peak in the early 1980s. This

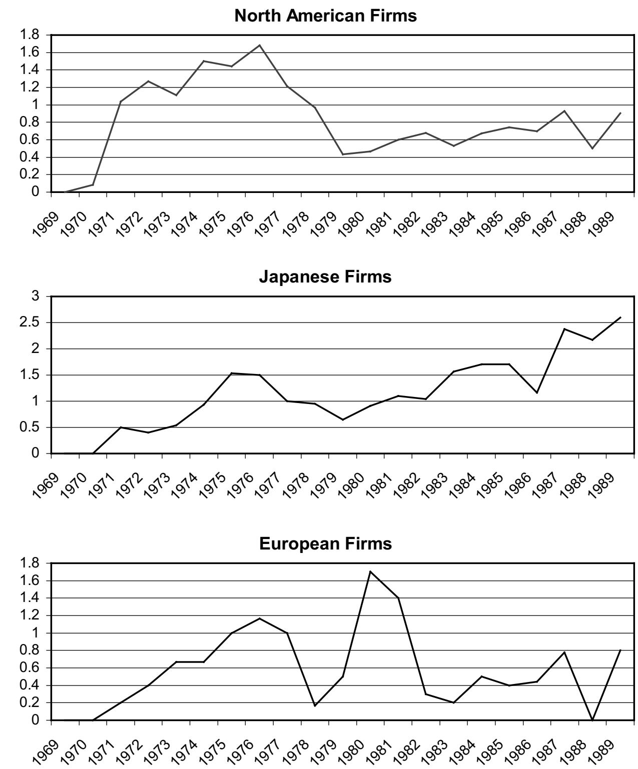

Figure 3 Average US FPD patents per firm.

trend continued beyond the emergence of a dominant design, with Japanese firms holding the majority of market share once large-scale manufacturing began.

Research design

The remainder of this paper explores the knowledge-diffusion networks that arose through the era of ferment in the FPD industry. Institutions arose to facilitate knowledge diffusion early in industry emergence. The Society for Information Display (SID) hosted technical conferences throughout the 1970s, and in 1981 initiated annual conferences that rotated between North America, Japan, and Europe. Mainstream physics journals published FPD articles, and some larger firms published technical advances in their own corporate journals.

One manager used an example that explains how these forums led to knowledge diffusion and important technical advances. Hughes Corporation demonstrated a 1-in LCD at the 1976 SID meetings but acknowledged the infeasibility of scaling it up to larger sizes. Eventually, a researcher from Bell Labs presented a theoretical paper that prompted an engineer from Brown Boveri to investigate one way of overcoming this scalability challenge. This contribution helped Sharp and Toshiba develop their own LCDs (Lenway and Murtha, 1996).

Cockburn and Henderson (1998) noted that corporate researchers publish extensively, and industrial researchers have reported that they value the opportunity to disseminate technical advances to peers (Allen, 1983; Debackere and Rappa, 1994). Both US and Japanese researchers in the semiconductor industry reported that their most important source of technical information, after colleagues within their own company, came from scientific articles and presentations (Appleyard, 1996), and Spencer (2001) reported that articles by corporate scientists appear to be of equal or greater relevance for industrial researchers than university publications.

Therefore, I followed Lievrouw (1989), Schott (1988), and others, and quantified knowledge diffusion by tracking citation patterns among industrial researchers' publications. The use of scientific literature held two advantages in this study. First, publications provided the data necessary to reconstruct knowledge-diffusion patterns over two decades. Second, these archival sources provided data on the full population of FPD firms, rather than a smaller sample biased by company deaths. Even so, it must be recognized that a reliance on publications and citations depicts only one formal mechanism for knowledge diffusion.

FPD firms were identified from a search of news articles, press releases, patents, scientific articles, and previous academic studies. Data on firms' publications came from the INSPEC database. The full dataset, including papers by university and industrial researchers, included articles in 39 countries and 19 languages. The 3448 articles written by researchers in FPD firms were used to construct the knowledge-diffusion networks, and citations of one industrial researcher by another (34,802 total) were aggregated to the firm level. Unlike patent citations, references in scientific papers reflect the discretion of authors rather than the mandate of a patent examiner. Therefore citations may represent personal or political, rather than scientific, motives. At the same time, since the authors themselves identified each reference, article citations are more likely to reflect some degree of knowledge transfer.

I explored standard network constructs of network *density*, *centralization*, *Euclidean distance*, *adjacency*, and *reachability*. Density reflects the proportion of potential ties between firms that have been completed. Centralization indicates the degree to which a small number of firms hold prominent network positions. Results report density and centralization based on both dichotomous ties, indicating the presence or absence of a citation, and valued ties, reflecting the number of citations between each pair. Euclidean distance uses multidimensional scaling to plot all firms using *x*–*y* coordinates to reveal which actors are 'close' to one another based on the number of ties between them. In this study, adjacency indicates the percentage of domestic and foreign firms that maintained at least one direct citation tie, and reachability indicates the percentage of domestic and foreign firms connected through a series of ties.

Technological *gatekeepers* and *representatives* are firm-level constructs that measure the degree to which a given firm channels knowledge from one group to another. Global gatekeepers absorb knowledge from foreign firms and convey it to domestic firms. Global representatives absorb knowledge from domestic organizations and convey it to foreign firms. Appendix A provides greater detail on all network measures.

I used UCINET 5.52 (Borgatti *et al.*, 1999) to construct and analyze regional and global networks. Regional networks included only direct communication between firms from the same region, based on the location of the firm's headquarters. Two firms (IBM and Philips) operated FPD R&D labs outside their home country, and the role of this foreign R&D was investigated explicitly in the last analysis.

Analysis is provided for three distinct periods based on points of transition during the early phase of commercialization. The first period (1969–1973) spans from initial FPD breakthroughs to the introduction of FPDs into basic applications such as calculators and watches. The second period (1974–1983) spans a time of increasing net entry to the industry and Period 3 (1984–1988) marks a period of declining numbers of FPD firms along with the first offerings of FPDs for relatively sophisticated applications such as pocket TVs and the introduction of prototypes of portable computers. Period 3 ends with the emergence of LCDs as the dominant design and the beginning of large-scale manufacturing. In order to compare patterns across time, network analyses span four time blocks of competition, with Period 2 broken into two blocks (1/1/1969–12/31/1973; 1974–1978; 1979–1983; 1984–1988). It was important that periods be of equal length in order to make meaningful temporal comparisons.

Table 1 FPD firms

		Europe	Japan	North America
Period 1	1969–1973	6	15	24
Period 2	1974–1978	8	20	30
	1979–1983	11	25	37
Period 3	1984–1988	11	25	39

Table 1 shows the number of firms operating in three regions. All Asian firms active before 1989 were Japanese. Two North American firms were Canadian, and the rest were from the US. European firms came from Finland, France, Germany, Italy, Netherlands, Switzerland, and the UK. As European firms were spread across diverse national innovation systems (NISs), this region's results should be treated cautiously.

The final analyses consider firm-level variables, including size (total employees), nationality of the firm's headquarters, and general innovative strength (total US patents during time block). Attributes of each firm's FPD investment included its research effort in FPDs (number of members of SID), industry tenure (years in FPDs prior to time block), and previous FPD innovations (FPD patents in time block). The firm's global strategy reflected the presence of foreign FPD R&D and international alliances (dummy variables). As few firms pursued global activities in any time period, conclusions about these final variables are tentative.

Longitudinal study

Density and centralization

Table 2 shows no clear trends in the density of the global network. Density in the European network was higher in the 1970s than the 1980s. Density levels in North America declined over time, with about 10% of potential ties bridged in Period 1, and only 4% bridged in Period 3. In contrast, density in Japan increased over time, with 0% of potential ties bridged in Period 1, and 15% bridged in Period 3.

In Table 3, large values indicate that a few participants emerged as central actors; small values indicate that most actors held similar positions. Although no clear trend arose in the global industry, interesting findings again emerged within regional networks. The North American network showed the highest centralization in the first two periods, and the lowest in Period 3. Japan displayed the reverse trend, showing higher centralization in Period 3 than in Period 1. The participation of firms from multiple countries may have driven inconclusive results in the European graph, suggesting the absence of an integrated European innovation system before 1989.

Global integration

Table 4 provides three measures of global integration. If most firms' average Euclidean distance from firms in other regions was no larger than their average distance from home-region firms, the knowledge-diffusion network would be globally integrated. However, according to Table 4, significant differences surfaced across all periods. Firms also lay adjacent to a significantly higher proportion of companies in their home region than foreign regions fairly consistently.

Finally, significant differences were present in the percentage of home-region and foreign firms reachable during Period 1, with firms connected to a larger proportion of home-region than foreign firms through paths of citation ties. However, significant differences disappeared during the next two periods. Therefore, although firms did not maintain as many *direct* ties with foreign firms as with home-region firms, they appear to have been *indirectly* connected to firms from all regions.

The fact that firms cited relatively few foreign firms directly, but could reach foreign firms' knowledge through paths of citations, implies that knowledge may flow from one region to another

Table 2 Network density

		Global network		Europe		Japan		North America	
		Dich	Valued	Dich	Valued	Dich	Valued	Dich	Valued
Period 1	1969–1973	0.05	0.10	0.17	0.20	0.00	0.00	0.10	0.24
Period 2	1974–1978	0.07	0.16	0.16	0.32	0.03	0.04	0.08	0.23
	1979–1983	0.05	0.12	0.05	0.11	0.04	0.06	0.06	0.17
Period 3	1984–1988	0.07	0.16	0.08	0.15	0.15	0.38	0.04	0.09

Table 3 Network centralization

		Degree centralization		Betweenness	Closeness
		Dichotomous	Valued	Centralization	Centralization
Global network					
Period 1	1969–1973	31.9	91.9	11.4	2.5
Period 2	1974–1978	28.9	126.3	5.3	1.9
	1979–1983	27.0	79.8	7.9	1.9
Period 3	1984–1988	24.6	111.5	5.8	1.7
European subnetwork					
Period 1	1969–1973	52.0	72.0	0.13	26.8
Period 2	1974–1978	30.6	77.6	0.10	1.9
	1979–1983	16.0	43.0	0.00	1.9
Period 3	1984–1988	24.0	83.0	0.04	8.0
Japanese subnetwork					
Period 1	1969–1973	7.1	7.1	0.0	1.0
Period 2	1974–1978	8.3	17.7	3.0	2.5
	1979–1983	18.3	25.9	2.8	3.9
Period 3	1984–1988	31.8	182.1	9.4	9.6
North American subnetwork					
Period 1	1969–1973	30.1	116.1	11.6	5.4
Period 2	1974–1978	24.0	115.7	8.6	3.2
	1979–1983	29.7	104.3	11.1	3.4
Period 3	1984–1988	15.1	57.7	8.4	2.6

Table 4 Global integration

	Period 1[a]	Period 2		Period 3
	1969–1973	1974–1978	1979–1983	1984–1988
Average Euclidean distance	0.40/0.43**	0.53/0.56***	0.30/0.35***	0.58/0.64***
Percentage of firms adjacent	0.19/0.04***	0.09/0.06*	0.07/0.06	0.11/0.07***
Percentage of firms reachable	0.34/0.29***	0.30/0.29	0.33/0.34	0.39/0.38

[a]Firms in home region/firms in other regions.
***$P<0.001$; **$P<0.01$; *$P<0.05$.

via indirect paths of knowledge diffusion. One explanation is that specific firms acting as global knowledge brokers may have facilitated this international knowledge diffusion by building bridges from one region to another.

Global gatekeepers and representatives

Gatekeepers and representatives act as knowledge brokers who play key roles in mediating the flow of technological knowledge from one group to another, in some cases bridging a structural hole (Burt, 1992) between one NIS and another. Global gatekeepers appropriate knowledge from foreign organizations and convey it to home-country firms, thus guiding knowledge from foreign countries into their NIS. For instance, some researchers have pointed out that Korean *chaebol* such as Samsung have served as a conduit of knowledge from the global innovation system (GIS) into Korea (Kim, 1993), and in the early 1900s firms such Imperial Chemical Industries and DuPont acted as global gatekeepers, absorbing technology from abroad and introducing it to the US market (Mowery and Rosenberg, 1998). In contrast, global representatives 'represent' their NIS by appropriating knowledge from domestic innovators and conveying it to foreign organizations. The US government has at times imposed restrictions on the global strategies of firms receiving government research subsidies in order to reduce the probability that they become global representatives by disseminating that US-developed knowledge abroad through strategic alliances or customer relationships (Murtha *et al.*, 2001). In this way, national and regional differences in the presence of global gatekeepers and representatives can influence the direction of knowledge flows in the GIS.

Table 5 presents correlations among variables,[2] and Table 6 presents results from a regression in which general firm characteristics, attributes of firms' FPD investments, and elements of firms' global strategies were used to predict Japanese and North American firms' global gatekeeper status. Preliminary analysis suggested that few firms emerged as knowledge brokers in Europe, providing further evidence of the absence of an integrated European innovation system prior to 1989. Therefore regressions exclude European firms.[3]

The relative importance of specific variables appears to change through the course of industry evolution. Firms' size predicted gatekeeping status in the first two periods but not in the third. Aspects

Table 5 Correlation table

	Mean	*s. d.*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
1. Gatekeeper	1.24	3.60	1.00									
2. Representative	1.18	3.09	0.51	1.00								
3. Size	125, 204	385,109	0.41	0.12	1.00							
4. Innovative strength	701.36	1019.15	0.33	0.43	0.25	1.00						
5. North America	0.61	0.49	0.03	−0.12	0.10	0.07	1.00					
6. FPD research effort	9.42	13.52	0.39	0.42	0.16	0.30	0.29	1.00				
7. Years in FPDs	5.38	5.30	0.32	0.36	0.12	0.40	0.02	0.41	1.00			
8. Previous FPD innovations	2.88	7.97	0.30	0.31	0.03	0.21	0.00	0.13	0.26	1.00		
9. Multinational R&D	0.01	0.12	0.45	0.45	0.08	0.13	0.10	0.50	0.13	0.14	1.00	
10. Int'l strategic alliance	0.01	0.10	0.22	0.46	0.04	0.32	−0.02	0.27	0.19	0.01	0.40	1.00

N=214; correlations above 0.13 are significant at $P<0.05$.

Table 6 Predictors of gatekeeper status

	Period 1	*Period 2*	*Period 3*
Firm			
Size	0.64 (0.00)**	0.52 (0.00)***	0.04 (0.00)
Innovative strength	−0.04 (0.00)	0.03 (0.00)	−0.09 (0.00)
North America	−0.03 (0.24)	−0.01 (0.53)	−0.16 (0.79)
FPD investment			
FPD research effort	−0.05 (0.01)	0.14 (0.03)$^{+}$	0.17 (0.04)
Years in FPDs	0.05 (0.25)	0.10 (0.08)	0.10 (0.08)
Previous FPD innovations	N/A	0.08 (0.03)	0.46 (0.06)***
Global FPD strategy			
Multinational R&D	N/A	0.36 (2.21)***	−0.03 (4.63)
International strategic alliance	N/A	N/A	0.36 (3.14)*
F	4.23**	25.89***	5.04***
Adj. R^2	0.30	0.61	0.34
N	39	112	63

Beta (std error).
$^{+}P<0.10$; $^{*}P<0.05$; $^{***}P<0.01$.

of a firm's FPD investment become important later on. Specifically, research effort emerged as marginally significant in Period 2, and previous FPD innovations were significant in Period 3. Efforts to pursue a global strategy contributed to gatekeeper status in both periods in which they were relevant, with the presence of foreign R&D significant during Period 2, and participation in international joint ventures significant in Period 3.

Table 7 presents results for a regression predicting global representative status. Again, firms' size predicted representative status in Period 1. Later, attributes of the firm's FPD investment, such as a large research effort (Period 2) and many previous FPD innovations (Period 3) predicted representative status. A firm's efforts to span borders, either by constructing foreign R&D labs or by undertaking an international joint venture, also increased its status as a global representative.

A firm's status as knowledge broker appears to hold implications for its later industry position. Of firms ranking in the top 10% of gatekeeper status during Period 3, 67% went on to become one of the 10 largest FPD producers within the next 2 years.[4] 100% of firms that were in the top 10% of global representatives became one of the 10 largest producers by 1990. In contrast, only about 9% of the firms in the lowest 90% of gatekeeper status, and about 5% of firms in the lowest 90% of representative status, became a top-10 manufacturer by 1990. In fact, only about 20% of these firms developed *any* large-scale FPD manufacturing capabilities at all in the next 2 years. ANOVAs presented in Table 8 show significant differences between gatekeeping and representation scores for producers *vs* non-producers ($P<0.01$).

Discussion

These empirical findings concerning knowledge-diffusion patterns in the FPD network, as well as previous scholarship on industry emergence, contributed to the development of six propositions presented here. Note that the structure of global technological networks may differ in non-science-based industries, technologies not characterized by a global dominant design, and industries in which most firms maintain globally dispersed R&D facilities.

Technological knowledge in industry emergence

Tables 2 and 3 show that the North American and Japanese industries displayed their greatest competitiveness when their regional knowledge-diffusion networks exhibited the highest density and centralization. Previous research articulates some of the mechanisms by which network density may contribute to the competitiveness of a national or regional network. Connectedness to a technological community allows firms to appropriate external advances (Nelson, 1990), increase internal research productivity (Cockburn and Henderson, 1998), cooperate to build an industry infrastructure (Van de Ven, 1993), and track and shape the institutional

Table 7 Predictors of representative status

	Period 1	*Period 2*	*Period 3*
Firm			
Size	0.50 (0.00)**	0.01 (0.00)	0.02 (0.00)
Innovative strength	0.01 (0.00)	0.02 (0.00)	0.15 (0.00)
North America	0.11 (0.45)	−0.21 (0.36)**	−0.26 (0.90)**
FPD investment			
FPD research effort	0.07 (0.02)	0.28 (0.02)**	0.21 (0.04)
Years in FPDs	0.22 (0.48)	0.10 (0.05)	−0.01 (0.09)
Previous FPD innovations	N/A	0.14 (0.02)$^+$	0.34 (0.07)**
Global FPD strategy			
Multinational R&D	N/A	0.40 (1.39)***	0.15 (5.27)
International strategic alliance	N/A	N/A	0.27 (3.58)*
F	4.83**	12.40***	9.78***
Adj. R^2	0.36	0.42	0.53
N	39	112	63

Beta (std error).
$^+P<0.10$; $^*P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$.

Table 8 Analysis of variance

	Variation	*SS*	*DF*	*MS*	*F-value*
Large-scale manufacturing					
Gatekeeper	Between groups	125.99	1	125.99	12.56**
	Within groups	611.70	61	10.03	
	Total	737.69	62		
Representative	Between groups	339.05	1	339.05	20.60***
	Within groups	1004.12	61	16.46	
	Total	1343.17	62		
Top ten FPD producer					
Gatekeeper	Between groups	167.88	1	167.88	17.97***
	Within groups	569.81	61	9.34	
	Total	737.69	62		
Representative	Between groups	593.43	1	593.43	48.28***
	Within groups	749.74	61	12.29	
	Total	1343.17	62		

**$P<0.01$; ***$P<0.001$.

environment evolving in their industry (Spencer, 2003).

The relationship between network centralization and competitiveness may be less generalizable, however. The fact that a region's firms interact predominantly with a small number of central firms gives a few firms the opportunity to strongly influence the development of their industry and technology. This influence may contribute to either positive or negative industry outcomes based on the technical viability and eventual commercial acceptance of those central firms' technologies.

Proposition 1: *Relatively high levels of density in a national or regional network will associate with higher global competitiveness for that region's industry.*

Of the three regions studied, the centralization and density of the regional knowledge-diffusion network increased over time only in Japan. Japanese firms also displayed less diversity in technological approaches to FPD design (with most pursuing LCDs), and were the first to install large-scale LCD manufacturing facilities. Network density and centralization may well facilitate firms' convergence on a dominant design for their emerging technology. The logic of this argument derives from the intersection of several research streams. Van de Ven (1993) suggested that institutional arrangements such as dominant designs co-evolve with the advances of innovating firms via repeated interactions among industry participants. Dense intra-industry networks may facilitate the types of knowledge diffusion and interaction that allow firms to build a consensus around a technological approach. Similarly, since scientists' choices of research question depend in part on the opinions of other scientists in their field (Zuckerman, 1978; Rappa and Debackere, 1992) and what is 'fashionable' in the scientific community (Crane, 1969; Barber, 1990), firms may influence one another's technical approaches through their scientific articles (Spencer, 2003). This scientific interaction can facilitate convergence on common technical approaches.

In addition, increased investments in a technology resulting from inter-firm learning and imitation should accelerate the design's speed of progress toward a commercially viable product (Allen, 1983; Podolny and Stuart, 1995), increasing the likelihood that the technology will win out as dominant design. Convergent technological approaches also attract investments by customers and firms in supporting industries (Wade, 1996), and allow an innovator to speak with a louder voice in influencing the emerging institutional environment to favor its technology (Mezias and Kuperman, 2000).

Network centralization may also contribute to dominant design emergence. Research suggests that, when a small number of firms hold substantial influence, they are better able to mandate an industry standard (Tushman and Rosenkopf, 1992). Similarly, the presence of a few high-status innovators in a regional network may jump-start the process of dominant design emergence by sending a signal about which technology is most likely to dominate. Dense networks, then, can help communicate the standard through the technological community. Early convergence on a dominant design may enable participating firms to make earlier commitments to manufacturing, and thus dissuade investments by rivals (Murtha *et al*., 1996). At the same time, early convergence can limit technical options, reduce research on promising alternatives, and limit firms' chances of developing a technological leapfrog.

Proposition 2: *National or regional networks that exhibit high levels of centralization and density will be more likely to facilitate convergence on a dominant design than networks with low levels of centralization and density.*

Cross-national variations in institutional structures, such as differences in the level of corporatism in countries' interest intermediation systems, may well contribute to different patterns of knowledge diffusion across countries. Countries with corporatist interest intermediation systems are characterized by enduring national interest groups that participate in the decision-making structure of the state, whereas countries with pluralist systems house more independent interest groups that arise to target specific issues and disappear once those issues are resolved (Wiarda, 1997). The prevalence of lasting social institutions such as industry associations and R&D consortia in corporatist systems such as Japan (Murtha *et al*., 1996) probably increases the density of knowledge diffusion in these countries' networks, particularly as a product moves toward commercialization. For example, the Japanese government has pursued policies to bring firms together in research consortia to hasten the development of LCDs, plasma displays, VLSI circuits and other technologies.

Countries with pluralist systems lack these enduring social institutions and coordinating mechanisms. In addition, the presence of an ideology supporting independence and competition among business organizations reduces firms' incentives to construct dense and lasting knowledge-sharing networks to coordinate technological approaches. For instance, Garud and Karnoe (2003) note that US wind turbine manufacturers showed a greater reluctance to share knowledge with one another than did their counterparts in more corporatist Denmark. And Spencer *et al*. (forthcoming) described how the US's initial approach to the SEMATECH consortium was compromised because member firms resisted divulging technological knowledge to one another. In this study, the Japanese network saw increasing density over time while the density in the North American network declined. In addition, Japan's peak density level across all time periods was about 50% higher than the density in the North American network at its peak.[5] Together, these arguments suggest that countries with pluralist systems are likely to foster fewer knowledge-sharing ties between innovating firms, leading to sparser knowledge-sharing networks.

Proposition 3: *Corporatist countries are likely to display denser knowledge-diffusion networks than pluralist countries.*

Regional and global networks

Labor market mobility, the presence of common suppliers and customers, participation in regional institutions, and informal interactions among scientists contribute to the diffusion of knowledge within cities, regions, and countries (Jaffe *et al*., 1993). At the same time, in many high-technology industries the need for global economies of scale and international product compatibility mandate a global dominant design (Spencer, 2003). One would expect that firms in such globally integrated industries would participate in global networks to both absorb advances from overseas and track the worldwide evolution of industry standards. Indeed, research suggests that firms operating in globally integrated industries may earn higher performance when they participate in their GIS as well as their NIS (Spencer, 2003). Based on this previous research, then, one would expect that, at a minimum, *explicit* knowledge available in firms' publications would easily diffuse through the GIS.

This study found that, in the FPD industry, the direct transfer of published scientific knowledge occurred more readily within countries and regions than between countries. Significant differences did not appear as relevant, however, in the *indirect* transfer of knowledge.

I suggest that the constructs of global gatekeepers and representatives can serve as valuable ways of considering the global diffusion of technological knowledge. Traditionally, 'gatekeeper' and 'representative' referred to scientists whose reputations inside and outside their organizations placed them in positions to act as brokers of technological knowledge (Allen, 1977). This paper extends the concept to suggest that an organization can act as a global knowledge broker by absorbing knowledge from firms in one country and passing it on to firms in another.

This study found that, early in industry emergence, firms' size distinguished global knowledge brokers from other firms. A firm's size may serve as a proxy for its ability to leverage its global networks in other industries, with large firms better able to draw on diverse technological networks to tap into knowledge concerning the new-to-the-world technology. Later, this general firm-level measure was replaced by attributes of the firm's FPD activity, itself, such as its FPD research effort and the number of previous FPD innovations patented. A firm's research effort and previous patents may reflect its absorptive capacity (Cohen and Levinthal, 1989). This standing as a strong innovator also probably attracts the attention of other firms and increases the chances that other organizations will track the research it performs (Podolny and Stuart, 1995). It is possible that the shifting importance of variables reflects the challenges inherent in obtaining reliable information about rivals. Early in industry emergence, innovators may evaluate other firms' contributions based on crude measures such as the firm's size. As the competitive landscape begins to take shape, firms are able to gain more detailed and more tacit knowledge regarding the quality of competitors' innovations, and replace these more general proxy variables with their own personal experience.

Proposition 4: *Early in the era of ferment, generic qualities such as firm size will act as important determinants of a firm's status as global knowledge broker. Later, attributes of the firm's investment in the technology will become important determinants of the firm's status as a global knowledge broker.*

In addition, across all relevant periods, FPD firms with strategies that spanned borders, either through global R&D investments or cross-national alliances, emerged as strong global gatekeepers and representatives. This suggests that firms with more direct relationships with foreign innovators, via either geographic proximity or formal agreements, may gain preferential access to knowledge, enabling them to mediate international knowledge flows.

Proposition 5: *Throughout industry emergence, the multinationality of a firm's technology strategy will influence its status as a global knowledge broker.*

When knowledge brokers lie across the only path between firms in different innovation systems, they effectively bridge a global structural hole (Burt, 1992), and may profit from their strategic position. Brokers hold access to unique sources of knowledge unavailable to their closest rivals. Additionally, brokers apply, filter, and reframe knowledge as they pass it on. And this intentional or unintentional reframing may help innovating firms shape the emerging institutional environment to favor their own technologies.

This study showed an association between a firm's status as a global knowledge broker in the last period before dominant design emergence and its ability to successfully make the transition into commercial production by installing large-scale manufacturing facilities. Future research should investigate the relationship between a firm's status as knowledge broker and later performance. Research must also determine whether acting as a knowledge broker, itself, contributes to a firm's competitiveness, or whether brokerage status and performance both associate with spurious underlying conditions.

Proposition 6: *Global gatekeepers and representatives are more likely to sustain their investment and capture market share after a dominant design has emerged in their industry.*

Conclusion

National institutional structures and government policies clearly influence the competitiveness of a country's firms (Porter, 1990; Kogut, 1991). This paper suggests that such influence is partially mediated by the knowledge-diffusion networks that arise among innovating firms. Institutional structures such as corporatism, and government policies that target specific innovators or discourage firms from pursuing global strategies, can affect the density and centralization of industry networks and the emergence of firms acting as global knowledge brokers. And these elements of network structure may influence the dynamics of industry emergence within a national or regional economy and the level of competitiveness of local innovating firms. Future research that empirically tests and elaborates on these relationships will facilitate policy makers' efforts to leverage or adapt their domestic institutions and policies to match the needs of innovators.

Several observations in particular deserve future attention and empirical exploration. First, it is clear that innovating firms' performance depends, in part, on the resources available in their NIS (Nelson and Rosenberg, 1993). This paper suggests that a country's competitive advantage stems not only from the presence of knowledge resources, but also from the configuration of the knowledge-diffusion network itself. Future research should test the argument that network structure contributes to the competitiveness of local firms.

Similarly, the presence of global knowledge brokers may enable firms to participate indirectly in the GIS without investing resources in monitoring the global environment, forging their own international ties, or otherwise implementing strategies to directly influence the evolution of their global industry. Therefore countries or regions that are connected to the GIS through global knowledge brokers may provide a particularly munificent environment for domestic innovators. Although further research is clearly necessary, this argument would suggest that government policies discouraging local firms from pursuing foreign R&D or international joint ventures may harm a range of domestic innovators. Future research should investigate whether significant performance differences arise between firms that build direct ties with their GIS, innovators that access their GIS indirectly through a knowledge broker, and firms that do not participate in their GIS at all.

Murtha *et al*. (1996) suggested that Japanese firms were able to dominate the FPD industry by installing large manufacturing facilities that deterred US entry. This paper suggests that Japanese firms' abilities to commit to early investments may have stemmed in part from the structure of Japan's knowledge-diffusion network. If network density and centralization contributed to Japanese innovators' abilities to converge on a dominant design before their US rivals, then Japanese firms faced less uncertainty at the prospect of mounting large FPD manufacturing investments. In this way, their national knowledge-diffusion network may have helped propel Japanese innovators past the era of ferment, so that they could leverage their strong manufacturing capabilities and marketing networks for commercial success. Future research must empirically test the relationships between network structure, convergence on a dominant design, and ability to make credible commitments to manufacturing.

The commercialization of new technologies comprises a critical source of economic growth for advanced economies. Greater understanding of the patterns of activity that arise in emerging industries should contribute to scholars' efforts to construct theories about technological innovation and managers' strategies for the next generation of technologies.

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Notes

[1]In Figures 1 and 2, and in later regressions, a firm was identified as entering and exiting the industry based on the first and last years in which it published an article, presented a conference paper, received an FPD patent, was mentioned in a newspaper article or press release, or was listed as an industry participant in an academic article on the FPD industry.

[2]Data were normalized based on the size of countries' industries and weighted to discount a firm's score when more than one company acted as a broker between a given pair of firms.

[3]Regression results remain largely the same when European firms are included. All variance inflation factors for both regressions fall under 3.

[4]Production data from Borrus and Hart (1994).

[5]Although several European countries may be characterized as corporatist, few corporatist institutions existed on a Europe-wide level prior to 1989.

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Appendix A

Network measures

Density

Density reflects the number of ties in a network divided by the total number of possible ties (Knoke and Kuklinski, 1982). Dichotomous measures identify only the presence of a tie between two firms (at least one citation occurs). Valued measures give more weight to ties when they are repeated (multiple citations occur). In Figure A1, the network is denser in Country B (9 of 30 potential ties completed) than Country A (5 of 30 ties completed).

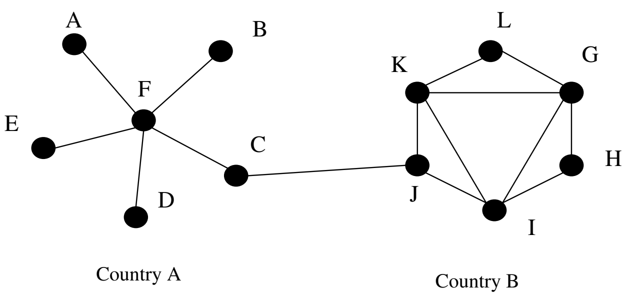

Figure A1.

Centralization

Centralization reflects the degree to which a small number of firms hold prominent positions in a network. A centralization index takes its greatest value when a single firm displays high centrality by maintaining ties to all other firms and these other firms have no ties to each other. Centralization is lowest when every firm has the same level of centrality (Wasserman and Faust, 1994). In Figure A1, centralization is higher in Country A than Country B, with Firm F displaying high centrality, and all other companies exhibiting low centrality. Firm-level centrality is measured in several ways:

(1) *Degree centrality* identifies firms as most central when they maintain ties to many other actors. (Firm F forged ties with all other firms in its country.)
(2) *Betweenness centrality* labels firms as central when they lie on geodesic paths that link other firms. A *geodesic* represents the path of shortest distance between any two points in the network. (Firm F lies on a geodesic between all other pairs of firms in its country.)
(3) *Closeness centrality* identifies a firm as most central when its geodesics to all other firms are of minimum length. (Firm F's geodesics to all firms in Country A are of length 1.)

Euclidean distance

Multidimensional scaling calculates proximities among actors in a network, using *x–y* coordinates to reveal which actors are 'close' to one another based on the number of ties that connect them (Wasserman and Faust, 1994). Euclidean distances based on multidimensional scaling range from zero to one.

$$\text{Distance} = \sqrt{(x_x - x_1)^2 + (y_2 - y_1)^2}.$$

Adjacency

Two firms are adjacent if at least one tie links them (Firms G and K are adjacent). For each firm, I calculated the percentage of home-region and foreign firms adjacent.

Reachability

A firm is reachable by another firm if a path of citation relationships can be constructed to link them. (In Figure A1, all firms are reachable by all other firms.) For each firm, I calculated the percentage of home-region and foreign firms that were reachable.

Knowledge brokers

Knowledge brokers bridge a gap between two *groups* of firms. (In Figure A1, Firms C and J act as knowledge brokers.) *Gatekeepers* absorb information from actors outside their group, and convey information to members of their group. *Representatives* absorb information from actors within their group, and convey information to actors outside their group. A firm's score as a global gatekeeper reflects the number of times it lies on a cross-national geodesic, citing a foreign firm, and being cited by a home-region firm. A firm's score as a global representative reflects the number of times it lies on the geodesic, citing a home-region firm, and being cited by a foreign firm. Both scores were normalized and weighted to allocate higher scores when a firm was the only link between other firms and a lower score when other alternative paths were available.

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