

**Mobility of Engineers and International Knowledge Transfer:
Technological Catching-Up in the
Korean and Taiwanese Semiconductor Industries**

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ABSTRACT

Does the mobility of engineers facilitate international knowledge spillovers and help newly industrializing countries catch up with developed countries? This study attempts to answer this question by tracing knowledge flows through the international mobility of semiconductor engineers. The paper uses patent data to track knowledge flows through the mobility of engineers. The study finds that engineers who moved from the US to Korea or Taiwan built their subsequent innovations based upon the knowledge of their previous firms in the US. Case studies based on field interviews further suggest that these mobile engineers have played significant roles in the technological catching-up of Korea and Taiwan.

Keywords: Mobility, knowledge flows, Taiwan, Korea, semiconductors

Foreign technology has historically played an important role in the industrialization of Europe, the United States, and Japan. More recently, newly industrializing countries, such as South Korea and Taiwan, have also depended on knowledge developed in industrialized nations for their economic development (Freeman and Soete, 1997). But can these countries catch up with the more advanced nations? After all, Cantwell (1990) has shown that most industrial fields remain dominated by a few countries over long periods of time. An explanation for this persistence is provided by endogenous growth theory, which suggests that technological catch-up is difficult because of the increasing returns to scale of physical and human resources and the geographical localization of technology (Romer, 1990). The theory suggests that when knowledge spillovers are geographically concentrated, a country that has a head start in the accumulation of knowledge tends to increase its productivity lead over time (Grossman and Helpman, 1991).

Despite such gloomy predictions from the new growth theories, Korea and Taiwan stand out as examples of countries that have indeed “caught up” and are now leaders in the semiconductor industry. Over the past two decades, Korea has leapfrogged from being a mere producer of discrete devices to being the world leader in the memory (DRAM) industry with a 41% market share in 1998. Samsung, a leading semiconductor firm in Korea, entered the VLSI business in 1983 and became the world’s first company to develop a 256M DRAM chip in 1994. Similarly, Taiwan entered the semiconductor business in the 1970s and now competes successfully as the world leader in areas such as Mask ROMs and foundry services. In 1999, in terms of the total shipment of semiconductors, Korea and Taiwan were ranked as #3 and #4, respectively, just behind the US and Japan (ERSO, 2000).

In less than 20 years, Taiwan and Korea not only dramatically increased their production capacities and market shares in the semiconductor industry, but also, more impressively, improved their R&D capabilities. As shown in Chart 1, in 1983, Korea and Taiwan were granted no semiconductor-related patents in the US, whereas Germany received 110 patents. In 1997, 14 years later, Korea and Taiwan were granted 386 and 267 semiconductor-related patents in the US, respectively, whereas Germany was granted only 155 such patents (Chang, 1999). In fact, the total number of semiconductor-related patents granted to Korea was larger than that of Germany, the UK, and France combined. Thanks to this explosive growth in semiconductor-related patents, in 1999, Samsung Electronics was ranked as the #4 company in terms of the total number of patents granted in the US in all technology classes. In the same year, fabless design houses in Taiwan were rated as #2 in the world, just behind the US, capturing 20% of world market shares measured in terms of revenues in the chip design area; these design houses also began to produce a substantial number of patents (ERSO, 2000).

Chart 1 About Here

These statistics clearly suggest that Korea and Taiwan caught up with Germany, the UK, and France in the global semiconductor industry, in terms of both market shares and patent numbers. In selected areas, the two countries are also threatening the leadership of the US and Japan. How did Korean and Taiwanese semiconductor firms acquire and develop technologies in such a rapid technological catch-up process? Almeida (1996) shows that part of the answer to their learning behavior can be attributed to the activities of their subsidiaries in the US, which source technology locally. But there is also evidence to suggest that the inter-country mobility of

experts has played a crucial role. In its extensive analysis of the “Asian miracle,” the World Bank (1993) emphasizes that the return of foreign-educated nationals has provided significant transfer of best practices and state-of-the-art knowledge. Recent case studies (Cho and Song, 1990; Hou and Gee, 1993; Kim, 1997; Cho, Kim, and Rhee, 1998) also provide anecdotal evidence of the importance of human-embodied technology transfer in the time-compressed learning processes of Korean and Taiwanese firms in the semiconductor industry. Based in part on such anecdotal evidence, the recent World Development Report on knowledge and economic development (World Bank, 1998) identifies the international movement of people as one of four principal channels for acquiring imported knowledge (along with trade, foreign direct investment, and technology licensing).

Human mobility within or across firms has played a very important role in transferring tacit knowledge or knowledge-building capabilities (Ettlie, 1980; Leonard-Barton, 1995; Chesbrough, 1999). In his pioneering work on the sociology of inventions, Gilfilian (1935) suggested that labor mobility, especially among engineers, erodes the differential level of knowledge among firms. However, in spite of voluminous literature on the international transfer of technology, the impact of inter-firm human mobility on the cross-border knowledge acquisition and building process has received surprisingly little formal attention or rigorous analysis (Ettlie, 1985).

In this paper, focusing on the technological catching-up case of Korean and Taiwanese semiconductor firms, we systematically examine the role of human-embodied technology transfer across national borders in the acquisition and building of knowledge. Using patent citation data, we empirically investigate whether Korean and Taiwanese firms have built upon the knowledge of US companies by hiring their engineers. Based on field interviews conducted in Korea and Taiwan and a review of relevant literature, we further investigate the role of engineer mobility in the rapid technological catching-up process of Korean and Taiwanese semiconductor firms.

THEORY AND PROPOSITIONS

Nature of Knowledge, Absorptive Capacity, and Learning-by-Hiring

The knowledge needed for innovation may be obtained from a variety of sources. Although a firm itself is the source of much of the knowledge used in innovation, few firms possess all the inputs required for successful and continuous technological development. Firms often have to turn to external sources to fulfill their informational requirements. In fact, a major contribution to a firm's knowledge base is likely to come from outside sources. Allen and Cohen (1969), in a study of 17 R&D laboratories, found that vendors, “unpaid outside consultants,” and informal contacts with government bodies and universities are important sources of information used in research. In a study of major product and process innovations at Du Pont between 1920 and 1950, Mueller (1966) observed that the original sources of most basic inventions came from outside the firm. Suppliers, buyers, universities, consultants, government agencies, and competitors all serve as sources of vital knowledge and expertise (Jewkes, Sawyers, and Stillerman, 1958).

For firms or nations which lag others technologically (henceforth termed “followers”), the challenge for technological catching-up is to acquire and build upon external knowledge that often resides in foreign countries or in their firms and institutions. The extent to which followers can acquire external knowledge is determined in part by the nature of knowledge (Zander and

Kogut, 1995) and by the followers' absorptive capacities (Cohen and Levinthal, 1990). State-of-the-art technologies, or the most valuable parts of knowledge, are often tacit (Winter, 1987). As we move further into the tacit domain, knowledge becomes increasingly difficult to separate from those who possess it. At low levels of codification, knowledge transfer requires rich mechanisms of communication to facilitate its transfer. One such mechanism is the transfer of people (Leonard-Barton, 1995). Tacit knowledge can be acquired only through experience or learning-by-doing and thus can be transferred best through training and human transfer.

The tacitness of knowledge often increases its value to the firm possessing it. A firm that holds a state-of-the-art technology is often reluctant to voluntarily transfer that technology, given that it can provide an important source of competitive advantage (since it is hard to imitate). Additionally, tacit knowledge may be embedded in the firm, making it difficult for other firms to imitate it or appropriate the rents from it. Thus, the tacitness of knowledge often leads to reluctance and inability on the part of technology holders to transfer their knowledge to other firms (Kogut and Zander, 1996). Even if technology holders are willing to transfer state-of-the-art knowledge to followers, the knowledge is often embedded in individuals, thus requiring the costly transfer of key personnel.

Organizational boundaries serve as knowledge envelopes and valuable knowledge is much more likely to be diffused within an organization than outside of it (Zucker, Darby, Brewer, and Peng, 1996). The sticky nature of tacit knowledge means, of course, that it does not necessarily flow easily or quickly even within a firm (Szulanski, 1996). Due to the limited speed and scope of diffusion across firm boundaries, it is difficult for outsiders to get access to and master such tacit and complex knowledge. As shown by Zander and Kogut (1995) and Almeida, Song, and Grant (1999), multinational firms are superior to alliances or markets as conduits of knowledge transfer and building, especially when the knowledge is tacit.

Identifying, acquiring, and assimilating valuable external knowledge, especially tacit knowledge, requires a firm to possess a considerable level of absorptive capacity (Cohen and Levinthal, 1990). Cumulative experience with a technology often determines the absorptive capacity of the recipient in acquiring such tacit knowledge. Therefore, absorptive capacity varies considerably according to the prior knowledge base and cumulative investment in learning capabilities. Firms seek to acquire knowledge from outside when there is a significant knowledge gap with industry leaders. Paradoxically, firms that developed some cumulative experience and a knowledge base are better positioned to acquire target technologies (Leonard-Barton, 1995).

Given the tacit nature of knowledge (often embedded in human capital within an organizational boundary) and the reluctance of "leading" firms to part with this knowledge, how does a follower gain access to this knowledge for technological catching-up? Studies have pointed to the use of alliances in acquiring knowledge (Mowery, Oxley, and Silverman, 1996) and to the advantages of co-location in technology-intensive regions (Almeida, 1996). Another mechanism that permits the acquisition of human-embodied knowledge is the hiring of experienced engineers who have worked on the relevant technologies in leading firms. Experienced engineers can improve a "scouting" firm's related knowledge base or cumulative experience with a technology and can thus reduce the cost and time of recognizing, accessing, and assimilating new technologies (Song, Almeida, and Wu, 2001). Moreover, the mobility of such highly experienced technology experts is not simply a one-time transfer of ideas and information, but also facilitates the transfer of capabilities or know-how permitting further knowledge building (Kim, 1997). As suggested by Perez and Soete (1988), a follower's

catching-up process can only be achieved through acquiring capabilities for participating in the generation and improvement of technologies, as opposed to the simple use of them. When an important technology is embedded in human brains, gaining even one or two key personnel can improve a follower's knowledge-building potential (Ettlie, 1985).¹ Thus, we propose:

Proposition 1: Follower firms (and countries) can acquire existing knowledge and build new knowledge necessary for technological catching-up by hiring experienced engineers who have previously worked for technology leaders in foreign countries.

Localized Nature of Knowledge Spillovers and Human-Embodied Technology Transfer

The issues concerning the tacitness of knowledge and human mobility are closely related to the notion, embedded in endogenous growth theory, of the geographical localization of knowledge spillovers (*e.g.*, Romer, 1986, 1990; Grossman and Helpman, 1991). Using patent citation data, Jaffe, Trajtenberg, and Henderson (1993) showed that knowledge spillovers tend to be geographically localized. Zucker, Darby, and Brewer (1998) suggested that localized knowledge spillovers occur due to the immobility of star scientists, or “intellectual human capital” tied to a particular location. Almeida and Kogut (1999) showed that in the semiconductor industry, knowledge tends to be localized only in certain regions characterized by high internal mobility and low cross-regional mobility. Both studies suggest that the lack of mobility or intra-regional mobility of talented engineers leads to localized knowledge spillovers. On the other hand, Zander and Kogut (1995) found that the turnover of key personnel significantly increases the hazard of involuntary knowledge spillovers in the form of imitation of technologies. In a study of the diffusion of semiconductor technology, Tilton (1971) also found that rapid diffusion occurred when there was high inter-firm mobility of scientists and engineers.

These findings suggest that if there is substantial inter-firm, inter-regional (or perhaps inter-country) mobility of key personnel, then knowledge can diffuse across borders quickly, even internationally, and can thus contribute to the technological catching-up of followers which hire these mobile engineers. Hence, we propose:

Proposition 2: Human mobility can mitigate the localized nature of knowledge spillovers and facilitate international knowledge spillovers.

Human Mobility and Knowledge-Building Patterns

We have proposed that the hiring of experienced engineers can improve a follower's (say Korea or Taiwan's) capabilities to acquire and build knowledge in the technological catching-up process. Hired engineers bring in cumulative experience of technologies acquired from their previous companies, which are located in regions or countries that are leaders in the particular technology. These engineers not only help absorb externally sourced technologies but also build knowledge by integrating external and internal sources of knowledge. The path-dependent nature of learning (Nelson and Winter, 1982) and local search behavior (Stuart and Podolny, 1996) suggest that hired engineers would be more likely to improve the knowledge base or

¹ World Bank (1998) noted that the gap in the capacity to create knowledge is even greater and more difficult to close than the knowledge gap between developing and developed countries.

knowledge-building capabilities of their new employers based upon knowledge mastered at their previous companies.

Through collaborative research, social interaction, and mentoring, engineers may influence the research directions of fellow researchers in the hiring company. As mentioned above, knowledge building activities by newly hired engineers are based on their prior knowledge and are manifestations of local search from the perspective of these engineers. However, from the perspective of the hiring company, knowledge building based on hired engineers' previous knowledge is not necessarily local search, but may instead represent the exploration of distant (and leading) knowledge from external sources. Followers tend to hire experienced engineers when they intend to develop technologies in new areas of technological innovation (Ettlie, 1985). Hired engineers could emerge as central actors in the networks of social interaction and act as leaders in research. Based on prior experience, knowledge, and social networks, hired engineers could serve as technological gatekeepers and boundary spanners who influence the source, flow, and direction of knowledge for subsequent knowledge-building activities. Hence, for engineers moving from the US (a leader) to Korea and Taiwan (followers), we offer the following hypotheses:

Hypothesis 1: Inventors, after moving to Korea or Taiwan, are likely to build upon the knowledge base of the *firm* of their previous employment in the US.

Hypothesis 2: Inventors, after moving to Korea or Taiwan, are likely to build upon the knowledge base of the *region* of their previous employment in the US.

Building new knowledge based on prior knowledge bases developed by hired engineers in overseas companies also indicates that international knowledge spillovers took place through human mobility. Thus, examining these knowledge-building hypotheses empirically provides a first step towards seeking the answer to the rapid technological catching-up puzzle of Korea and Taiwan.

STATISTICAL ANALYSIS

Samples and Patent Citations

We use patent citation data to trace the knowledge building patterns of followers from Korea and Taiwan by scouting experienced engineers from the US in the semiconductor industry. The semiconductor industry is a particularly appropriate arena within which to study international technology development and the role of mobility, since it is the apotheosis of a knowledge-based industry. The industry has remained at the leading edge of scientific discovery, pushing continually at the limits of the physical sciences – not just in electronics, but also in quantum physics, electromagnetics, optics, lasers, metallurgy and materials sciences, chemistry, and lithography.

To identify mobile engineers who (1) are capable enough to file multiple patents in the US and (2) moved from US to Korea or Taiwan, we first constructed a record of the career paths of semiconductor engineers with patenting records from a longitudinal patent and patent citation database. Specifically, we identified engineers who initially filed patents for US semiconductor firms and then later filed patents for Korean or Taiwanese firms. To identify engineers who moved across borders, we listed the names of every engineer named on a semiconductor patent

in Korea or Taiwan between 1975 and 1995. We then ran a match for these names with the inventors of every semiconductor patent invented in the US. We found 78 probable matches (last name, first name, middle initial) for inventors who had patented first in the US and then subsequently in Korea or Taiwan. We then examined each of the patenting records carefully to filter out false matches or problematic cases.² To measure the inter-country knowledge influences brought about by the mobility of semiconductor engineers, we developed a patent database of the career paths of the final sample of 28 engineers.³ The 28 engineers filed a total of 82 patents after moving to Korea or Taiwan and 72 patents before moving. While some information on mobility is undoubtedly missed, the data permit interesting analysis.

The patent document has extensive information that is useful to the study of innovation and innovative influences. A patent document provides data on the geographic location and the technology of an innovation. In addition, patent citations permit us to infer the scientific and technological influences on a particular invention. A list of citations for each patent is made through a uniform and rigorous process applied by the patent examiner as a representative of the patent office. The patent applicant is obliged by law to specify in the application any and all of the “prior art” that the applicant is aware of. The list of patent citations so compiled is available on the patent document, along with information on the inventor, his or her geographic location, the inventor’s company (the “assignee”), and technology types.

To investigate the knowledge-building hypotheses, we examine whether mobile engineers who moved from the US to Korea or Taiwan are subsequently more likely than expected to cite patents from (1) the firm or university of their original employment in the US, and (2) the state or region of their original employment in the US.

Methods

We conduct T-tests based on the case-control methodology used by Jaffe, Trajtenberg, and Henderson (1993) and Almeida (1996). The patent citation analysis is carried out using the case-control method by focusing on (1) the patents (henceforth “original patents”) filed by the mobile engineers for their original firms in the US and (2) the citations by their patents subsequent to their moves to firms in Korea and Taiwan. In order to evaluate the hypothesis that knowledge is transferred across countries through the mobility of engineers, this case-control study investigates the extent to which the patents cited after the cross-country move, which represent knowledge spillovers from previous innovations (cases), and comparable (along technical and temporal lines) patents which are not cited (controls), differ with respect to their location (region) and firm (owner). We expect to find that the cited patents are more likely to belong to the prior company (or region) of employment of the engineer than the control patents.

First, every “original patent” (or the patents filed by the engineer before moving from the US) is listed. Next, the patents filed by the engineer after the move to Korea or Taiwan are listed (“new patents”) and every patent cited by these “new patents” is identified. Thus, we have a list

² The process of determining a real cross-country move from a false one is subjective. If the area of patenting differed dramatically across time, or if the engineer’s career path remained unclear, we did not include the inventor in the final sample. Also, if the names were very common or if there was evidence suggesting that multiple inventors were patenting using the same name, we did not include these names.

³ If the final list included a false positive (*i.e.*, an engineer who did not move), this would add noise to the data and thus reduce our chances of finding significant results. Thus, an error in identifying the mobile inventors would introduce a conservative bias.

of “original patents” and a list of “cited patents.” After this, the geographic location, the patent owner (usually a firm), and other temporal and technological details relating to the original and cited patents are compiled. We are interested in the extent to which the cited patents match the original patents. To adjust for any bias due to the existing distribution of technological activity, we follow Jaffe et al. (1993) in the construction of a “control sample.” For each cited patent, we identify a corresponding control patent. This patent is identified such that the patent (technology) class is identical to that of the cited patent and the application date is as near as possible to that of the cited patent. This control patent thus resembles the cited patent in terms of technology and time of innovation. Since the control patent, however, is not cited by the new patent, the frequency of a match between the original patent and the control patent in terms of assignee organization or region reflects the existing concentration of patenting activity. The frequency of matches between the original patent and the control patent sets a baseline frequency against which we compare the frequency of original patent-cited patent matches.

Let us illustrate the design of the statistical test. Let P_{cit} be the frequency probability that the assignee (or region) of the cited patent matches the assignee (or region) of the original patent for the particular engineer. Let P_{con} be the corresponding frequency probability that the control patent belongs to the same assignee as the original patent for the particular engineer. Assuming binomial distributions, the null hypothesis is

$$H_0: P_{cit} = P_{con}$$

and the alternate hypothesis is

$$H_a: P_{cit} > P_{con}$$

The t-statistic is calculated as follows:

$$t = (P_{cit} - P_{con}) / [(P_{cit}(1 - P_{cit}) + P_{con}(1 - P_{con})) / n]^{0.5}$$

The 't' statistic tests the difference between two independently drawn binomial proportions. A positive significant value of Student's t indicates support of the proposition that mobility influences knowledge flows. The tests were carried out at the regional level as well.

Statistical Results

The main results of the case-control tests for both samples are given in Table 1. The “number of citations” corresponds to the total number of citations – 572 by the 82 “new” patents. “A” and “B” are the percentages of citations and controls, respectively, that belong to the same firm, state, or country as the corresponding original patent. The t-statistic tests the equality of the control and citing proportions, as described previously. It can be seen that we have only partial support for the hypotheses.

Table 1 About Here

Our main hypothesis (Hypothesis 1), testing the transfer of firm-level knowledge through the mobility of engineers, is strongly supported. After moving to Korea and Taiwan, engineers continue to build on the knowledge of their previous firms in the US. The findings for Hypothesis 2, testing the effects of mobility on the transfer of regional knowledge, are also positive but are not significant. Engineers, once they move across countries, do cite previous patents from firms located in the region they once worked. However, this regional effect is not strong enough to generate significant results.

CASE STUDIES

The above statistical analysis shows that engineers who moved from the US to Korea or Taiwan tended to build subsequent knowledge in recruiting companies based on prior knowledge that they mastered in the US. This finding suggests that mobile engineers facilitated international knowledge spillovers and represented an important basis for technological catching-up. To further illuminate the role of these mobile engineers in the technological catching-up process of Korea and Taiwan, we conducted a series of field interviews in the two countries in 1999 and 2000, as well as an extensive literature review. Because rapid technological catching-up took place as a mix of various modes of technology sourcing, including scouting experienced engineers abroad, the case studies below cover the evolution of modes of technology sourcing in general, with a special emphasis on learning-by-hiring through the mobility of engineers.

Technological Catching-Up Case of Korea

Korean semiconductor firms have achieved one of the most remarkable technology catching-up cases in the post-war era. In the case of Korea, big business groups called *chaebols* played crucial roles in the rapid growth of the semiconductor industry. During 1983 and 1984, largest *chaebols* in Korea – Samsung, Hyundai, and – made massive investments in semiconductors under Samsung’s initiative. Initially, Samsung’s late chairman Byung-Chull Lee scouted Dr. Im-Sung Lee, who had worked for GE, IBM, and Sharp, as a technical advisor. With the help of Dr. Lee, Samsung scouted four more highly experienced Korean semiconductor engineers from the US. These engineers played important roles in laying out Samsung’s technology acquisition strategies in the early years.

Since their entry into the DRAM business, Korean semiconductor firms have used multiple modes of technology acquisition – technology licensing, internal development, technology-seeking foreign direct investment, and “scouting” for experienced engineers – simultaneously. Initially, technology licensing played an important role in acquiring key technologies. Between 1983 and 1988, Korean semiconductor firms entered 101 technology licensing agreements – 66 cases of these were with US firms. For example, Samsung licensed chip designs and masks of 64K and 256K DRAMs from Micron Technology in the US and licensed CMOS process technology and 16K SRAM designs from Sharp in Japan. Samsung initially approached major DRAM makers in the US and Japan, such as NEC, Toshiba, Texas Instruments, and Intel, to license DRAM technologies, but all of them refused. Finally, Micron Technology, a start-up firm at the time, agreed to license DRAM technologies in order to overcome its financial trouble. However, the company was very reluctant to reveal any important know-how that could be used for Samsung’s subsequent development efforts.

Foreign semiconductor equipment makers also helped Koreans firms learn manufacturing technologies quickly. Samsung was the first DRAM company in the world to adopt the 6-inch and then the 8-inch wafer fabrication equipment. As the first adopter, Samsung was able to get full technical support from equipment makers who had strong incentives to provide evidence of the yield-enhancing capabilities of their new equipment. Hyundai and LG soon followed suit. As a result, Korean firms mastered advanced manufacturing technologies and improved yields rapidly.

A notable factor in the technological progress of the three major Korean semiconductor firms is that, instead of relying exclusively on imported technology through licensing, all three

major players improved their abilities (and absorptive capacity) rapidly by investing heavily in internal R&D activities from the beginning. Recognizing the lack of a prior knowledge base in the DRAM business, Samsung and Hyundai set up R&D labs in Silicon Valley in 1983, at the same time as their entrance into the DRAM business. Using these overseas R&D labs, they scouted Korean engineers who worked for US companies.

These ethnic Korean engineers in the US who were scouted by Korean firms played crucial roles in the technological catching-up process. Since 1965, the most talented Korean engineering students have begun moving to the US to earn advanced graduate degrees. The triggering event was the Immigration Act of 1965, or the so-called Hart-Cellar Act, that significantly opened the doors of immigration based on the possession of scarce skills. The Hart-Cellar Act drastically increased the number of Korean engineering students who pursued graduate degrees in the US. Because there was little opportunity for them to utilize their advanced skills in Korea, a majority of them stayed and worked for US companies. As Korean *chaebols* with deep pockets began to enter technology-intensive industries such as the semiconductor industry in the 1980s, they recruited these experienced engineers and managers who resided in the US. A majority of them decided to return to Korea. However, some Korean engineers, especially Korean-American engineers, however, did not want to move to Korea, although they were willing to work for Korean firms. An important objective of setting up R&D labs in Silicon Valley was to harness these ethnic Korean engineers, as well as non-Korean engineers, who wanted to stay in Silicon Valley. In some cases, the recruiting companies paid these engineers salaries that were three or four times higher than those of their own CEOs!

In the initial stages of technology development, the R&D labs in Silicon Valley made attempts not only to absorb and assimilate licensed technologies for mass production in Korea, but also to build new knowledge. For example, SSI, Samsung's R&D lab in Silicon Valley, played a key role in assimilating 64K DRAM designs and production processes just 6 months after Samsung's announced entry in 1983 into the DRAM business.⁴ Moreover, just 10 months after developing 64K DRAM based on the licensed technology from Micron, SSI developed its own design for 256 K DRAMs, which was rated superior to the licensed design from Micron Technology. For R&D activities in SSI, Samsung hired highly experienced Korean design and process engineers from IBM, Zilog, National Semiconductor, Intel, and Intersil. Along with other Korean and American engineers, including several designers who moved from Mostek, these experienced Korean engineers led the development of designs and processes for 256K DRAM. In a peak year, SSI hired 260 local engineers, including a substantial number of Koreans. Hyundai also set up an R&D lab in Santa Clara in 1983 and at one time employed 430 local engineers. LG also established a relatively small-scale R&D outpost in Sunnyvale in 1984 and scouted 115 local semiconductor engineers.

These local engineers, many of them ethnic Koreans, in overseas R&D labs brought in tacit knowledge that the Korean firms initially lacked. In addition, these overseas R&D labs served as training grounds for Korean engineers who were educated and trained in Korea. They also served as information scanning outposts to acquire the latest technical information, as well as to monitor and identify important new technological trends that were taking place in Silicon Valley or the US.

Korean semiconductor firms also improved their own internal R&D capabilities in Korea. Samsung invested 12.6% of its sales in R&D activities in 1987, employing 966 researchers,

⁴ American and Japanese competitors predicted that Samsung would not be able to produce 64K DRAM within 3 years.

including 20 with (mostly American) Ph.D. degrees. In the same year, Samsung spent about 4% of its sales for royalty payments. Initially, the bulk of R&D activity took place in the US and all manufacturing activity took place in Korea. Korean firms forged active interaction between R&D labs in Silicon Valley and corporate R&D labs and wafer fabrication plants in Korea by promoting joint research, consulting, and training. These processes facilitated quick and effective knowledge transfer from R&D labs in Silicon Valley to those in Korea. Experienced engineers, hired from US companies, secured key posts in R&D labs and plants in Korea as well. Starting from the development of 1M DRAM, R&D labs in Korea began to play increasingly important roles. As a result, the importance of both Silicon Valley labs and technology licensing as modes of technology acquisition has decreased rapidly in the 1990s.

Engineers, hired from the US, continued to play key roles in the subsequent knowledge building process. For example, Dae-Je Jin, a Stanford Ph.D. who had worked for one of IBM's semiconductor R&D labs, went on to serve as a team leader in the development of 64M DRAM at Samsung Electronics. Chang-Gyu Hwang, an MIT Ph.D. who had worked as a researcher at Stanford University and as an advisor of Intel, subsequently led the development team for the 256M DRAM at Samsung. According to an internal company document from Samsung, among 36 development team leaders as of 1989, fourteen senior engineers (39%) had work experience overseas. Twelve of them both earned graduate degrees (ten Ph.D.s) in the US and worked for US companies before they joined Samsung.⁵ An additional fourteen out of 36 team leaders (39%) earned graduate degrees – twelve of them Ph.D. degrees – from major US research universities, although they did not have work experience in US companies. Only eight team leaders (22%) – six of them with Ph.D. degrees – did not study or work abroad. Among 36 team leaders, nine senior engineers worked in SSI, Silicon Valley. Eight of the nine senior engineers at SSI had research experience in US companies after they earned advanced degrees in the US. These figures show the dominance of “returned brains” who were educated and/or worked in the US in the early history of Samsung's technology development. Over time, as Samsung has emerged as a world leader in DRAM technology, the ratio of “returned brains” in key technical posts has decreased and locally educated and trained engineers have played increasingly important roles.

This anecdotal evidence illustrates the importance of human-embodied technology transfer in the time-compressed learning process of the Korean semiconductor industry. Based on their prior experience and knowledge bases, the key engineers who occupied major posts in domestic and overseas R&D labs and corporate headquarters steered the direction of technology acquisition and development strategies and offered time and cost-saving advice and solutions when these companies faced technological bottlenecks. These engineers and their valuable tacit knowledge helped Korean semiconductor firms overcome the initial lack of expertise and absorptive capacity in a short time. Furthermore, the movement of these engineers to Korean firms brought not only advanced external knowledge, but also capabilities to build improved knowledge based on the combination of internally accumulated and externally acquired knowledge.⁶

⁵ Two more senior-level engineers – one with a Ph.D. from Japan and the other with a bachelor's degree from the US – had work experience overseas.

⁶ Although the mobility of engineers from overseas or from government research institutions took place frequently, inter-firm mobility among rival firms in Korea did not become active until recently. Samsung, Hyundai, and LG showed intense rivalry and tried to limit the exchange of information, knowledge, and resources among them. For example, when Hyundai tried to scout

Technological Catching-Up Case of Taiwan

Taiwan has followed somewhat different evolutionary paths in its development of the semiconductor industry. Whereas *chaebols* played a pivotal role in Korea, the government took initiatives in the emergence of the Taiwanese semiconductor industry. While Korea focused mainly on DRAMs, Taiwan developed its strengths in foundry services, Mask ROMs, and application-specific IC (ASIC) chips. While *chaebols* pursued vertical integration from the design to the testing of chips, the Taiwanese semiconductor industry developed a network of specialized firms. Another difference was that government-sponsored research institutions played much more important and direct roles in absorbing foreign technologies and developing R&D capabilities in the case of Taiwan, whereas in Korea, private firms played key roles.

Despite these differences, there exist substantial similarities between the technology sourcing strategies of Taiwan and Korea. Both countries used multiple modes of technology sourcing and have changed the relative importance of each mode over time. As was the case in Korea, ethnic Taiwanese or Chinese engineers in the US played pivotal roles in transferring technical know-how and, more importantly, knowledge-building capabilities. Taiwan relied heavily on technology licensing, but like Korea, Taiwan has invested aggressively in developing its own R&D capabilities. Similar to the Korean case, alliances or joint ventures with foreign firms became more widely used over time.

Let us illustrate the history of the catching-up process of the Taiwanese semiconductor industry with a special focus on the role of returned brains from the US. The origin of the Taiwanese semiconductor industry goes back to 1973, with the initiatives of Dr. Yun-Hsuan Sun, Minister of Economic Affairs. Dr. Sun, a former electrical engineer, established the Industrial Technology Research Institute (ITRI), a leading government research institution, in 1973. He then set up the Electronics Research & Service Organization (ERSO) under ITRI in 1974. ITRI/ERSO played a pivotal role in identifying, acquiring, absorbing, developing, and disseminating semiconductor-related technologies in Taiwan (Aoyama, 1999; Chang, 1999; Mathews and Cho, 2000). To lay out a long-term development plan for the semiconductor industry in Taiwan, Dr. Sun also set up the Technical Advisory Committee (TAC) in 1974. Dr. Wenyuan Pan, a Chinese-American engineer who headed the R&D efforts of RCA, organized TAC with a group of experienced ethnic Chinese semiconductor engineers in the US. The active consultation efforts of TAC to the government suggest that, from the inception of the semiconductor industry, ethnic Chinese engineers in the US played an important role.

The government also established Hsinchu Science-Based Industrial Park (HSIP) in 1980 and provided various incentives to attract high-tech firms, including start-up firms. HSIP was located near ITRI/ERSO and two major research universities in Taiwan. An important goal of HSIP was to lure ethnic Taiwanese engineers, many of them graduates of the two universities in Hsinchu, from the US back to Taiwan. To achieve this goal, HSIP made substantial investments

two key Samsung engineers, including Dr. Dae Je Chin, Samsung's chairman met with the President of Korea and asked the President to step in (Chang, 1999). The President mediated the situation and made both engineers return to Samsung. However, some junior engineers from Samsung, who had developed the most advanced technologies, moved to Hyundai and LG and led the domestic technology diffusion.

towards making living and educational conditions in the park comparable to those in the US. HSIP introduced the first bilingual education programs in Taiwan to some schools in the park, so that the children of returnees from the US could adjust smoothly. In addition, the HSIP administration, as well as ITRI, opened branch offices in Silicon Valley. A primary role of these branch offices was to persuade Taiwanese engineers to return home by providing information and local contacts (Saxenian, 1999). The branch offices also developed databases of Taiwanese engineers in the US and shared them with Taiwanese firms.

As was the case in Korea, technology licensing played an important role in Taiwanese efforts to acquire advanced technologies. In the case of Taiwan, ITRI/ERSO often licensed technologies on behalf of private firms, absorbed these technologies, and then disseminated them to the private sector. Once imported technology was absorbed successfully, ERSO often spun off the project. ERSO provided staff, equipment, and technology to spin-off firms that became leading semiconductor firms in Taiwan such as United Microelectronics Corporation (UMC), Taiwan Semiconductor Manufacturing Corporation (TSMC) and Vanguard. ERSO and the Taiwanese government took a substantial portion of equity stakes in these spin-off firms.

In the 1990s, private firms began to take initiatives in licensing foreign technologies. For example, TSMC licensed technologies from AMD and Philips, while UMC licensed technologies from SGS Thomson. Moreover, private firms also engaged in joint ventures with foreign firms to acquire technologies. For example, TSMC linked up with Fujitsu to acquire 64M DRAM manufacturing technologies. Acer entered the semiconductor industry by establishing a joint venture with Texas Instruments.

From the early developmental stage of the industry, besides licensing technologies, Taiwanese semiconductor firms and ITRI/ERSO actively invested in developing their own R&D capabilities. In addition to domestic R&D investments, most leading companies also set up R&D labs in Silicon Valley. Recently, as some Taiwanese companies developed world-class technological capabilities, they began to upgrade their relations with foreign partners from licensing to joint development. For example, Macronix and UMC conducted joint development efforts with Philips and Intel, respectively.

In terms of the development of indigenous technological capabilities, a unique characteristic of the Taiwanese semiconductor industry is the proliferation of fabless design houses. As of April 2000, there are 127 design houses in Taiwan. In 1999, the total revenue of these fabless design houses reached US \$2.3 billion. Taiwan captured 19.6% of the world market share of fabless chip design segments, just behind the US.⁷ The explosive growth of specialized design houses in Taiwan was made possible due to the emergence of its world-leading foundry service business as well as the rapid growth of Taiwan's PC sector. The establishment of TSMC as the world's first foundry firm in 1987 resulted in a ten-fold increase in the number of design houses in Taiwan in just one year (from 4 to more than 40). Because the majority of foundries, design houses, and PC makers were located in Hsinchu, these design houses enjoyed close interactions with their customers and suppliers. Most fabless design houses were founded by ex-researchers of ERSO or returned engineers from the US.

Similar to the case of Korea, returned engineers from the US played pivotal roles in Taiwanese efforts to absorb foreign technologies and develop their own knowledge-building capabilities. As shown in Chart 2, the number of returned brains has increased rapidly since the late 1980s. In HSIP, over 3000 returned engineers worked in private companies (HSIP, 1998).

⁷ Because Japanese and Korean semiconductor firms pursued vertical integration strategies, there were very few fabless design houses in Japan and Korea.

By 1998, more than 30% of Taiwanese engineers who studied in the US returned home, compared to only 10% in the 1980s (Saxenian, 1999).⁸

Chart 2 About Here

From the 1960s through the 1980s, as was also the case in Korea, many elite engineering students in Taiwan went to the US to earn advanced degrees and then stayed because there was little chance for them to utilize their advanced knowledge back home. In the 1980s, according to National Science Council statistics, Taiwanese students topped the rankings of the total number of foreign-born engineering students at the graduate level. Since the late 1980s, as Taiwan aggressively invested in the semiconductor industry and as income levels and living and political environments improved substantially, a significant number of these engineers began to return home. Government incentive schemes for entrepreneurial activities and the rapid development of venture capital infrastructures also encouraged talented Taiwanese engineers in Silicon Valley to start their own businesses in Taiwan. In addition to the improvement in Taiwan's domestic conditions, glass ceilings that Taiwanese engineers encountered in many US firms also facilitated their return back home, where they could be promoted to the top or play more influential roles. Also, Taiwanese engineers who were not native English speakers often faced personal and professional isolation in Silicon Valley, which at the time was dominated by white men (interviews at ITRI/ERSO).

Many returned engineers started their new careers at ITRI/ERSO or at private firms in Taiwan. Many key researchers at ITRI/ERSO had earned their degrees and then worked overseas. Among researchers who joined ITRI/ERSO between 1994 and 1999, 442 earned doctoral degrees abroad and 480 earned master's degrees overseas. Many returnees who initially joined ITRI/ERSO became founding members of spin-off ventures, started their own design houses, or were scouted by private-sector semiconductor firms. For example, TSMC was established in 1987 by the initiative of Morris Chang, who had served as the president of ITRI. Morris Chang had been a senior vice president at Texas Instruments in charge of semiconductor production and also served as president of General Instruments, before joining ITRI.

Recently, more returnees have begun to found their own firms. As of 1998, 109 companies out of 222 Taiwanese companies in HSIP were founded by returned brains from the US. These returned engineers have maintained their personal and professional relations with friends and colleagues, many of them ethnic Chinese, in the US. Feelings of personal and professional isolation in the US encouraged Taiwanese engineers in Silicon Valley to develop strong personal and professional bonds among themselves. Many of them had already known each other because they were mostly graduates from several elite universities in Taiwan. These social communities further evolved into professional associations such as the Chinese Institute of Engineers (CIE), which was established in 1979. Even after some of these engineers returned to Taiwan, they often maintained their social networks with Taiwanese engineers in the US, and thus, returnees served as gatekeepers linking Taiwanese firms to Silicon Valley firms. Returnees often exchanged technical information with and sought technical advice from their friends and

⁸ Some Taiwanese engineers kept their families in California and functioned as "moonlighters," working in both Silicon Valley and Taiwan by traveling between the two regions several times a month.

former colleagues in the US. CIE, by providing an important source of information, training, legal, and financial help, also played an important role in fostering the entrepreneurial activities of Taiwanese engineers in Silicon Valley (Aoyama, 1999).

As mentioned above, a widespread perception of a glass ceiling in US firms encouraged many Taiwanese engineers to return home. At the same time, the same perception promoted a significant increase in the number of start-up firms founded by Taiwanese engineers. These Taiwanese start-up firms in Silicon Valley also had strong incentives to cultivate close linkages to returnees and companies in Taiwan, as Taiwan emerged as the leading foundry service provider as well as a global PC powerhouse. Recently, Taiwanese venture capitalists and private firms have often provided seed capital to Silicon Valley start-up firms founded by Taiwanese engineers.

The effort to develop a close linkage between Silicon Valley and Taiwan culminated in the establishment of Monte Jade Science and Technology Association. The primary goal of the association was to bring together Taiwanese engineers in Silicon Valley and Taiwan to promote business cooperation, investment, and technology transfer between executives and companies in Taiwan and Silicon Valley (Aoyama, 1999; personal interviews). The association has conducted various activities linking people in both regions and has thus, served as an important mechanism for returned engineers to maintain their personal and social links to ethnic Taiwanese engineers in Silicon Valley.⁹

CONCLUSIONS

Through patent citation analysis and in-depth case studies primarily based on field interviews, we found support for the role of the cross-country mobility of experts in transferring knowledge from the US to Korea and Taiwan in the rapid technological catching-up process of both countries in the semiconductor industry. The case-control study suggests that semiconductor engineers who move from US universities and firms carry with them firm-specific knowledge and are able to build upon this knowledge within their new firms in follower countries. The study also indicates that this knowledge flow across borders has a “local” character to it – engineers are able to carry firm-embodied knowledge, but are less able to transfer knowledge embodied in regions.

The in-depth case studies in this paper further illuminate the importance of the mobility of engineers in the technological catching-up process of followers. Returned brains from the US, which is the center of innovation in the semiconductor industry, enhanced absorptive capacity and the knowledge-building capabilities of followers in Taiwan and Korea in a time-compressed fashion. These returnees helped semiconductor firms in Taiwan and Korea, which were latecomers, to identify and acquire the appropriate technologies that leaders in the US had already developed. Thus, these firms were able to reduce the time and cost of acquiring advanced technologies significantly, with less trial-and-error experimentation. The significant contribution of returned brains was made possible by aggressive investments by both Taiwan and

⁹ Because key engineers in private firms, especially spin-off firms from ERSO, were often alumni of ERSO or alumni of several leading research universities in Taiwan, informal exchange of information also took place actively domestically, even among rival companies (Aoyama, 1999; interviews at ITRI/ERSO).

Korea in building their own in-house R&D capabilities from the very early stages, when they still licensed almost all technologies. Returned brains also played important roles in training local engineers and recently, these locally trained engineers began to produce a substantial number of US patents.

The crucial role of mobile engineers as carriers of important tacit knowledge is not unique to the case of Taiwan and Korea. Human mobility across firms has played a very important role in transferring tacit knowledge or knowledge-building capabilities in the domestic context as well (Ettlie, 1980; Leonard-Barton, 1995). This phenomenon was especially conspicuous in the US, and is “almost legendary in places like Silicon Valley (Chesbrough, 1999: 461). For example, in the US semiconductor industry, engineers from early technology leaders, such as Fairchild, IBM, AT&T, and Texas Instruments, were scouted by start-up firms or incumbent technology laggards and contributed to their technological catching-up or even subsequent breakthrough innovations (Rogers and Larson, 1984). Several leading semiconductor firms, such as Intel, were founded by engineers who had worked for Fairchild. Similarly, the mobility of engineers from IBM, Memorex, and Control Data contributed to the successful entry of current leaders in the hard disk drive industry, such as Seagate (Chesbrough, 1999). By scouting key engineers from incumbent technology leaders, rival firms or start-up firms accessed technically advanced firms’ extensive know-how and knowledge-building capabilities at a fraction of the cost and time of creating them in-house. In the international context, mobile engineers from the US also played important roles in the emergence of high-tech industries in Israel and Ireland (Saxenian, 1999).

Among countries that witnessed their best and brightest students move to the US, China and India have not yet benefited much from “reverse brain drains.” Given that there is a huge number of ethnic Chinese and Indian engineers working in high-tech firms in the US, there is a good possibility for us to witness reverse brain drains from the US to India and China in the near future.¹⁰

The successful technological catching-up experience of Taiwan and Korea, partly based on the effective utilization of returned engineers from the US, offers some policy implications for other developing countries such as China and India, which are trying to develop their own high-tech industries. Both Taiwan and Korea were concerned about brain drains initially because a majority of their elite engineering students moved to the US and did not return home (Hou and Gee, 1993). However, the brain drain in the 1960s and 1970s turned out to be a blessing and formed a basis for the reverse brain drain in subsequent periods when both countries began investing heavily in high-tech sectors in the 1980s.

However, as we saw in the case of both Taiwan and Korea, attracting experienced engineers back home does not take place automatically. The governments and private firms tried their best to encourage experienced engineers overseas to return home. These engineers considered returning home only after they found that there were good opportunities for them to utilize their advanced skills at home and that their skills would be compensated adequately. As seen in both cases, rising income levels and improvements in living and educational

¹⁰ The Chinese government seems to recognize the importance of mobile engineers in the technological catching-up process. In 1999, the Chinese Premier sent a letter to more than 20,000 Chinese engineers in the US who moved from the mainland China and urged them to return home, while guaranteeing preferential treatments and compensation packages.

environments were important prerequisites for facilitating the reverse brain drain. In addition, setting up R&D labs in the US turned out to be an effective way for companies in both countries to hire talented ethnic Korean and Taiwanese engineers who did not want to return to their home countries due to personal or professional reasons. As the World Bank also emphasized in their recent reports (1993; 1999), we suggest that returned brains from developed countries can offer a short cut for developing countries to acquire state-of-the-art knowledge and develop subsequent knowledge-building capabilities in the process of technological catching-up.

In addition to the above policy implication, this study has some implications for research in international technology transfer, new growth theory, and developmental economics. First, by focusing on the mobility of engineers and subsequent knowledge building, this study examined the linkage between human mobility and inter-firm knowledge transfer. As Ettlé (1985) lamented, few previous studies have empirically investigated the impact of human mobility on the innovation process at the organizational level, mainly due to data constraints. Our database on cross-border engineer mobility and patent citations enabled us, to some extent, to fill the empirical void regarding this important topic. Second, this study highlighted the importance of human-embodied technology transfer, which has been relatively neglected by existing studies of international technology transfer. We suggest that learning-by-hiring offers a mechanism to overcome obstacles and harness the advantages presented by technically- and organizationally-bound technologies. Finally, by focusing on the role of returned human capital in the “catching-up” of Korean and Taiwanese semiconductor firms, this study attempted to offer an added insight into the leader-follower debate between neo-classical theory and endogenous growth theory. Also, by showing that inter-firm human mobility across national borders can mitigate the localized nature of knowledge spillovers and accelerate international R&D spillovers, the study provided additional evidence of the role of human mobility in the spatial patterns of knowledge spillovers.

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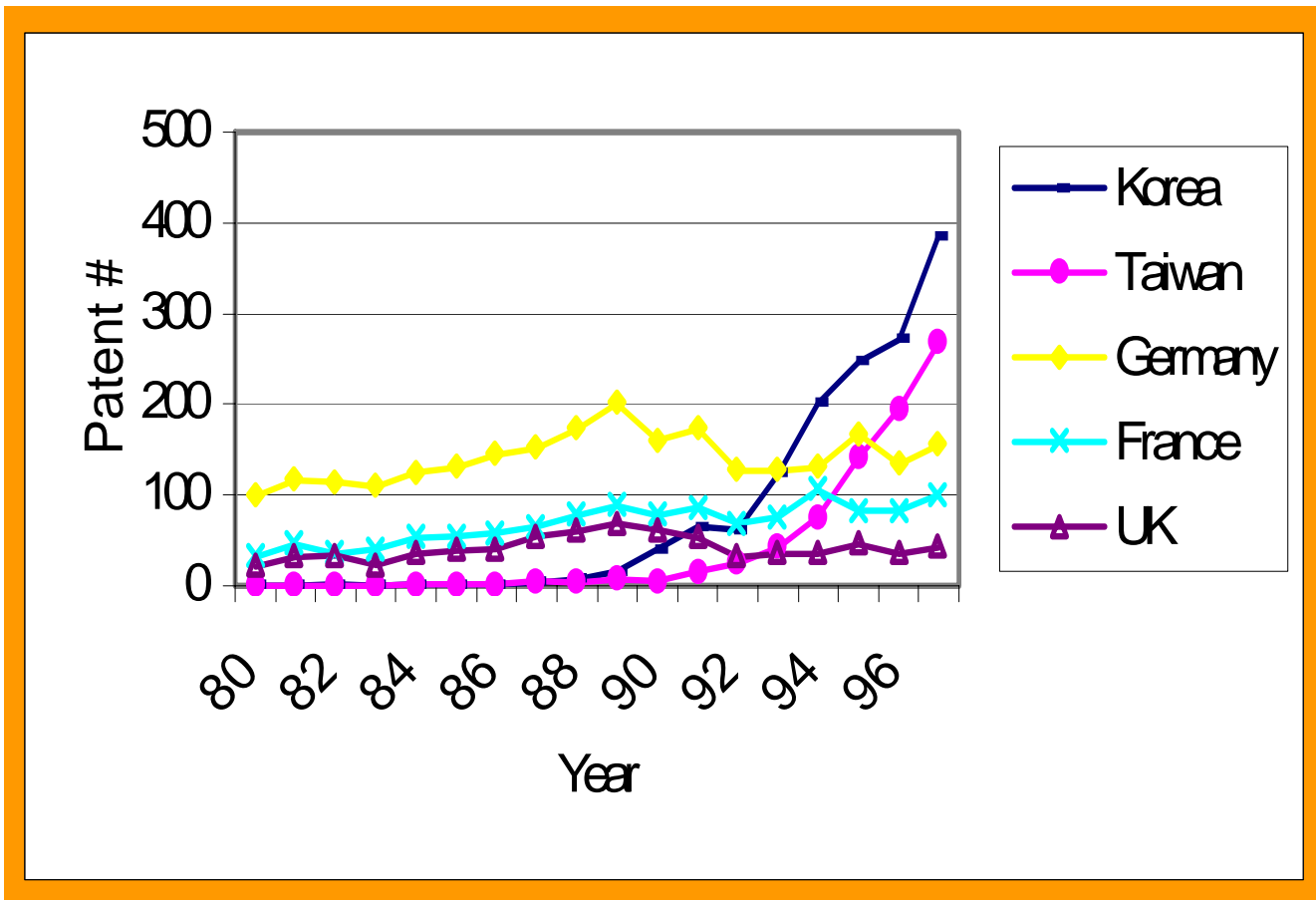
REFERENCES

- Allen, T. and Stephen C. (1969). Information flow in research and development laboratories. *Administrative Science Quarterly* 14: 12-20.
- Almeida, P. (1996). Knowledge sourcing by foreign multinationals: Patent citation analysis of the US semiconductor industry. *Strategic Management Journal*, special issue on 'Knowledge and the Firm': 155-165.
- Almeida, P. and Kogut, B. (1999). The geographical localization of ideas and the mobility of patent holders. *Management Science*, July, 955-967.
- Almeida, P., Song, J., and Grant, R. (1999). *Are Firms Superior to Alliances and Markets? An Empirical Test of Cross-border Knowledge Building*. Mimeo.
- Aoyama, S. (1999). *Haiteku netwaku bungyo (Division of Labor in High Tech Network: Why is the Taiwanese semiconductor industry so strong?)*. Hakutou Publishing: Tokyo, Japan (in Japanese).
- Cantwell, J. (1989). *Technological innovation and multinational corporations*. Oxford: Basil Blackwell.
- Chang, S. (1999). *Institutions and evolution of capability: The case of technological catching-up in semiconductors*. Unpublished doctoral dissertation. Case Western Reserve University.
- Chesbrough, H. (1999). The organizational impact of technological change: A comparative theory of national institutional factors. *Industrial and Corporate Change*, 8: 447-485.
- Cho, D. and Song, J. (1991). Samsung jeonja bandoche bumun (The semiconductor division of the Samsung Electronics). In Cho, D. (ed).
- Jaemi itnun kyengyeong iyagi II (Business cases in Korea Volume II). United Consulting Group, Seoul: Korea (in Korean).
- Cho, D., Kim, D., and Rhee, D. (1998). Latecomer strategies: Evidence from the semiconductor industry in Japan and Korea. *Organizational Science*, 9: 489-505.
- Cohen, W. and Levinthal, D. (1990). Absorptive capacity: A new perspective on learning and innovation. *Administrative Science Quarterly*, 35: 128-152.
- ERSO (Electronic Research and Service Organization). (2000). Internal document.
- Ettlie, John. (1985). The impact of interorganizational manpower flows on the innovation process. *Management Science*, 31: 1055-1071.
- Ettlie, J. (1980). Manpower flows and the innovation process. *Management Science*, 26: 1086-1095.
- Freeman, C. and Soete, L. (1997). *The economics of industrial innovation* (3rd Edition). The MIT Press. Cambridge, MA.
- Gilfillan, S.C. (1935). *The sociology of inventions*, Chicago, IL.
- Grossman, G. and Helpman, E. (1991). *Innovation and growth in the global economy*. Cambridge, MA: MIT Press.
- Hobday, M. (1995). *Innovation in East Asia: The challenge to Japan*. Edward Elgar.
- Hou, C. and Gee, S. (1993). National systems supporting technical advance in industry: The case of Taiwan. In Nelson, R. (ed). *National innovation systems: A comparative analysis*. Oxford University Press: 384-413.
- HSIP (Hsinchu Science-based Industrial Park) Administration. (1998). *Annual Report*.
- Jaffe, A., Trajtenberg, M., and Henderson, R. (1993). Geographic localization of knowledge spillovers as evidenced by patent citations. *Quarterly Journal of Economics*, 108: 577-598.

- Jewkes, J., David S., and Stillerman, R. (1958). *The Sources of Invention*. London: Macmillan.
- Kim, L. (1997). The dynamics of Samsung's technological learning in semiconductors. *California Management Review*, 39 (3): 86 – 100.
- Kogut, B. and Zander, U. (1996). What firms do: Coordination, identity, and learning. *Organization Science*, 7: 502-518.
- Leonard-Barton, D. (1995). *Wellsprings of knowledge: Building and sustaining the sources of innovation*. Harvard Business School Press.
- Mathews, J. (1997). A Silicon Valley of the East: Creating Taiwan's semiconductor industry. *California Management Review*, 39: 26-53.
- Mathews, J. and Cho, D. (2000). *Tiger Technology: The creation of a semiconductor industry in East Asia*. Cambridge University Press.
- Mowery, D., Oxley, J., and Silverman, B. (1996). Strategic alliances and interfirm knowledge transfer. *Strategic Management Journal*, 17, 77-91.
- Nelson, R. and Winter, S. (1982). *An Evolutionary Theory of Economic Change*. Cambridge, MA: Belknap Press of Harvard University Press.
- Perez, C & Soete, L. (1988). Catching up in technology: Entry barriers and windows of opportunity. IN Dosi, G., Freeman, C., Nelson, R., Silverberg, G., and Soete L. (eds). *Technological change and economic theory*. London, Pinter: 458-479.
- Stuart, T. and Podolny, J. (1996). Local search and the evolution of technological capabilities. *Strategic Management Journal*, 17:21-38.
- Romer, P. (1990). Endogenous technological change. *Journal of Political Economy*, 98 (5): s71-s102.
- Rogers, Everett & Larson, Judith. 1984. Silicon valley fever. Basic Books, New York: NY.
- Saxenian, A. (1999). *The Silicon Valley - Hsinchu connection: Technical communities and industrial upgrading*. Mimeo.
- Song, J., Almeida, P., and Wu, G. (2001). *Learning-by-hiring: When is mobility useful?* Mimeo.
- Szulanski, G. (1996). Exploring internal stickiness: Impediments to the transfer of best practice within the firm. *Strategic Management Journal*, 17: 27-43.
- Winter, S. (1987). Knowledge and competence as strategic assets. In David J. Teece (Ed.), *The Competitive Challenge – Strategies for Industrial Innovation and Renewal*: 159-184.
- Tilton, J. (1971). *International diffusion of technology; the case of semiconductors*. Brookings Institution, Washington D.C.
- World Bank. (1998). *World development report: Knowledge for development*. Oxford University Press.
- World Bank. (1993). *The East Asian miracle: Economic growth and public policy*. Oxford University Press.
- Zander, U. and Kogut, B. (1995). Knowledge and the speed of the transfer and imitation of organizational capabilities: An empirical test. *Organization Science*, 6: 76-92.
- Zucker, L. G., Darby, M., and Brewer, M. (1998). Intellectual human capital and the birth of U.S. biotechnology enterprises. *American Economic Review*, 88: 290-306.
- Zucker, L., Darby, M., Brewer, M., and Peng, Y. (1996). Collaboration structure and information dilemmas in biotechnology: Organizational boundaries as trust production. In Kramer, R. and Tyler, T. (Eds.), *Trust in Organizations*: 90-113. Thousand Oaks, CA: Sage.

Chart 1

Trend of Semiconductor-related Patents in the US



Source: Chang (1999)

Table 1
Results from Case Control T-Test

	REGION	FIRM
NUMBER OF PATENT CITATIONS	572	572
A = PATENT CITATION MATCHING %	19.76	8.39
B = PATENT CONTROL MATCHING %	17.13	3.49
A/B	1.15	2.4
t -STATISTIC	1.15	3.52

Chart 2
Cumulative Number of Overseas Taiwanese Engineers Returning to Hsinchu SBI Park

