

Patent citations and international knowledge flow: the cases of Korea and Taiwan

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Abstract

This paper examines patterns of knowledge diffusion from the U.S. and Japan to Korea and Taiwan using patent citations as an indicator of knowledge flow. We estimate a knowledge diffusion model using a data set of all patents granted in the U.S. to inventors residing in these four countries. Explicitly modeling the roles of technology proximity and knowledge decay and diffusion over time, we find that it is much more likely for Korean patents to cite Japanese patents than U.S. patents, whereas Taiwanese inventors tend to learn evenly from both. We also find that both Korea and Taiwan are surprisingly reliant on relatively recent technology.

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1. Introduction

Korea and Taiwan are two newly industrializing economies that have achieved tremendous technological progress and economic growth. Both have graduated

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from imitation to innovation within a single generation, by building their indigenous technological capabilities and moving up the technology ladder. Technology diffusion from the U.S., Japan, and other OECD economies has played an important part in the two economies' transition from labor-intensive manufacturing to technology- and human-capital-intensive manufacturing. Technology from more advanced economies benefits these countries in two distinct ways. Imported capital goods, embodying new technology, directly increase the productivity of the using industries in the importing country. In addition, researchers or inventors in less-developed countries can utilize the knowledge that they "import" to foster the development of indigenous new technologies. These knowledge imports are partially embodied in the import of high-technology goods, and partially disembodied in direct and indirect communication among researchers.

There is a growing literature on international technology diffusion. Most of these studies focus on technology diffusion embodied in traded goods. Coe and Helpman (1995) examined R&D spillovers¹ among OECD countries. They constructed a foreign R&D stock using the import shares of a country's trading partners and found a strong link between domestic total factor productivity and foreign R&D stock, which they interpreted as evidence of international R&D spillover. Keller (2001) explored the extent to which R&D in one G-7 country spills over to productivity growth in other G-7 countries. He found that geographical proximity is important, and that much of the variation in the magnitude of bilateral spillovers can be explained by patterns of trade, investment and language. Coe et al. (1997) examined north–south R&D spillover. They found that total factor productivity in developing countries is significantly boosted by the R&D stock of industrial countries, which they computed as the import-share-weighted sum of the R&D expenditures of a developing country's trading partners in the north. They interpreted this as evidence of north–south R&D spillover.

Because these studies focus on productivity growth in the country receiving technology flows, they cannot distinguish between the productivity benefits associated with the use of imported high-technology goods in production, and benefits arising because flows of knowledge from advanced economies facilitate research and invention. In this paper, we focus specifically on the inventive process in Korea and Taiwan. We investigate the pattern of *knowledge* flows from the U.S. and Japan to Korea and Taiwan, using patent citation data as a proxy for knowledge flows. Although we have no information on the mechanism by which knowledge is flowing, we isolate the impact on the research process in the receiving country, as distinct from productivity gains associated solely with the use of imported goods.

¹ The term "spillover," which implies a non-pecuniary externality flowing from the sender to the recipient, is widely used in this literature. Since we know nothing about the mechanism of knowledge transfer, we use instead the term "knowledge flow," except where citing the results of others.

Our approach builds on that of Jaffe and Trajtenberg (1999), which examined patterns of patent citation among the U.S., U.K., France, Germany, and Japan as an indicator of international flows of knowledge. They found significant evidence of geographic localization that fades slowly as knowledge diffuses over time. They also found interesting country differences, with Japan being highly localized, but more focused on recent developments, and flows from the U.S. to the U.K. being the most intense bilateral flow, suggesting a possible role for language and/or cultural connections.

We use patent citations as an indicator of knowledge flow from technologically advanced to developing economies. We extract from the NBER Patent Citations Data File (Hall et al., 2001) all patents taken out in the U.S. by Korea, Taiwan, Japan and the U.S. from 1963 to 1999.² We explore first the simple statistics of these data regarding the rate and technological composition of inventions in Korea and Taiwan over time. Both of these countries have seen a dramatic acceleration in their patenting over time, with Taiwan in particular now among the lower end of “first world” countries in terms of patents per capita.

We then present simple statistics regarding the frequency with which inventors in each of these countries cite patents originating in the U.S. and in Japan. We use these data to try to answer two questions. First, how does north–south knowledge diffusion differ among the country pairs in our sample? Second, what underlying factors contribute to the patterns of diffusion that we observe? We start with simple comparisons of overall citation rates, and then proceed to examine these rates after controlling for a number of factors likely to affect observed citation rates over time.

Given the non-rival and non-excludable nature of knowledge use, we assume that there is an international stock of knowledge, upon which every economy can draw to facilitate its own technological innovation. The OECD economies create most of this stock, whereas the developing economies are able to tap into this stock constrained by the availability of the channels of knowledge diffusion and their abilities to absorb and adapt new knowledge. An implication of situating our study in this context is that we should observe similar patterns of knowledge flow from the north to two similar economies in the south. Any disparity in knowledge diffusion should be accounted for by economy-specific characteristics in the south.

The rest of the paper is organized as follows. Section 2 describes the data used in this paper. We present some stylized patterns of knowledge diffusion using patent citation as a proxy. Institutional background for technological change in Korea and Taiwan is presented in Section 3. We discuss several stylized patterns of patent citation between the U.S., Japan, Korea, and Taiwan in Section 4. Section 5 describes the knowledge diffusion model. We discuss how the empirical results

² In utilizing patents taken out in the U.S., we focus on inventions for products intended (at least in part) for world trade, and for process inventions whose outputs are exported (at least in part). For the remainder of the paper, we use the shorthand “patents” to refer to “patents granted in the U.S.”

from estimating the diffusion model can account for the stylized patterns we observe in Section 6. Section 7 concludes.

2. The data

The data set used in this study consists of all utility patents granted by the U.S. Patent and Trademark Office (U.S.PTO) to inventors residing in Korea, Japan, Taiwan, and the U.S. from 1977 to 1999. The data are from the NBER Patent Citations Database (Hall et al., 2001).³ The data elements that we utilize are:

- the country of residence of the primary inventor;
- the dates of application and grant for the patent;
- the U.S.PTO patent classification; and
- the identity of previous patents contained in the citations or “references made” in each patent.

When a patent is granted by the U.S.PTO, it is assigned to one of over 400 patent classes according to its technological area. We use these three-digit patent classes for some of our analyses. For other purposes, it is desirable to have a more aggregated technological classification. The U.S.PTO classification system does not have a hierarchical structure, so there is no way within the U.S.PTO system to aggregate patent classes. Jaffe and Trajtenberg (1999) have grouped the patent classes into six major technological categories: Chemical; Computers and Communications; Drugs and Medical; Electrical and Electronic; Mechanical; and All Other.

Patent citations serve an important legal function, since they delimit the scope of the property rights awarded by the patent. Thus, if patent B cites patent A, it implies that patent A represents a piece of previously existing knowledge upon which patent B builds, and over which B cannot have a claim. The applicant has a legal duty to disclose any knowledge of the “prior art,” but the decision regarding which patents to cite ultimately rests with the patent examiner, who is supposed to be an expert in the area and hence to be able to identify relevant prior art that the applicant misses or conceals. We assume that the frequency with which a given country’s inventors cite the patents of another country is a proxy for the intensity of knowledge flow from the cited country to the citing country. For further discussion of the limitations of using citations data for this purpose, see Jaffe and Trajtenberg (1999) and Hall et al. (2001). Jaffe et al. (2000) present survey evidence regarding the extent to which citations reflect actual knowledge flows

³ The patent database begins in 1963, but the citation information does not begin until 1975, and the number of patents from inventors in Korea and Taiwan is very small before the mid-1970s. For these reasons, our analysis focuses on 1977–1999.

between inventors. They find that citations are a noisy indicator of knowledge flow, in the sense that knowledge flow is much more likely to have occurred where a citation is made; but many citations also occur in the absence of any knowledge flow.

Table 1 presents statistics of patent counts and citation counts of the U.S., Japan, Korea, and Taiwan. Table 1 shows the aggregate number of patents, the distribution of patents over the six categories defined by Jaffe and Trajtenberg, and

Table 1
Basic patent statistics

		1985		1998		Average over all years	
		Patents	Cites	Patents	Cites	Patents	Cites
(1)	US: all classes	39,556	5.7	80,291	0.4	47,252	4.0
	Chemical	21%	5.4	14%	0.2	9591	3.7
	Computers and communications	8%	9.1	20%	0.8	4190	5.8
	Drugs and medical	7%	10.3	15%	0.3	3286	6.4
	Electrical and electronic	17%	5.5	15%	0.3	7785	3.7
	Mechanical	22%	4.2	15%	0.3	10,624	3.2
	Other	26%	5.2	20%	0.3	11,776	3.8
(2)	Japan: all classes	12,746	3.1	30,840	0.1	10,843	2.1
	Chemical	20%	3.3	15%	0.1	2142	2.2
	Computers and communications	13%	4.5	26%	0.2	1811	2.7
	Drugs and medical	4%	3.7	5%	0.1	493	2.6
	Electrical and electronic	20%	3.4	23%	0.2	2339	2.1
	Mechanical	28%	2.2	21%	0.1	2731	1.6
	Other	14%	3.1	10%	0.1	1327	2.1
(3)	Korea: all classes	41	3.5	3259	0.2	342	0.9
	Chemical	17%	2.1	11%	0.1	55	0.5
	Computers and communications	10%	2.3	28%	0.2	162	1.0
	Drugs and medical	5%	1.5	2%	0.2	15	1.3
	Electrical and electronic	5%	2.5	35%	0.2	190	1.0
	Mechanical	22%	2.7	14%	0.1	61	0.7
	Other	41%	5.2	11%	0.1	47	1.1
	Receptacles	12%		0.50%			
	Apparel and textile	10%		2%			
(4)	Taiwan: all classes	174	3.0	3100	0.2	679	1.5
	Chemical	7%	2.7	8%	0.1	52	1.1
	Computers and communications	3%	3.3	10%	0.3	51	1.9
	Drugs and medical	2%	2.5	2%	0.1	21	1.9
	Electrical and electronic	13%	3.4	34%	0.3	173	1.4
	Mechanical	22%	1.7	19%	0.2	156	1.4
	Other	52%	3.4	27%	0.2	239	1.6
	Furniture, house fixtures	11%		6%			
	Miscellaneous	20%		10%			

the average number of citations each patent received for the six technological categories in each of the four countries. In columns (1) to (4), we report these statistics for 1985 and 1998. The year 1985 was chosen because this was the year when Korea and Taiwan began to have a balanced portfolio of patents. The averages of the statistics over all years are reported in the last two columns.

The first thing to note about Table 1 is that although the absolute numbers of patents are still only fractions of those of the U.S. and Japan, Korea and Taiwan are catching up very rapidly. In 1985, for example, Taiwan was granted 174 patents, or 0.4% of the U.S. total and 1.4% of the Japanese total. Thirteen years later, Taiwanese inventors claimed 3100 patents, a 17-fold increase and equivalent to 4 and 10% of the U.S. and Japanese totals, respectively. During the same period, Korea managed to increase its patent count from 41 to 3259, an almost 80-fold increase.

Secondly, Table 1 suggests that even with the much larger number of patents they are now receiving, the patent portfolios of Taiwan and Korea are specialized in terms of technological field. The U.S. and Japan innovate in many technological areas, due to their size and comprehensive technological capabilities. On the other hand, the distributions of Korean and Taiwanese patents are more concentrated in certain areas and have changed considerably over the years. In 1998, 35% of Korean patents and 34% of Taiwanese patents belong to the Electrical and Electronic category. The same fraction is 15 and 21% for the U.S. and Japan, respectively. Indeed, the two categories of Electrical and Electronic and Computers and Communications together account for 63% of all Korean patents granted in the U.S. in 1998.⁴

As a more systematic measure of the concentration of patenting in these countries across technological fields, we calculate the Herfindahl–Hirschman Index (HHI) of patent concentration across the approximately 400 three-digit patent classes, for each of the four economies. As shown by Hall et al. (2001), the HHI measure is biased upward when the number of patents on which it is based is small. Essentially, if there is a modest “true” probability of a random patent being in one of many classes, the true concentration may be low; if very few patents are actually observed, they can only be in a few classes, and the measured concentration will be high. Assuming the unobserved distribution across classes is multinomial, and the observed draws from that distribution are independent, Hall, Jaffe, and Trajtenberg show that an unbiased measure of the true concentration is given by

⁴ For Korea and especially Taiwan, unlike the U.S. and Japan, the “other” category captures an extremely large fraction of patents. In Table 1, we report the two largest sectors within the “other” category. For Korea these are Receptacles and Apparel and Textile. In the Taiwanese case, the “miscellaneous” group accounts for as much as 20% of the patents Taiwan received in 1985 and 10% in 1998. The second largest group in the “other” category for Taiwan is Furniture and House Fixtures.

$$\hat{H} = \frac{N \cdot HHI - 1}{N - 1},$$

where \hat{H} is the bias-adjusted Herfindahl measure, N is the number of patents, and HHI is the traditional Herfindahl, calculated as the sum of squared shares across patent classes. As N grows large, \hat{H} converges to the traditional measure, but for small N the adjustment can be quite large. For example, if there are eight patents spread evenly across four classes, the HHI is 0.25, but \hat{H} is about 0.14. If there were only four patents spread across four classes, the HHI would still be 0.25, but \hat{H} is actually zero.

Fig. 1 presents the bias-adjusted Herfindahl across patent classes over time for each country.⁵ It shows the technological concentration of Taiwan as similar to that of Japan up until the mid-1990s, after which there is evidence of a significant upward trend. This is at least partly associated with the increasing focus on electronics patents that is visible in Table 1. The technological concentration of Korea varies much more from year to year, but appears to be rising over time. In the 1980s, it was comparable to that of Japan, but by the mid-1990s was about twice as high. As discussed below in connection with Fig. 3, rising technological concentration in the 1990s in Korea was accompanied by a similar rise in concentration across patent assignees. Large Korean business groups, or Chaebols, associated with Samsung, Hyundai, and Goldstar made major investments in penetrating specific high-tech industries, and this seems to be reflected in the concentration of patenting in these entities and the sectors they targeted.

The trends in overall technological concentration for Korea and Taiwan mask to some extent significant shifts that have occurred with respect to *which* areas are most important. The share of Electrical and Electronic patents in total Korean patents increased from 5% in 1985 to 35% in 1998, whereas the share of All Other patents declined from 41 to 11% during the same period. The fraction of Electrical and Electronic patents increased from 13 to 34% for Taiwan, with the decline again occurring in the All Other category. Besides the size difference between the northern and the southern economies, and the fact that Korea and Taiwan have been fast developing, we suspect the uneven patent portfolios of Korea and Taiwan may also have to do with the industry policy of the two economies, which is characterized by targeting, or preferential policies to promote certain industries (Amsden, 1989; Dollar and Sokoloff, 1994).

Lastly, we compare the technological significance of the four economies' patents using the average number of citations a patent receives as an indicator of the patent's quality. Given the strong evidence of the geographical localization of patent citation (Jaffe et al., 1993), the average cites we report in Table 1 are based

⁵ The unadjusted HHI is much higher for Korea, and to a lesser extent Japan, in the early years when their patent totals were relatively low.

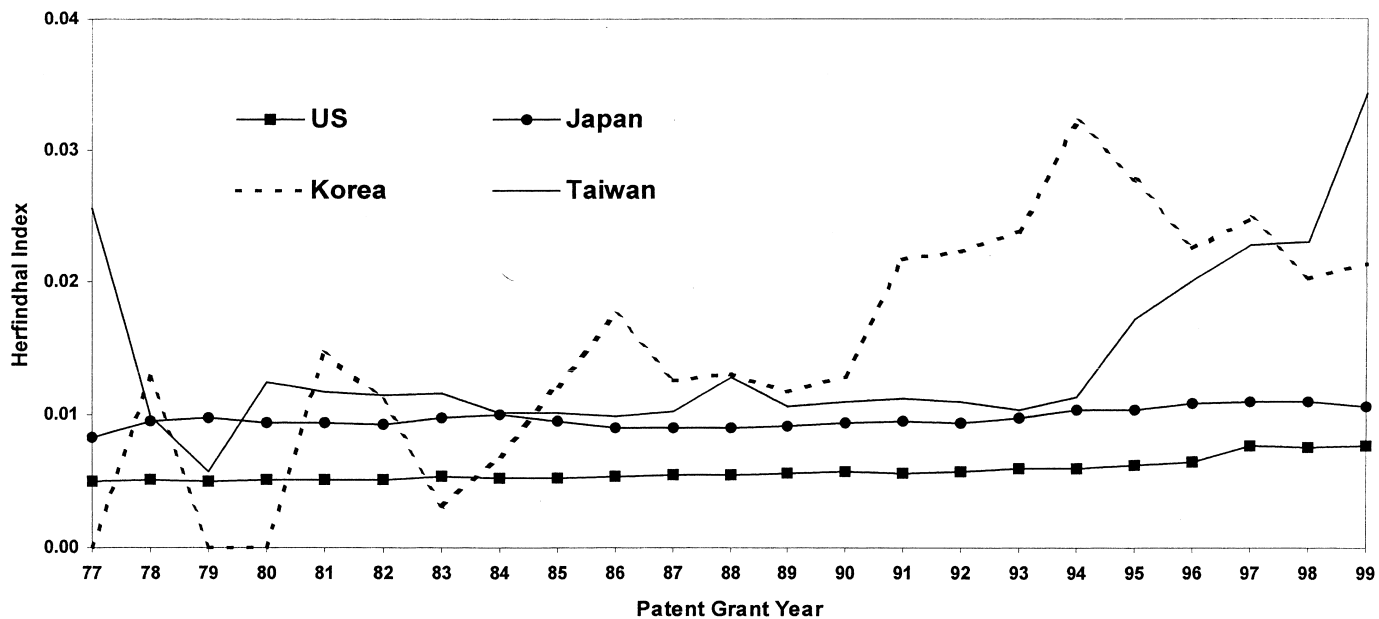


Fig. 1. Herfindahl index of patent concentration across patent classes (bias-adjusted).

on citations made by U.S. patents only. In looking at citations from the U.S. to patents of Japan, Korea, and Taiwan, the phenomenon of geographical localization is held constant, permitting comparisons of citation rates for these three recipient countries.

The average citations per patent over all years suggests that Japanese patents are technologically more significant than Korean and Taiwanese patents. However, this comparison is potentially misleading, because it does not control for the age distribution of the patent portfolios. Japan has many more older patents, which are more highly cited simply because they have been around longer, while Korea and Taiwan have patent portfolios weighted towards younger patents that are less highly cited. It is more appropriate to compare citation intensities for patents from the same cohort. Although the average of 3.54 cites a 1985 Korean patent receives is largely driven by patents in the other categories, Korean and Taiwanese patents receive at least as many citations as Japanese patents in the Mechanical and the Electrical and Electronic categories respectively in 1985. At the end of the data period, no patents have received very many citations because very little time has passed in which to observe them, but limited information suggests rough parity between Korea and Japan, and Taiwanese patents are actually more highly cited in all categories than those of Japan.

3. Korea and Taiwan: from imitators to innovators

We will not elaborate on the economic success that Korea and Taiwan have achieved in the second half of the twentieth century. It has been documented and debated extensively elsewhere (World Bank, 1993; Krugman, 1994). Our focus is the role of knowledge diffusion from the U.S. and Japan in the technological progress that Korea and Taiwan have obtained. With successful export-oriented development strategies and interventionist governments, both Korea and Taiwan have worked hard to move up the international technology ladder. In this process many Korean and Taiwanese companies have graduated from imitators of Western technology to genuine innovators (Kim, 1997). The electronic industry, where, for example, Korea's Samsung and Taiwan's Acer are already world players, is often cited to attest to the success story.

We plot the number of patents per 100,000 people for the U.S., Japan, Korea, Taiwan, and Israel from 1977 to 1999 in Fig. 2 to provide some further comparison. The performance of Korea and Taiwan has been very impressive. Korea started from a low base—0.02 in 1977—but managed to increase it to 7.57 in 1999. The number of patents for every 100,000 Taiwanese increased from 0.31 to 16.78 from 1977 to 1999. During the same period, Israel, another newly industrializing economy with a cutting-edge high-tech sector (Trajtenberg, 2001), increased the number of patents for every 100,000 Israelis from 2.57 to 12.94. In 1994 Taiwan surpassed Israel for the first time on this measure of innovation

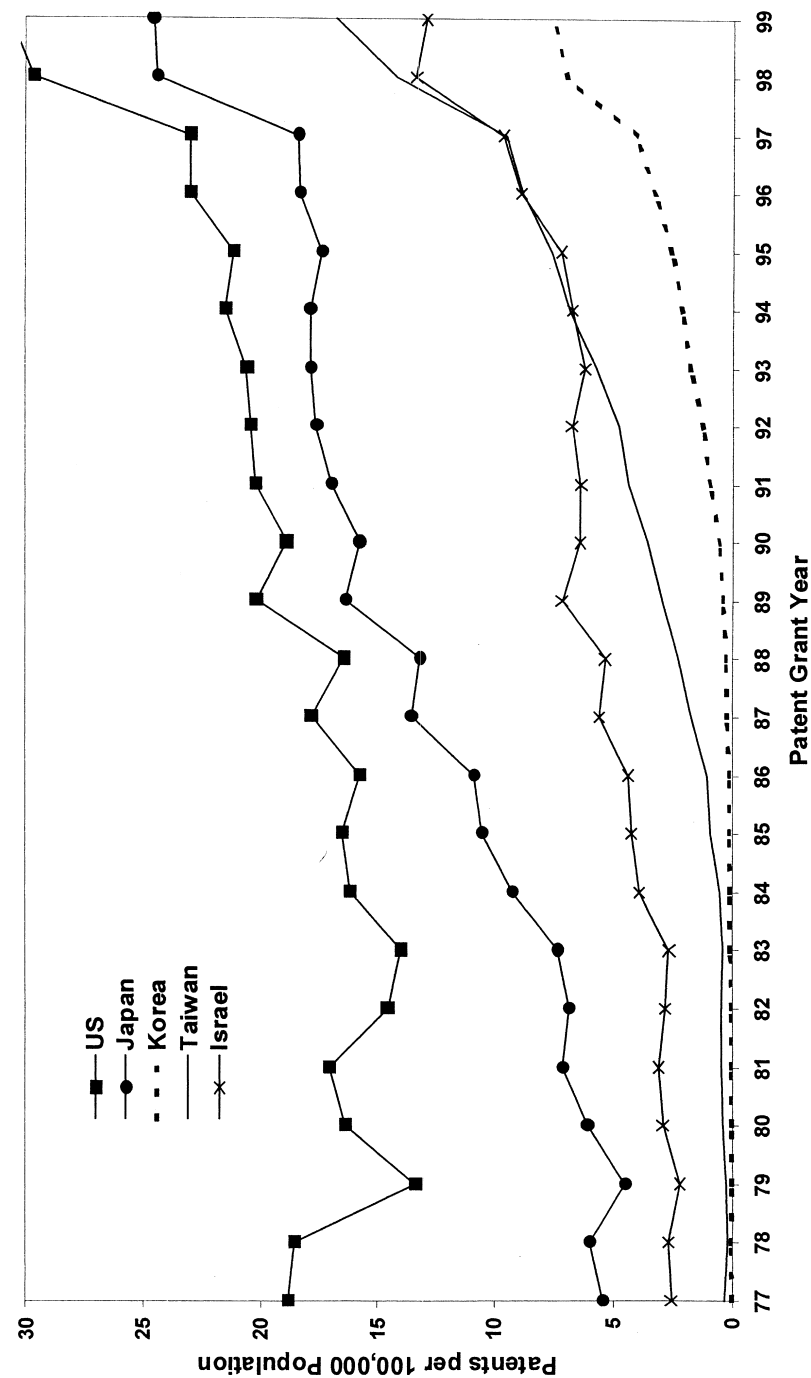


Fig. 2. Patents per capita.

output. Impressive as their performance has been, Korea and Taiwan are still minor players in the world innovation scene, at least in terms of the number of patents. Fig. 2 indicates that the dominance of the U.S. and Japan shows no sign of shrinking. Nonetheless, Korea and Taiwan have come a long way in catching up with other world innovators.⁶

Korea's and Taiwan's success is due to both their expanding indigenous technological capability and their relentless effort to acquire technology from the West. The two endeavors are complementary to each other and reinforce each other, as an economy's ability to absorb new technology or knowledge depends on its indigenous R&D capability (Cohen and Levinthal, 1989). New knowledge absorbed in turn broadens and deepens an economy's technological base, leading to opportunities of further indigenous innovation. Table 2 compares R&D intensity as measured by the ratio of R&D expenditure to GDP for the U.S., Japan, Korea, and Taiwan. In about two decades, R&D expenditure increased from 0.6% of GDP to 2.9 and 2.1% in Korea and Taiwan, respectively. In fact, the 1998 R&D–GDP ratio of Korea exceeded those of Germany (2.3%), France (2.2%), and Great Britain (1.83%), and was similar to those of the U.S. and Japan.

Technology diffusion and knowledge flow from developed economies, particularly Japan and the U.S., have played an important role in the success of Korea

Table 2
Research and development intensity in the U.S., Japan, Korea, and Taiwan

	R&D as a share of GDP (%)					
	1978	1982	1988	1990	1995	1998
U.S.	2.2	2.5	2.7	2.7	2.6	2.8
Japan	1.8	2.2	2.7	3	2.7	3
Korea	0.6	1	1.9	1.9	2.7	2.9
Taiwan	0.6	0.9	1.3	1.7	1.8	2.1

Source: OECD Basic Science and Technology Statistics, 1999; U.S. NSF website (www.nsf.gov); National Statistical Office of Korea website (www.nso.go.kr); and National Science Council of Taiwan website (www.nsc.gov.tw).

⁶ Another indication of the innovativeness of Korea and Taiwan is their effort to venture into new technological areas. Between 1996 and 1999, the U.S.PTO created a number of new patent classes in response to increasing patent applications in relatively new technological areas. Manuel Trajtenberg has suggested, but never implemented, testing the proximity of a country to the world technology frontier by examining the fraction of patents that are in newly created classes. Applying this test to Korea and Taiwan produces startling results. In 1999, approximately 19% of patents granted to both Korea and Taiwan were in classes new since 1996, compared to 15% for Japan and only 12% for the U.S. The significance of this comparison is greatly mitigated, however, by detailed examination of the classes involved. Many of these patents are in a single class, Semiconductor Device Manufacturing Process (84% of “new-class” patents for Taiwan and 43% for Korea). The heavy patenting by Korea and Taiwan in this category is not surprising given the success of their semiconductor industry. While this is an important “high-tech” industry, it is not clear that it is particularly indicative of truly cutting-edge technology.

and Taiwan. Hobday (1995) identified several mechanisms through which Korea and Taiwan have acquired foreign technology. These include foreign direct investment (FDI), joint ventures, licensing, original equipment manufacture (OEM), and capital goods import. Korea and Taiwan have much in common in their relationships with Japan and the U.S. Both Korea and Taiwan were colonized in the first half of the twentieth century by Japan. Both received substantial aid from the U.S. after the Second World War. Both have made the U.S. their major export market. However, there are major differences between their economies as well.

In venturing into new industries and technologies, Korea has relied on big business groups, the Chaebols, which bear much resemblance to their Japanese antecedent, the Zaibatsu. Taiwan has seen a large number of small and medium enterprises playing an active role. In Fig. 3 we plot the Herfindahl index of patent concentration across patent assignees for the four economies.⁷ Korea's high concentration of patent assignees certainly reflects the role of big business groups in the country's economic life. In fact, the degree of concentration increased steadily from the late 1980s to early 1990s and has been rising again since 1997, despite efforts by the Korean government to reduce the role of the large Chaebols. The degree of concentration of inventors in Taiwan is lower than that in Korea, but it has also been rising and is still much higher than the concentration in the U.S. and Japan. The U.S., having the most liberal and dynamic innovation system in the world, not surprisingly has the most diversified population of inventors.

The two often-cited channels of technology transfer and diffusion, FDI and capital goods import, have also played different roles in the two economies. As Hobday observed, Korea has shown a greater reliance on Japan for capital goods import than Taiwan. This is no historical accident. The Korean government undertook a restrictive policy towards FDI after the 1970s, which led to a limited role of FDI in Korea's economic development. Instead, "Korea promoted technology transfer in the early years through the procurement of turnkey plants and capital goods" (Kim, 1997, p. 42). In Table 3 we present statistics on FDI and capital goods import for Korea and FDI for Taiwan. Japan clearly dominates the U.S. in Korea's capital goods import, consistently accounting for between 40 and 50% of Korea's enormous capital goods import. In a study of intra-industry trade between Japan and Korea in the machinery industry, Tahara-Domoto and Kohama (1989, p. 18) reported that "at the beginning of the 1980s, Korean government worried about the heavy dependency on the machinery parts imported from Japan. In spite of the increasing trend of local content ratio, more than 90% of the parts imported from foreign countries for various electronics products was from Japan."

⁷ Again, these numbers have been corrected for the bias due to low patent counts in the early years. The patent "assignee" is the legal entity to which the property right is assigned. To the extent that members of the Chaebol accept patent assignments as distinct entities, our measure of concentration arguably understates the true concentration by treating these affiliated but distinct entities as separate.

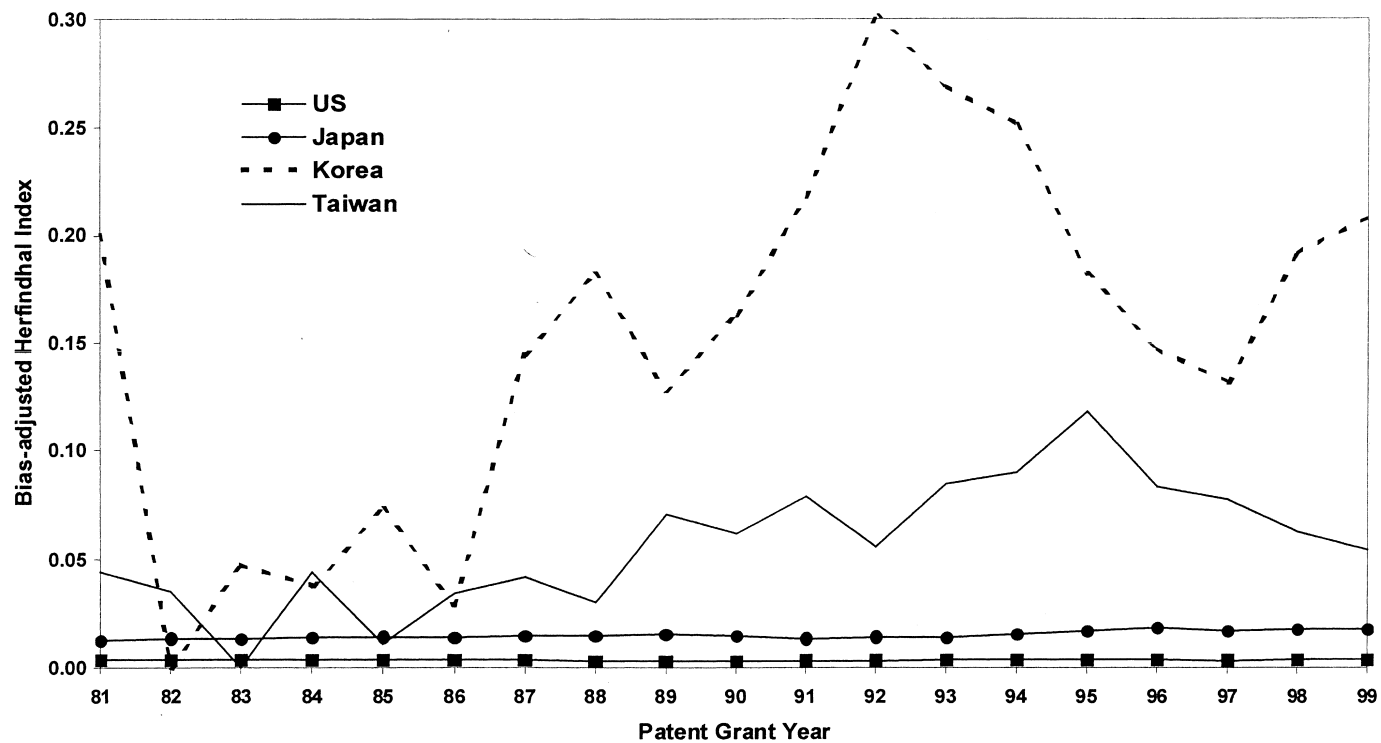


Fig. 3. Herfindahl index of patent concentration across assignees (bias-adjusted).

Table 3
FDI and capital goods import in Korea and Taiwan (million U.S. dollars)

	1972–1976	1977–1981	1982–1986	1987–1994
<i>Korea</i>				
FDI				
Japan	71%	42%	50%	34%
U.S.	15%	33%	33%	28%
Total	879.4	720.6	1767.70	8891.2
Capital goods import				
Japan	50%	51%	41%	43%
U.S.	22%	22%	24%	28%
Total	8841	27,978	50,978	188,104 ^a
<i>Taiwan</i>				
FDI				
Japan	21%	27%	33%	33%
U.S.	38%	48%	34%	23%
Total	598.7 ^b	1013.1	2580.9	11,929

Source: The Korean data are from Kim (1997, pp. 40–41). The Taiwanese FDI data are from Ministry of Economic Affairs (1996).

^a The Korean capital goods import is for the period “1987–1993”.

^b The Taiwanese FDI data is for the period 1971–1975 (Chou, 1988).

The Taiwanese government’s more liberal policy towards FDI led to a larger role of FDI in Taiwan than in Korea. The U.S. and Japan account for the majority of foreign direct investment in Korea and in Taiwan. In the early 1970s, as Table 3 shows, 71% of Korea’s FDI was from Japan and only 15% was from the U.S. In Taiwan, on the other hand, 38% was from the U.S. and 21% was from Japan. This pattern remained in the late 1970s and early 1980s. Since then, Japan has become the largest investor in both economies. Taiwan’s connection to the U.S. semiconductor industry through Taiwanese engineers working in the U.S. played an important role in the development of the electronics industry in Taiwan (Mathews, 1995; Saxenian, 2000). According to Mathews and Cho (2000), Taiwan’s strategy of developing the semiconductor industry was largely the brainchild of a group of Taiwanese engineers working in the U.S. semiconductor industry. And the whole industry started off with the licensing of an IC fabrication technology from the U.S. semiconductor firm RCA in 1976.

In sum, Korea and Taiwan are graduating from imitation to genuine technological innovation and are fast catching up with advanced economies. However, the technological gap remains. The U.S. and Japan have maintained a close economic association with Korea and Taiwan through investment and trade. To the extent that FDI and trade are potential facilitators of knowledge diffusion, the economic connections between the U.S./Japan and Korea/Taiwan are likely to have an impact on the patterns of knowledge diffusion.

4. Patent citation, technology proximity, and knowledge diffusion

The validity of using patent citations as an indicator of knowledge flow has been extensively discussed elsewhere (Jaffe et al., 1993, 2000). Not all inventions are patented; not all knowledge flows are captured by citations; at best, citations capture only codifiable knowledge and cannot capture transfers of tacit knowledge. As a result, patent citation is a coarse and noisy measure of knowledge flow. It does, however, contain much useful information that provides insight into how knowledge may diffuse across geographical and technological regions as well as over time.

An additional limitation of our analysis is that we have information only on patents granted by the U.S. patent office, and on citations to patents granted by the U.S. patent office. We limit the bias this may introduce by comparing only *relative* rates of citations made by non-U.S. inventors, thus eliminating any “home bias” in citations made by U.S. inventors to U.S. inventors. Of course, if there are systematic differences between the patenting or citation practices of Korean and Taiwanese inventors, these could be a potential source of bias. We believe, however, that any such bias is unlikely to have a significant impact on the interpretation of our results. First, the patent office examiner makes the final decisions on what citations to include, so purely frivolous or personal motivations for citation are unlikely to have a significant impact. Second, if there are systematic tendencies in a given country to make citations to another country, these are likely to reflect patterns of contact and communication between the countries. Such communication is precisely the phenomenon for which we are using citations as a proxy, so its affect on citation rates should not be considered a bias.

Fig. 4 presents a rough picture of how patent citation has evolved for Korea and Taiwan. We observe the following stylized facts. First, the U.S. and Japan appear to be the major source of international knowledge flow to Korea and Taiwan. The share of citations made by Korean and Taiwanese patents to their U.S. and Japanese counterparts consistently accounts for over 70% of all citations they make. Second, both Korean and Taiwanese inventors have made more citations to U.S. patents than to Japanese patents. Third, there seems to be a trend for the shares of citations to U.S. and Japanese patents to converge, particularly for Korea from the mid-1980s to 1997. Fourth, Fig. 4 also seems to suggest that Korea makes a larger fraction of citations to Japanese patents than Taiwan, whereas Taiwanese inventors cite relatively more U.S. patents.

Stylized fact one suggests that the U.S. and Japan are the major sources of knowledge flow for Korea and Taiwan. Indeed, this is part of the reason we choose to focus on the U.S. and Japan as originators of external knowledge that Korea and Taiwan draw upon. It is also consistent with the close economic association of Korea and Taiwan with the U.S. and Japan, which we discussed in the previous section. It is tempting to interpret stylized facts two to four as indicating different

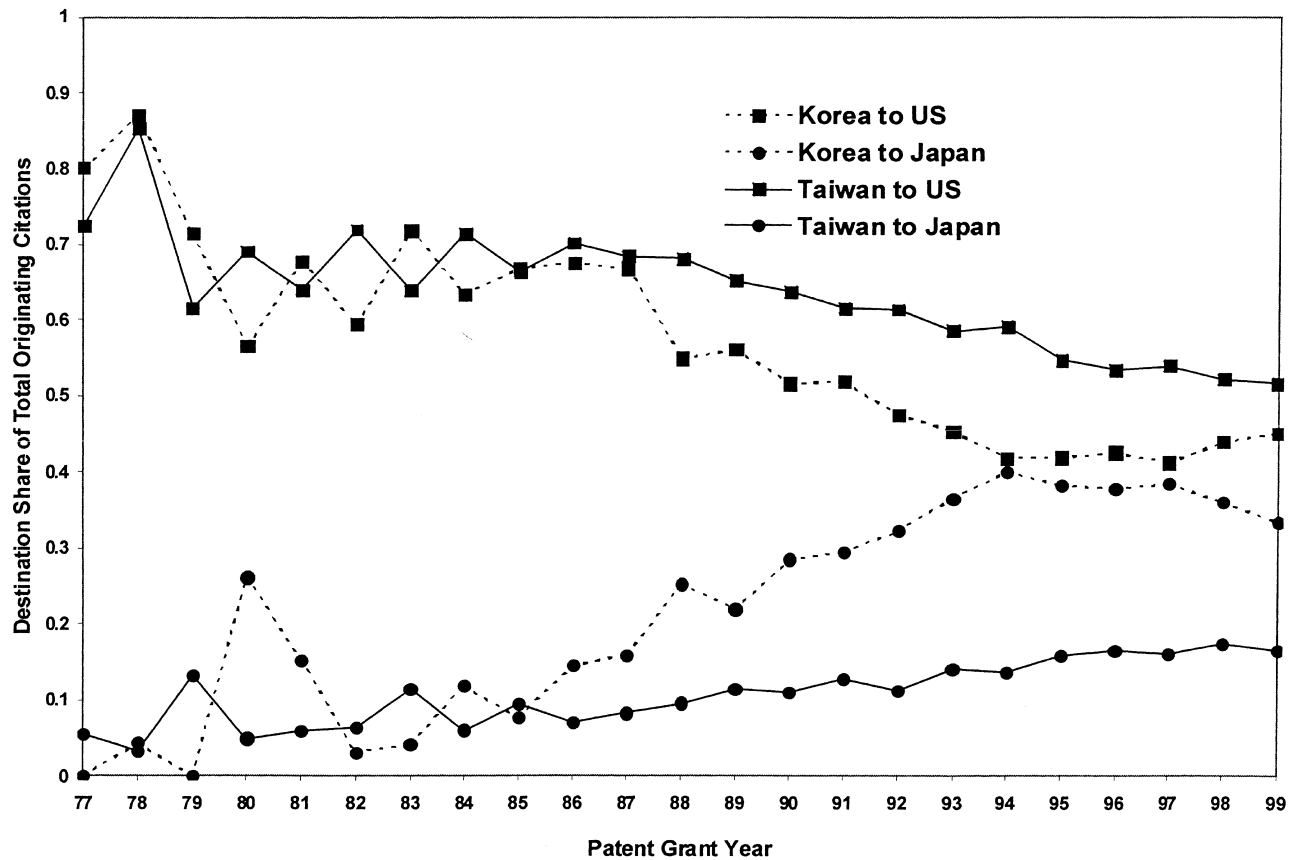


Fig. 4. Japan and U.S. shares of citations made by Korea and Taiwan.

patterns of knowledge diffusion from the U.S. and Japan to Korea and Taiwan. As we will see, interesting as they are, some of these stylized facts may be artifacts that result from the fact that the raw share of total citations fails to account for certain factors that can potentially distort the picture.

4.1. Citation frequency and knowledge flow

One problem with the share of citations measure is that it does not account for the change in the absolute number of the potentially citable patents in the source economy. The number of patents (taken out in the U.S.) by U.S. inventors is larger than the number taken out by Japanese inventors, although the Japanese total has been rising much more rapidly. This makes it more likely, all else equal, for *any patent* to cite U.S. patents than to cite Japanese patents, with this difference declining over time. To the extent that the relative patenting rates of the two countries reflect their relative rates of knowledge creation, the tendency for more citations to the country that produces more patents could be an accurate reflection of the relative contribution of the U.S. and Japan to knowledge flows. It is likely, however, that the “propensity to patent in the U.S.” is different for the two countries, and has been changing over time. To the extent this is the case, both the greater rates of citation of U.S. patents relative to Japan, and the decline in that difference over time, are likely to be artifacts of differential patent propensities, rather than reflections of differences in knowledge flow. For this reason, we develop measures of citation intensity that control for differences in the rate of patenting by the source country.

To remove the effects of the patenting rate of the source country, we interpret the intensity of knowledge flow as the likelihood that any given inventor in a recipient country will cite any given invention created in a potential source country. This intensity measure does not necessarily capture the overall magnitude of knowledge flow; it is better interpreted as the strength of the communication pathway from the cited country to the citing country. To estimate the likelihood or frequency of citation from Korea and Taiwan to the U.S. and Japan, we adopt a slight modification of the citation frequency measure defined in Jaffe and Trajtenberg (1999):

$$CF_{i-j,t} = \frac{NC_{i-j,t}}{NP_{i,t}NP_{j,t}^D}, \quad (1)$$

where $CF_{i-j,t}$ denotes the frequency of country i 's patents that are granted in year t citing all potentially citable patents taken out by country j up to t . The numerator of the right-hand side of (1), $NC_{i-j,t}$, represents the total number of citations made by i 's patents granted in year t to j 's patents. The denominator is the product of the number of i 's patents in year t ($NP_{i,t}$) and the number of *potentially citable* patents in country j as of year t . The number of citations and the number of citing

patents are given in the data. It is not immediately clear how the number of potentially citable patents should be constructed. This is the number of patents in the cited country j , which can be cited by an inventor in country i as of year t . Since the knowledge embodied in patents becomes obsolete, the total stock of patents of country j up to year t would not be a proxy for this variable. Instead of trying to construct some kind of measure of an effective pool of patents of the cited country, we propose the following *relative* citation frequency measure:

$$RCF_{k-i-j,t} = \left(\frac{NC_{k-j,t}}{NC_{i-j,t}} \right) \left(\frac{NP_{i,t}}{NP_{k,t}} \right), \quad (2)$$

where $RCF_{k-i-j,t}$ is the ratio of the frequency of country k citing country j to that of i citing j in year t . Eq. (2) says that, for example, the relative frequency of Korean (k) and Japanese (i) inventors citing a U.S. (j) patent is equal to the ratio of the number of citations Koreans make to U.S. patents in year t over the number of Korean patents in year t , multiplied by the inverse of this same ratio for Japan. By looking at the Korean citation frequency to the U.S. *relative* to that of Japan, we remove effects due to the number of U.S. patents available to be cited.

The relative citation frequency measure in Eq. (2) is particularly helpful in assessing the fourth stylized fact we identified above, i.e., is it more likely for Korean (Taiwanese) inventors to cite Japanese (U.S.) patents than Taiwanese (Korean) inventors? In Fig. 5 we plot four series: Korean citations to the U.S. relative to Japanese citations to the U.S. (RCF_{KUJ}), Taiwanese citations to the U.S. relative to Japanese citations to the U.S. (RCF_{TUJ}), Korean citations to Japan relative to U.S. citations to Japan (RCF_{KJU}), and Taiwanese citations to Japan relative to U.S. citations to Japan (RCF_{TJU}). These ratios are fairly volatile early in the period, probably due to the relatively small number of citing patents in Korea and Taiwan, but they settle into a reasonably stable pattern in the mid-1980s. For both Korea and Taiwan, the rate of citation to the U.S. is similar to that of Japan, i.e., the relative citation frequency is approximately unity, with perhaps some weak evidence of a higher rate for Taiwan in the 1990s. In contrast, citations from these countries to Japan are at different rates than citations to Japan from the U.S. Korea cites Japan at close to twice the rate that the U.S. does, while Taiwan cites Japan at a rate approximately one-half to two-thirds the U.S. rate.

4.2. Technology proximity and knowledge flow

One factor that may account for the observed patterns of citation from the U.S. and Japan to Korea and Taiwan is the degree of closeness or similarity between countries in technological space. In other words, if both Japan and Korea do disproportionately more R&D and therefore patent more intensively in electronics than Taiwan and the U.S., then we would expect Korean inventors to cite Japanese patents more often than Koreans cite U.S. patents, and more often than Taiwanese

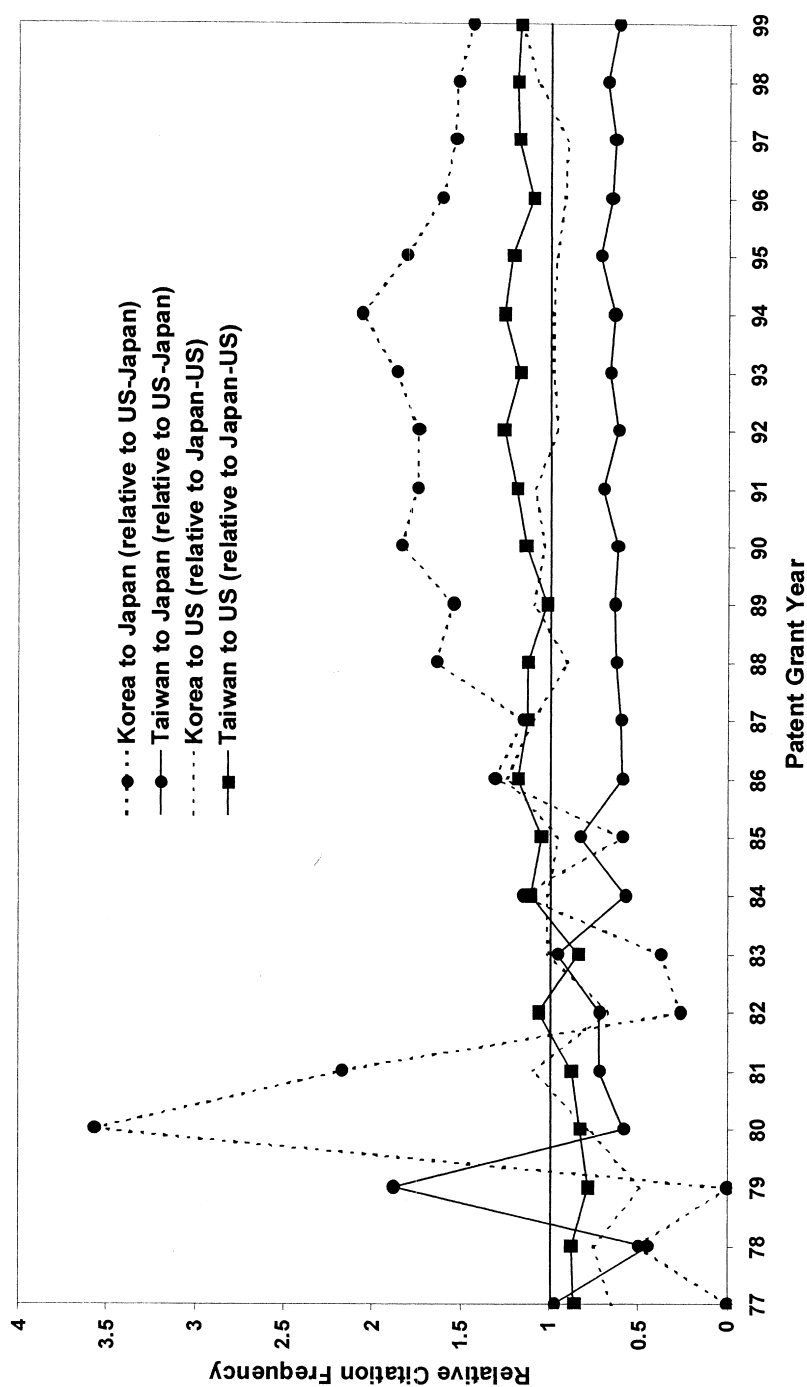


Fig. 5. Relative citation frequency.

patents cite Japanese patents. The technology space is multi-dimensional, with each dimension defined by a unique technological area. We use the patent technological class information to construct a measure of the closeness between two countries in the technology space.

The U.S.PTO assigns each granted patent into one of the 400+ three-digit patent technological classes. Each class represents a unique technological area. The distribution of a country's patents can be thought of as a 400-element vector, with each element being the number of patents assigned to a specific patent technology class. These 400 patent classes span the technology space. We can then compute the closeness between two countries in the technological space as the distance between the two vectors of patent distribution. Following Jaffe (1986) and Jaffe and Trajtenberg (1999), we use the following variable to measure the technological proximity of two countries in a given year:

$$Tprox_{i,j,t} = \sum_{n=1}^{400} f_{n,i,t} f_{n,j,t}, \quad (3)$$

where technology proximity between countries i and j in year t , $Tprox_{i,j,t}$, is the sum of the product of $f_{n,i,t}$, the share of country i 's patents in year t allocated to patent class n , and $f_{n,j,t}$, the counterpart for country j . The greater the extent to which the two patent distribution vectors overlap, the bigger the technology proximity between the two countries. When the two vectors are orthogonal, $Tprox$ will be zero. It will be at its maximum when the two vectors are identical.

In Fig. 6, we plot the technology proximities Korea–U.S., Korea–Japan, Taiwan–U.S. and Taiwan–Japan. The most striking contrast is between the Korea–Japan technology proximity and the Taiwan–Japan technology proximity. Korea is much closer to Japan in the technology class distribution of patents than Taiwan is to Japan. This difference increased from the mid-1980s to 1996, and has since shrunk slightly as Taiwan and Japan have moved slightly closer to each other. On the other hand, although Korea resembles the U.S. more than Taiwan does, the difference is not large and has been stable. Comparing Figs. 5 and 6 we can see that the technology proximity differences vis-à-vis Japan seems quite consistent, with the observation that the citation frequency from Korea to Japan is higher than that of Taiwan to Japan. The small and stable difference between the Korea–U.S. and Taiwan–U.S. technology proximities also corresponds to the difference between Taiwanese and Korean citation rates to the U.S. (relative to the Japanese rates) in Fig. 5.

Thus, at a descriptive level, we observe a pattern of significant citation of Japanese and U.S. inventions by Korean and Taiwanese patents, with differences that appear to have some connection to patterns of technological proximity. We now move on to an econometric estimation of a model of the citation process that incorporates the effects of technological proximity, and allows more explicitly for the gradual diffusion and obsolescence of knowledge over time.

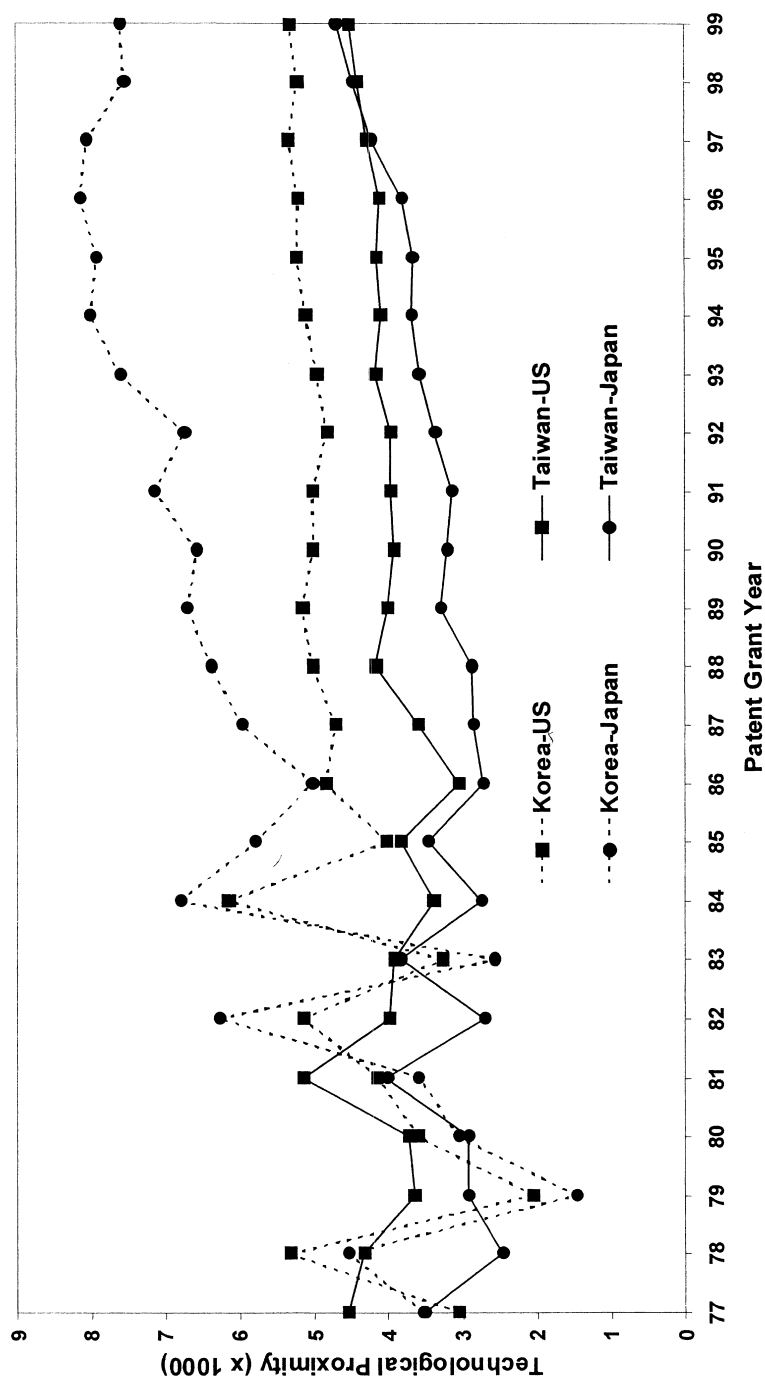


Fig. 6. Technological proximities.

5. A model for knowledge diffusion

We have examined citation frequency at the country level. The basic unit of analysis is, for example, the frequency with which Korean patents granted in 1990 cite all U.S. patents. This formulation subsumes within the overall average frequency of citations the time path over which knowledge transfer occurs. On the one hand, knowledge becomes obsolete and therefore a given invention is less likely to be cited as it ages. On the other hand, due to language, geographical, trade, and other barriers, the accessibility of a new invention increases as that invention ages. The two effects offset each other. To account for these factors, we move the unit of our analysis to a more specific level and specify the following citation frequency equation as in Jaffe and Trajtenberg (1999):

$$CF_{iT,jt,g} = (1 + \gamma Tprox_{iT,jt,g}) \alpha(i,j,g,T) e^{(-\beta_1 ij(T-t))} [1 - e^{(-\beta_2 (T-t))}] + \varepsilon_{iT,jt,g}, \quad (4)$$

where $CF_{iT,jt,g}$ is the frequency of country i 's patents in year T citing country j 's patents in technology area g in year t .⁸ $Tprox$ is the technology proximity index measuring the technological closeness of the citing country i 's patents in year T and the cited country j 's patents in year t in one of the six technology subclasses, g .⁹ The rate at which a piece of knowledge embodied in a patent becomes obsolete is measured by β_1 , which is allowed to vary across country pairs. β_2 measures the rate of diffusion, i.e., all else equal, how fast a piece of knowledge travels across geographical and technological areas. The various indices take on the following values: i =Korea, Taiwan, U.S., Japan; j =U.S., Japan; T =1977, ..., 1999; t =1963, ..., 1998; g =1, ..., 6. For citing countries, we include the U.S. and Japan for comparison with earlier studies, although our main interest focuses on the citing behavior of Korea and Taiwan.

In addition to the above three basic parameters, we also examine how the citation frequency differs across technological and geographical areas, and time by including a number of shift parameters, which are collectively denoted by $\alpha(i,j)$:

$$\alpha(i,j,g,T) = \alpha_{ij} \alpha_g \alpha_T, \quad (5)$$

where all α 's enter in multiplicative form.¹⁰ For example, for α_{ij} , there are eight parameters for the eight country pair combinations: U.S.–U.S., U.S.–JP, JP–U.S., JP–JP, KR–U.S., KR–JP, TW–U.S., and TW–JP. When Eq. (4) is estimated, one

⁸We report results in which patents are dated by the year in which the patents were granted. We have also estimated Eq. (4) with all patents dated by year of application. Except for the coefficients on the year effects themselves, the results are qualitatively the same.

⁹Jaffe and Trajtenberg (1999) derive Eq. (4) from an underlying model in which a single patent cites other patents with a probability that is increased by γ if the patents are in the same class.

¹⁰There are six α_g 's, one for each technological area, and 23 α_T 's, one for each T .

of the parameters, say $\alpha_{\text{U.S.}-\text{U.S.}}$, is set to one as the reference case. If $\alpha_{\text{KR}-\text{U.S.}}$ is estimated to be 0.5, it means a Korean patent is only half as likely to cite a U.S. patent as a U.S. patent is to cite a U.S. patent. We also allow the rate of decay, β_1 , to differ across country pairs by including β_{ij} , which is similar to α_{ij} by construction.

As we mentioned before, the relative citation frequency patterns we observe in Fig. 5 are cumulative in the sense that the citation frequency has been aggregated over all the lags between t and T , to use the notation in Eq. (4). The parameters α_{ij} and β_{ij} help us to decompose this aggregate difference into two components: on average how much more likely it is for, say, Korea to cite the U.S. relative to the U.S. citing the U.S., and how much faster (slower) Korea cites the U.S. than the U.S. cites the U.S. α_{ij} and β_{ij} have offsetting effects on the cumulative citation frequency: higher α means a higher probability of citation across all lags, while higher β_1 means the rate of citation decays more quickly, which (holding other parameters constant) reduces the cumulative total made by any given lag.

6. Results

The model in Eq. (4) is estimated with weighted nonlinear least square (NLS). As long as the error term ε is not correlated with any of the regressors in (4), the NLS estimation should yield consistent estimates. We weight each of the observations to account for potential heteroskedasticity with the reciprocal of $(NP_{jtg}NP_{iT})^{1/2}$, where NP_{jtg} is the number of potentially citable patents and NP_{iT} is the number of potential citing patents in the cell defined by j , t , g , i , and T .

Results from estimating various variations of the model are presented in Table 4. Column (3) represents the “full” model as presented in Eq. (4). Column (1) constrains the obsolescence effects to be the same for all country pairs. Column (2) suppresses the technological proximity effect. Column (4) explores whether, given the rapid changes in apparent citing behavior visible in Figs. 4 and 5, there are measurable differences in citation rates from Korea and Japan after 1990, controlling for other effects.

All parameters estimated are highly statistically significant, far above conventional confidence levels. The adjusted R^2 of the model, ranging from 0.46 for the bare-bones version to 0.80 for the full model, suggests that the model fits the data reasonably well. The technology proximity parameter is very significant, both economically and statistically. The coefficient from the full model indicates that, all else equal, citations to patents in the same patent class as the citing patent are over 500 times as likely as citations to patents in other classes. This is approximately five times larger than the proximity effect Jaffe and Trajtenberg (1999) estimated. It is unclear why we get this larger technological proximity effect. It appears to be due partly to the fact that we are using data through 1999,

Table 4
Diffusion function estimation

	(1)	(2)	(3)	(4)
$\gamma(Tprox)$	577.76* (34.97)		576.30* (31.70)	580.05* (32.01)
$\alpha_{JP-U.S.}$	0.40* (0.004)	0.46* (0.01)	0.48* (0.01)	0.48* (0.01)
$\alpha_{KR-U.S.}$ (pre-1990)	0.39* (0.01)	0.49* (0.03)	0.57* (0.02)	0.56* (0.04)
$\alpha_{KR-U.S.}$ (post-1990)				0.57* (0.02)
$\alpha_{TW-U.S.}$ (pre-1990)	0.42* (0.01)	0.37* (0.02)	0.52* (0.02)	0.51* (0.03)
$\alpha_{TW-U.S.}$ (post-1990)				0.52* -0.02
$\alpha_{U.S.-JP}$	0.47* (0.004)	0.44* (0.01)	0.43* (0.01)	0.43* (0.01)
α_{JP-JP}	0.88* (0.01)	2.56* (0.03)	1.64* (0.02)	1.64* (0.02)
α_{KR-JP} (pre-1990)	0.49* (0.01)	1.34* (0.05)	0.86* (0.02)	0.93* (0.05)
α_{KR-JP} (post-1990)				0.86* (0.02)
α_{TW-JP} (pre-1990)	0.38* (0.01)	0.35* (0.03)	0.48* (0.03)	0.53* (0.05)
α_{TW-JP} (post-1990)				0.47* (0.03)
$\beta_{1,JP-U.S.}$		1.09* (0.01)	1.13* (0.01)	1.13* (0.01)
$\beta_{1,KR-U.S.}$		1.21* (0.04)	1.30* (0.03)	1.30* (0.03)
$\beta_{1,TW-U.S.}$		1.08* (0.04)	1.16* (0.03)	1.16* (0.03)
$\beta_{1,U.S.-JP}$		0.93* (0.01)	0.93* (0.01)	0.93* (0.01)
$\beta_{1,JP-JP}$		1.55* (0.01)	1.55* (0.01)	1.55* (0.01)
$\beta_{1,KR-JP}$		1.45* (0.03)	1.48* (0.03)	1.48* (0.03)
$\beta_{1,TW-JP}$		1.15* (0.06)	1.18* (0.05)	1.18* (0.05)
β_1	0.23* (0.001)	0.20* (0.001)	0.20* (0.001)	0.20* (0.001)
β_2	1.19E-6* (5.70E-08)	3.39E-6* (7.60E-08)	9.83E-7* (4.30E-08)	9.78E-7* (4.30E-08)
No. of obs.	27,600	27,600	27,600	27,600
Adjusted R^2	0.77	0.74	0.80	0.80

whereas the previous work had used data only through 1994.¹¹ Part of the difference must, however, be attributed to differences in the citation behavior of these countries.

The α parameter for each country pair captures the overall average rate of citation, relative to citations by U.S. patents to U.S. patents, which is normalized to unity. Consistent with the previously noted finding of geographic localization, all of these are less than unity, except for Japan–Japan, which indicates extreme localization of Japanese citations, consistent with previous findings. The effects of greatest interest for this group of parameters are the estimates for Korea–U.S., Korea–Japan, Taiwan–U.S., and Taiwan–Japan. The striking result is that Korea cites Japan at a rate 86% of the base U.S.–U.S. rate, while all of the other estimates are in the 50–60% range. What this says is that, on average, Korea is almost as close to Japan as the U.S. is to itself. This is higher than any other cross-border rate found previously; it suggests, for example, that Korea is closer to Japan in this sense than the U.K. is to the U.S. (estimated at 0.72 in Jaffe and Trajtenberg, 1999). In contrast, the rates for Korea citing the U.S. and for Taiwan citing both Japan and the U.S. are slightly lower than most of the pairwise estimates for G-5 countries found by Jaffe and Trajtenberg. Overall, then, Taiwan draws on Japan and the U.S., and Korea draws on the U.S. at rates consistent with their being slightly more remote in terms of knowledge flows than G-5 countries are from each other.

While these α coefficients shift the rate of citation at all lags, the β_1 parameters capture the speed with which citations decay. The estimated base value for β_1 (again, corresponding to citations from the U.S. to the U.S.) is about 0.2, implying a modal lag of about five years—i.e., on average, the peak of the citation frequency occurs about five years after a patent is granted. This value is similar to that found by Jaffe and Trajtenberg. The estimates for each country pair indicate the decay rate relative to this base, with an estimated value greater than unity implying faster decay. Interestingly, all of the Korea and Taiwan estimates are greater than 1, implying a focus on more recent inventions, compared to citations made by U.S. inventors. This is particularly true for Korea, whose values of 1.30 (for citations to the U.S.) and 1.48 (for citations to Japan) exceed the estimate for Japan citing the U.S. and approach the estimate of 1.55 for Japan citing itself. Thus Taiwan and, particularly, Korea appear to behave in a manner similar to Japan, focusing more narrowly on recently developed technology to an extent significantly greater than is the case in the other G-5 countries. This is particularly interesting, given that it might have been supposed that Korea and Taiwan are “catching up,” potentially adapting and building on older technology than would

¹¹ Patent examination appears to have become less thorough in recent years, which could lead to a reduction in “harder to find” citations outside of the applying patent’s class. See Hall, Jaffe and Trajtenberg (2001). When we confine our estimation to pre-1994 citations, the proximity effect is reduced somewhat, but is still much larger than in previous work.

be of interest to more technologically advanced economies. The age of their citations is not, however, supportive of such a view of the nature of their innovation.

Comparison of columns (2) and (3) shows that there is some degree of interaction between the technological proximity effects and the estimated citation parameters. In particular, the estimated α for Korea citing Japan is increased significantly if the technological proximity effect is suppressed (1.34 in column (2) as compared to 0.86 in column (3)). In effect, part of the high rate of citation can be attributed to the close technological proximity of the two countries, visible in Fig. 6. Once this effect is controlled for, the “pure” citation frequency is not estimated to be as high. Other contrasts between columns (2) and (3) are not as easy to relate to the contrasts in Fig. 6. This could be because there is variation in the proximities between countries at the lower level of aggregation used in the estimation, and also because all of the pairwise effects are changing simultaneously between columns (2) and (3), including those in the reference case of U.S.–U.S.

Comparison of columns (1) and (3) illustrates how overall citation rates are affected by both the multiplicative α effects and the obsolescence effect captured by β_1 . When β_1 is allowed to vary, Japan–Japan and Korea–Japan evidence high rates of obsolescence, which reduce the predicted number of citations at later lags. If this variation in obsolescence rates is suppressed as in column (1), the model attempts to fit the lower citation rates at high lags by reducing the *overall* citation intensity parameterized by α . Thus, the α effects for Japan–Japan, Korea–Japan, and Korea–U.S. are reduced in column (1). Allowing both the α and the β_1 parameters to vary in column (3) allows the model to fit both the higher overall citation intensity and the higher obsolescence of these pairs.

Finally, Column (4) was motivated by differences in citation patterns from Korea and Taiwan in the latter part of the time period that appears in Figs. 1, 3, 4, and 5. We allowed both the α and the β_1 parameters to differ in value for citations made before and after 1990. As can be seen, however, there are no large differences in these parameters. This means that the changes visible in the figures were not associated with changes in the underlying citation rate, after controlling for other factors such as technological proximity.

Using the estimated coefficients in column (3) of Table 4, we calculated simulated citation distributions. These simulated frequencies are driven by the estimated the α and β_1 parameters, as well as the technological proximities between countries. In Fig. 7 the estimated frequencies of Japanese, Korean, and Taiwanese patents citing U.S. patents are plotted, as a function of time elapsed after initial patent grant. The rising and then falling citation probability is the combination of the diffusion and obsolescence effects estimated in the model. The combination of similar α and higher β_1 for Korea is visible in that the simulated citation frequency is initially higher and then lower for Korea as compared to Taiwan. Overall, the pattern of citation of these three countries to the U.S. is

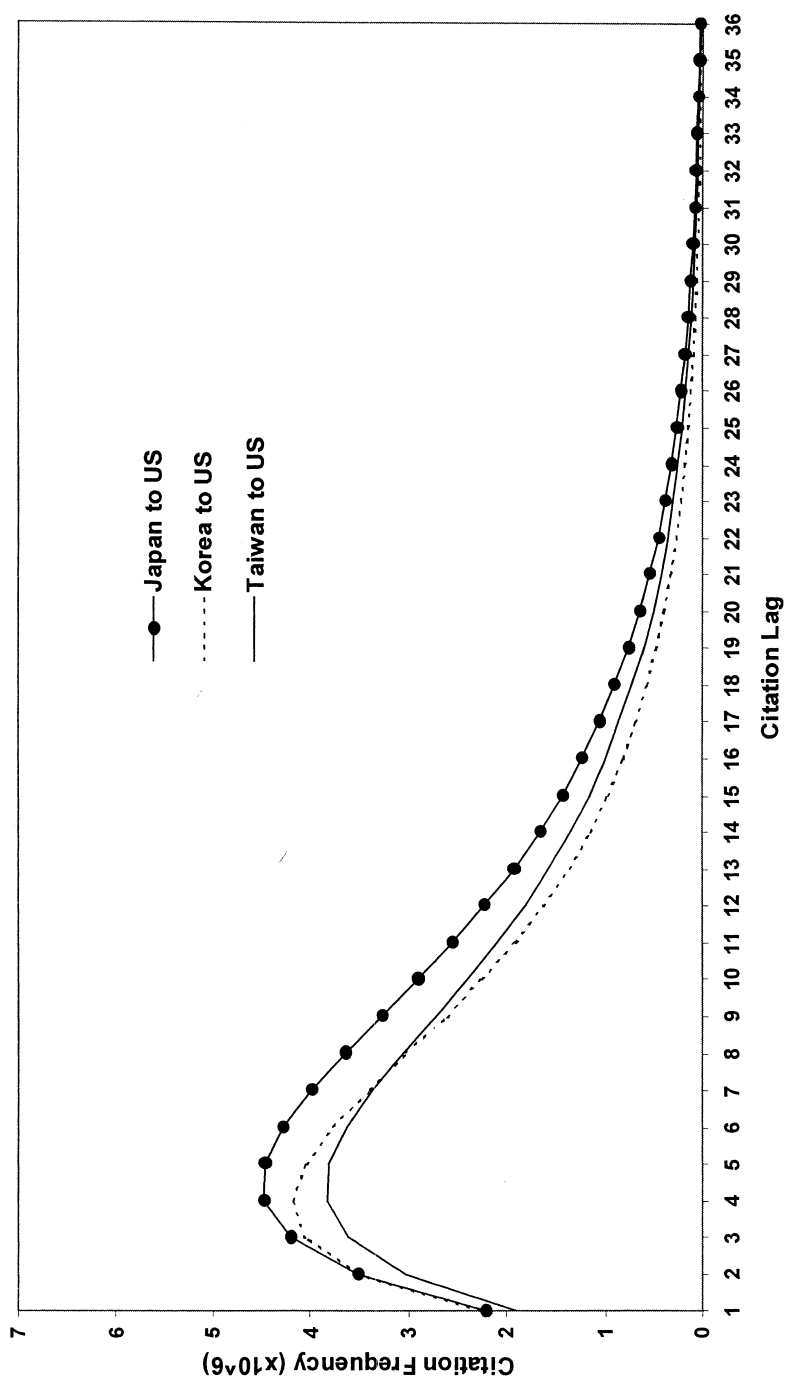


Fig. 7. Simulated frequency of citation to U.S.

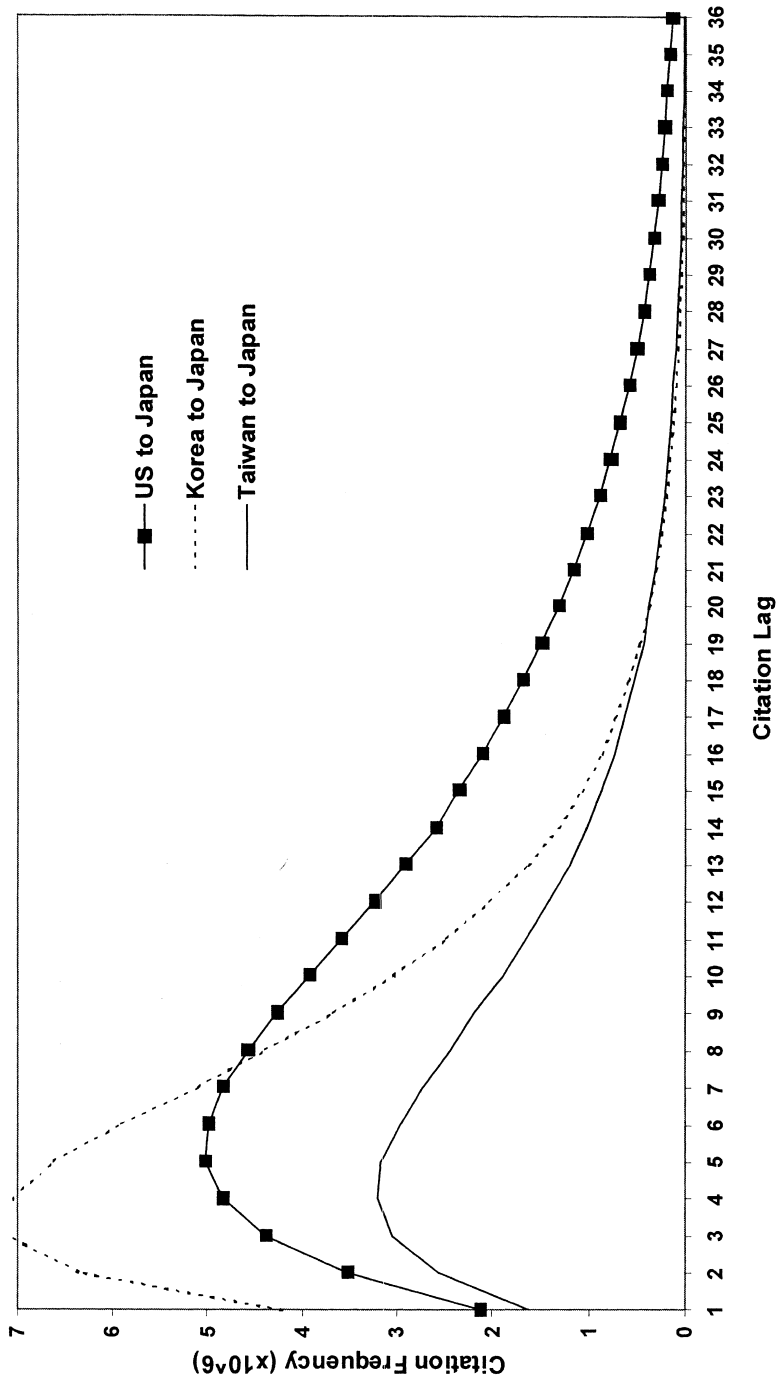


Fig. 8. Simulated frequency of citation to Japan.

similar, showing again the surprising extent to which Korea and Taiwan behave like Japan with respect to citation of U.S. patents.

The much more intensive knowledge flow from Japan to Korea than to Taiwan is dramatically displayed in Fig. 8, where the estimated frequencies of Korean, Taiwanese, and U.S. patents citing Japanese patents are plotted. Not only do Korean patents cite Japanese patents much more intensively than do Taiwanese patents, but the Korean citations also occur faster than Taiwanese ones. A year after a Japanese patent is granted, the likelihood that a Korean patent cites it is over two times greater than the likelihood that it is cited by a Taiwanese patent. The peak frequency of the Korean citations is more than two times as large as that of the Taiwanese citations. The modal lag for the Korean citation frequency distribution is four years, whereas the Taiwanese modal lag is six years.

7. Conclusions

Korea and Taiwan are graduating from imitation to innovation. The number of patents granted in the U.S. to these two economies has been growing rapidly. On per capita patent count terms, Korea and Taiwan are catching up with the lower-tier developed economies. Anecdotal evidence suggests that knowledge diffusion from the advanced economies, particularly the U.S. and Japan, played an important role in this catching up process. We used patent citation as an indicator of knowledge diffusion to investigate the pattern and intensity of knowledge flow from the U.S. and Japan to Korea and Taiwan. With a knowledge diffusion model that explicitly takes into account the role of technology proximity and knowledge decay and knowledge diffusion over time, we analyzed several stylized patterns that are derived from simple citation statistics.

We found interesting differences between the citation practices of Korea and Taiwan. Korea is much closer to Japan than it is to the U.S., whereas Taiwan draws on both Japan and the U.S. with similar frequency. Further, the frequency of citation of Taiwan to the U.S. and Japan (after controlling for other effects) is similar to the frequency of citation of Korea to the U.S., making the high frequency of citation of Korea to Japan the “outlier” among these four country pairs. This high-citation dependence of Korea on Japan is partly due to their technological proximity. Even after controlling for technological proximity, however, the dependence of Korea on Japanese technology is higher than has been found among any of the G-5 countries.

Our model estimation implies that patents in the same three-digit patent class are about 500 times more likely to cite other patents in the same class than patents in other classes. This technological proximity effect is five times larger than had been found in previous studies using citations data. We have tried to explore the source of this difference, within the limitations of our data. As noted above, a small part of the difference is due to our inclusion of more recent citations. But the

rest of the difference has to be due to differences in the citations of these countries, or differences in the technology fields in which these countries patent.

It is possible that patents from Korea and Taiwan are more prone to citations within patent classes, which would be consistent with their representing more incremental and less “basic” inventions than those of the G-5 (Hall et al., 2001). But it is also possible that part of what we are picking up as the technological proximity effect reflects closeness among these countries along *other* dimensions; i.e., the technological proximity variable is “picking up” the effects that we are trying to capture in the α_{ij} parameters. Because technological proximity does not vary much for a given country pair, it is difficult to identify econometrically variations that may exist across countries in the magnitude of the technological proximity effect. Thus, without expanding the study to many more country pairs in order to allow the technological proximity parameter to vary across countries, it is not possible to know for sure whether these countries are “truly” more inclined to citations within patent classes, or whether our estimate is contaminated by other effects.¹² This is a topic for future research.

The patterns of knowledge flow that we have identified seem to be consistent with the anecdotal evidence various authors have provided that Japan and the U.S. have played an important role in the economic development of Korea and Taiwan through investment and trade. Korea maintains a very close link to Japan economically and technologically, and the export-oriented development model that Korea has followed closely mirrors the earlier path followed by Japan (Petri, 1988). Our data show that Japan is a more important source of foreign direct investment and capital goods for Korea than is the U.S. The fact that there is a higher incidence of Taiwan citing U.S. patents than Japanese patents is also consistent with the argument that foreign direct investment from the U.S. and linkage of Taiwanese firms to U.S. firms through returning students and Taiwanese expatriates working in the U.S. play an important role in Taiwan’s technological progress, particularly in the electronics industry. Therefore, our study points to the potential linkage between international knowledge flow and foreign direct investment and trade in capital goods.

The other strong finding is that Korea and, to a lesser extent, Taiwan exhibit rapid obsolescence, implying focus on relatively recent inventions and neglect of older technology in their citation patterns. This is somewhat surprising given their presumed distance from the world technology frontier. In this behavior they resemble Japan; indeed, they are more like Japan in this respect than are other G-5 countries. This apparent focus on “rapid” adaptation of recent technology would be a fruitful area for future research.

¹²If one believes that our estimate of the technological proximity effect is implausibly large, this implies that our estimate of the likelihood of citation among these countries *controlling for technological proximity* is biased downwards, because the technological proximity effect is accounting for too much of the empirically large citation frequency.

Our analysis of patent citation data has yielded several interesting patterns of knowledge diffusion from the U.S. and Japan to Korea and Taiwan. Although knowledge has the property of being non-rival and non-exclusive, it follows different paths in diffusing across countries. Many authors have proposed various channels through which knowledge diffusion may be facilitated, such as foreign direct investment, international trade, scholarly exchange, exchange of personnel, so on and so forth. Therefore, an interesting research avenue we would like to pursue is whether and to what extent these channels may facilitate knowledge diffusion from world innovators to developing countries. This line of research is likely to generate interesting policy implications, particularly for developing countries.

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