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by

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Department of Economics
SCAPE Working Paper Series
Paper No. 2008/02 - March 2008
http://nt2.fas.nus.edu.sg/ecs/pub/wp-scape/0802.pdf

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January 13, 2008

Abstract

East Asia is emerging as a hub of technological innovation. This paper investigates the extent to which East Asia has become a source of international knowledge diffusion and whether such diffusion is localized to the region. Using citations made by U.S. Patent and Trademark Office (USPTO) granted patents to other USPTO patents as an indicator of knowledge flow and estimating a model of international knowledge diffusion, I find strong evidence corroborating the hypothesis of increasing regionalization of knowledge flow in East Asia. Korea and Taiwan, the region's leading innovators, cite each other at least as frequently as they cite the US and Japan. Such knowledge flow has substantially intensified since the mid 1990s. With the exception of Thailand, all of the East Asian economies that I examine, Hong Kong, Singapore, China, and Malaysia, cite Korea and Taiwan at least as frequently as they cite the US and Japan. The "G5" group, which includes Britain, Canada, France, Germany and Italy, has been the least often cited source of knowledge for East Asia.

*I thank Milan Brahmbhatt for helpful comments and advice. I also thank Lim Kwanghui for providing the 2003-04 data from the NUS Patent database that he maintained and Li Jia for superb research assistance in downloading and processing the raw inventor data from the USPTO web site. Financial support from the NUS Academic Research Fund (R-122-000-091-112) is gratefully acknowledged. All remaining errors are my own.

1 Introduction

Technological progress in East Asia in the past decades can perhaps be best characterized as from "imitation to innovation"(Kim, 1997). Leading the pack are Korea and Taiwan, who have joined the ranks of world class innovators and have built a robust national innovation system (Kim and Nelson, eds, 2000). The rest of the Asian tigers, Hong Kong and Singapore, particularly the latter, have also become regional hubs of R&D excellence. The rest of East Asia are still at a stage of imitation, although some of them, especially China, are fast catching up. The dynamism of technological change in East Asia, which ultimately sets the pace of economic growth and development, raises the question of why do some countries rise rapidly up the technology ladder while others are still struggling from behind? This paper focuses on a piece of the puzzle and investigates the intensity and determinants of knowledge flow within East Asia and beyond.

The idea that economically backward countries can expect to catch up with leading countries by exploiting the technology gap goes back to at least Gerschenkron (1962). It is more cost effective to absorb and utilize existing advanced technologies than reinventing the wheel. As a country learns, absorbs, and imitates, it moves closer to the world frontier and as it does so, the "easy" gains from imitation dwindle and the need to innovate becomes paramount. However, as Cohen and Levin (1989) argued and showed, learning and innovating are not mutually exclusive, but rather complement each other. In the process of learning and imitating, a country gradually adds to its base of knowledge and experience, which determines its innovative capability. Innovation on the other hand generates knowledge that enables the innovator to absorb more effectively knowledge and knowhow in the public domain. Learning and knowledge diffusion is therefore a critical element of economic development.

International knowledge diffusion is subject to barriers of geography, language, and culture.[1] Jaffe et al. (1993) found that knowledge spillover, measured by patent citations, tended to be localized in the US. Jaffe and Trajtenberg (1998) reported evidence that inventors from the US and Britain cited each other more frequently than those from

[1] See Keller (2004) for a comprehensive survey

other G5 countries, suggesting that language might be a factor in limiting the scope of international knowledge diffusion. Hu and Jaffe (2003) studied patent citations made by Korean and Taiwanese inventors up to 1999. They found that Korea received more knowledge diffusion from Japan than did Taiwan, whereas Taiwan cited relatively more frequently the US than Korea did. This seems to be consistent with the cultural and historical linkages among these economies.

The East Asian economies that I examine in this study are linked together geographically and culturally. Some of them, such as China, Taiwan, Hong Kong and to a certain extent, Singapore, share the same language. The East Asian economies are also closely integrated through trade and investment. Hong Kong and Taiwan have traditionally been the main sources of China's foreign direct investment. Manufacturing industries, particularly the electronics and the machinery industries are tightly integrated in the region. As Korea and Taiwan acquire the status of world class innovators, as Hong Kong and Singapore build on their R&D strength, and as China aspires to be at the world technology frontier, it is natural to expect increasing intensity of knowledge flow amongst the East Asian economies and there to arise a technology ecosystem in East Asia. The main objective of this study is to investigate the pattern and intensity of knowledge diffusion within East Asia and between it and the rest of the world.

The rest of the paper is organized as follows. Section 2 reviews the economics literature of studies that use patents and patent citations as indicators of technological innovation. It also sketches the basic dimensions of the U.S. Patent and Trademark Office(USPTO) patents and patent citation database used for this study. The following section then summarizes a number of stylized patterns of invention and knowledge flow in East Asia using the patents and patent citations data. Section 4 subjects to statistical test the hypothesis of regionalization of knowledge diffusion in East Asia by estimating a model of international knowledge diffusion. The last section concludes.

2 The literature and the data

2.1 Patents and patent citations as economic indicators

There is a long history of employing patents as economic indictors to study the rate and direction of technological change. The ground breaking work of Schmookler (1966) and Scherer (1965a,b) had shown both the enormous promise and the daunting challenge of making use of patent statistics. The shortcomings of patents as an indicator of inventive activity are well known. Not all inventions are patentable given the criteria of novelty, usefulness, and non-obviousness; not all patentable inventions are patented since the effectiveness of patents as a means to protect intellectual property relative to other instruments such as secrecy and lead time varies from industry to industry. The distributions of the economic value and the technological value of patents are highly skewed. All these issues are put on conspicuous display in the recent patent explosion and the controversy surrounding it, which have been thoroughly documented and analyzed in Jaffe and Lerner (2004).[2]

Nevertheless, patents provide an extraordinary and unique window to look into the black box of technological innovation notwithstanding all the noise and distortions. This is reflected in the voluminous economic studies that use patent statistics in various and different ways to obtain a better understanding of the role of technological change in economic growth and development. Griliches (1990) placed the research program of using patent statistics to study technological change in historical perspective and envisioned a rich and promising research agenda that is still being pursued by numerous economists.

Patent citations are another rich source of information that have been made widely available with the computerization of patent records. There is some parallel between patent citations and citations made by an academic article to other articles. It is in this sense that patent citations, particularly non-self citations, have been used as an indicator of knowledge flow. However, different from academic journal citations, patent citations serve an important legal function by delimiting the scope of the property rights awarded

[2] Patent explosion is not limited to the US. Hu and Jefferson (2005) investigated the causes of the recent patenting surge at China's patent office.

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. This makes patent citations perhaps less arbitrary than academic journal citations but also opens door to the possibility that citations may have been inserted by the patent examiner, and therefore may not track the flow of knowledge.

However, the usefulness of patent citations has been confirmed in a number of studies. Trajtenberg (1990) found a robust correlation between citation-weighted patent counts and consumer surplus from the invention and diffusion of computer tomography. In a direct attempt to address the issue of how noisy is patent citation as an indicator of knowledge flow, Jaffe et al. (2000) reported results from a survey of inventors who have cited other inventors in their patent applications. They found 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. In the paper that also serves as the documentation that accompanies the patents and patent citation database that they have constructed and made available to the public, Hall et al. (2001) delineate the conceptual, operational, and modeling issues that users of the data may come across.[3]

2.2 USPTO patents and patent citations data

The data set used in this study consists of all utility patents granted by the U.S. Patent and Trademark Office from 1963 to 2004. The nationality of a patent is determined by the country of residence of the first inventor at the time the patent application was filed. The data for 1963 to 1999 are from the NBER Patent Citations Database [4] (Hall, Jaffe and Trajtenberg, 2001), which has been updated by Bronwyn Hall to 2002.[5] The 2003-

[3]See also Jaffe and Trajtenberg (1998)
[4]http://www.nber.org/patent/
[5]http://emlab.berkeley.edu/users/bhhall/index.html

2004 patents and patent citation data are taken from the NUS Patent Database except the patent nationality variable, which I constructed using inventor data files downloaded from the USPTO website.The NUS Patent database does not contain the assignee code that is used in the NBER patent data. I matched the assignee names in the 2003/04 data with those in the NBER data up to 2002 in order to retrieve the assignee codes for 2003/04 patents.

An important variable from the patent database that I use is the technology class of a patent. The USPTO assigns all patents it grants to one of about 480 three-digit patent classes according to the technological areas of the patents. To obtain a broad overview of the technology field concentration of East Asian patents, I need a more aggregated technological classification system, which the USPTO's technology classification system does not provide. 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. The technology class information forms the basis of several variables I shall construct to differentiate technology opportunity across technological fields and locate a country's position in the technology space.

[Insert Figure 1 here]

3 Patenting and patent citing in East Asia

In 2003 the R&D to GDP ratio reached 2.45 and 2.63 percent respectively for Taiwan and Korea, far exceeding the European Union average of 1.83 percent and approaching the level of the US of 2.6 percent. Singapore's R&D expenditure as a percentage of GDP reached 2.25 percent in 2004. China had managed to double its R&D-GDP ratio from 0.65 percent in the mid 1990s to 1.3 percent in 2003. Clearly East Asia has shifted into high gear in technological innovation. Higher R&D expenditure has led to rapid increase in the number of USPTO patents awarded to inventors from East Asia.

3.1 East Asia's patenting performance

Taiwan overtook Italy in 1994 in the number of USPTO patent grants; Korea reached the same milestone in the following year. In the following decade, both Taiwan and Korea went on to surpass first Canada, then Britain, and finally France. By 2004, Taiwan and Korea had respectively become the fourth and fifth largest recipients of USPTO patents, after the US, Japan, and Germany.

Figure 1 plots the numbers of USPTO patents for the East Asian economies and for the US and Japan to provide a picture of world-wide trend. There seem to be three tiers of innovators in East Asia based on USPTO patent grants. Korea and Taiwan lead the pack, followed from a good distance by Singapore, China and Hong Kong in the middle, and Thailand and Malaysia at the bottom. China perhaps belongs to a different category from the city economies of Hong Kong and Singapore given its dynamic economy, sheer size, and R&D resources. Since this study is based on patents and patent citations alone, I will group it with Hong Kong and Singapore for ease of presentation.

While all East Asian economies have seen their patent grants increasing rapidly from the mid to late 1990s, Singapore seems to stand out. Its number of USPTO patents had quintupled from 88 in 1996 to 449 in 2004, breaking away from its arch-rival, Hong Kong, by a large margin. At least part of the difference seems to have to do with Singapore's insistence on keeping some manufacturing activity, which is dominated by electronics, in the country despite the outsourcing trend, whereas Hong Kong has seen most, if not all, of its manufacturing moving across the border to China. The welfare implication of these different economic development strategies is hard to ascertain.

[Insert Figures 2-4 here]

How good are East Asian patents?

The highly skewed distribution of patent values renders it difficult, if not impossible, to evaluate a country's technological innovation performance on the basis of raw patent counts. While East Asia has been catching up or even, in the cases of Korea and Taiwan, overtaking some of the world's leading innovators, does the "quality" of East Asian patents measure up to that of the latter? It is no small task to estimate the quality or economic and technological significance of a patent. However, in the same spirit that the influence of an academic article can be measured by the number of citations it receives, patent citation provides a potential metric to assess the quality of a patent.

Trajtenberg et al. (1997) proposed two intuitive measures of patent quality that can be computed with relative ease using patent citations data.

$$q_i = 1 - \sum_{j=1}^{n_i} S_{ij}^2 \tag{1}$$

q_i measures the "originality" ("generality") of patent i when S_{ij} is the share of backward (forward) citations, i.e., citations made (received) by patent i, which come from patent class j. The second term on the right hand side of (2) is the Herfindhal index (HHI) of citation distribution.[6] A patent is therefore considered more basic or fundamental if it cites patents from a wide range of patent classes, as it signals that the patent draws on prior art in different technological fields. Likewise, if a patent is subsequently cited by patents from a wide range of patent classes, it presumably has far reaching impact and is therefore deemed a general invention. Since one involves backward citations and the other forward citations, care needs to be taken in ensuring the comparability of patents given that patent citation data are truncated. Originality and generality scores can vary if patents under comparison have been granted in different years or belong to different patent classes without necessarily implying any underlying quality difference.

An additional note of caution is that in my study, some East Asian countries have very few patents if any in certain technology class. This means that there are few if any patent citations, made or received, to compute the originality and the generality. In such cases, the originality or generality measure obtained may be driven a few exceptional cases making it unrepresentative of the countries' intrinsic inventive capability. This is particularly true for Malaysia and Thailand. I will therefore focus my discussion on the quality comparison between Korean and Taiwanese patents and their U.S. and Japanese

[6]To account for the small sample bias of the conventional HHI, I use the adjusted Herfindhal index that Bronwyn Hall proposed to compute the generality/originality measure, i.e., $\frac{N^* HHI-1}{N-1}$.

counterparts.

[Insert Table 1 here]

THe originality scores for East Asian patents and their Japanese and U.S. counterparts are tabulated in Table 1. The originality of these countries' patents is compared across six technology categories and between two time periods: 1991-1995 and 2000 to 2004. This gives me 12 cohorts of patents.

In general the East Asian patents appear to be quite original compared with U.S. and Japanese patents, particularly with the latter. For the 1991-1995 cohort, the originality score of all East Asian chemical patents is higher than that of Japan. But the potential small sample bias is evident. Since the computation of originality uses backward citations, all else equal, younger cohort of patents are expected to have higher originality score as they have more patents to cite as compared with older patents. This is generally true with the patents of U.S., Japan, Korea, and Taiwan, and to some extent of Singapore as well. The pattern for the other East Asian economies is much less systematic. For example, Chinese patents have actually become less original, even in absolute terms, over the decade in five out of the six categories. Nor is it plausible that Malaysian chemical patents have been consistently the most original.

Nevertheless, concentrating on the latter period and Korea, Taiwan, Japan, and the U.S., we can still see some interesting patterns. Whereas the U.S. appears to be more original in every field than the other three, the gap between Japan and Korea and Taiwan is modest in a number of areas. Taiwan seems to be close to Japan in chemical, computers and communications, and mechanical patents; Korea, on the other hand, overtakes Japan in drugs and medical and mechanical, and closes in in computers and communications, and electrical and electronics. These seem to be consistent with general perceptions about the two East Asian economies' relative technological strength.

[Insert Table 2 here]

The effect of truncation on generality is the opposite from that in the case of originality. Since generality is based on forward citations, older patents have been around longer and therefore have accumulated more citations all else equal. This is true with all Japanese and U.S. patents as Table 2 shows. It is also true with Taiwanese patents and

Korea patents, except for the latter's drug patents. Again the U.S. has a clear lead in every category. But the gap between Korea and Taiwan with Japan is much smaller than their gap with the U.S. Focusing on the latter period, Korea and Taiwan are quite close to Japan in computers and communications. Korea is also close to Japan in electrical and electronics and even overtakes Japan in mechanical in terms of the generality of patents.

In the appendix, I include two tables that tabulate the average number of backward and forward citations respectively for the East Asian economies, Japan and the U.S. The patterns of the quality of patents revealed by the originality and generality scores are also confirmed by the citation count. One last note of caveat is that the lead of the U.S., as shown by the originality, generality, and citation count, may be overstated to the extent that both the citing and cited patents in my analysis are USPTO patents and that the USPTO patent examiners are more likely to insert citations to other USPTO patents than to patents granted by the foreign inventor's home patent office.

[Insert Figures 2-4 here]

Technology class concentration of patents

In which technology fields have the East Asian economies been innovating and taking out patents? Figures 2-4 plot, for East Asia and the US and Japan, the shares of patents coming from these six major technological categories.

Electrical and electronic and computers and communications are the two areas where most of the economies take out their patents. This is indicative of the abundant technology opportunity and the high propensity to patent in these two technological areas. Nonetheless, East Asian patents seem to have come disproportionately from these areas. For example, electrical and electronic patents account for 40 and 50 per cent of all Korean and Taiwanese patents respectively, and the share has been hovering around 50 percent for Singapore as well. These figures are much higher than the 30 percent for Japan and 20 percent for the US. Both China and Malaysia have also seen a surge of their patenting in the electrical and electronic field.

The focus of the East Asian economies on the electrical and electronic field is not a coincidence. The East Asian electronics industry is highly integrated with a high degree of specialization. Korea leads the world in DRAM technology and LCD manufacturing. This creates demand for semiconductor and other components from the region. Taiwan's wafer foundry industry is among the world's most sophisticated and generates demand for the testing and packaging services in other East Asian economies. Hu and Jefferson (2004)'s recount of the process of the recent rapid development of China's semiconductor industry shows a dominant role played by the investment and technology transfer from the Taiwanese semiconductor industry. One would naturally expect such close proximity in technology space driven in part by economic integration to ease and stimulate knowledge diffusion.

3.2 Proximity in technology space of East Asian economies

Technology opportunity constrains the scope of R&D of the regional economies and may have led to their specialization in a similar range of technological fields where there is a relative abundance of technology opportunity and therefore knowledge diffusion. For example, rapid advances in solid state physics and materials science engendered rapid development of the electronics industry, particularly the semiconductor industry. East Asia has seized upon the opportunity through the integration of the industry within the region and by investing in R&D in the electronics field. This suggests that the technology portfolio, or the position of a country in the technology space relative to others, can explain part of the regionalization of knowledge diffusion.

I use uncentered correlation between the technology class distributions of the patents of two East Asian economies to measure how close the two economies are in technology space.[7] An economy's relative position in the technology space reflects the constraints of technology opportunity and its R&D resource allocation. I define the technology space as a 428-dimension space corresponding to the 428 three-digit patent classes used by the USPTO. The innovation activity of each EA economy in each year is then projected to this technology space positioned by a 428-element vector with each element occupied by

[7] Jaffe (1986) used uncentered correlations as weights to construct a measure of knowledge pool that he found to be highly correlated with firm performance.

the share of USPTO patents the economy takes out in that year in the technology class concerned. Therefore the technology proximity between two economies, i and j, in year t, is defined as:

$$TP_{ijt} = \frac{V'_{it}V_{jt}}{\sqrt{V'_{it}V_{it}}\sqrt{V'_{jt}V_{jt}}} \tag{2}$$

where V_{it} is a 428-element vector of patent class shares of country i's USPTO patents granted in year t. TP is bounded between 0 and 1 and monotonically increasing in the similarity between two economies' patent portfolio, which I use to measure the technological proximity between the two economies.

Figure 5 depicts how close the East Asian economies are to US, Japan, and G5 in the technology space.[8] Overall East Asian economies have been moving closer to the US and Japan in the technology space. Korea is noticeably closer to Japan than to the us. Korea is also closer to Japan than the others in East Asia. G5 has been furthest away from East Asia, although the distance seems to have been shrinking somewhat in recent years.

[Insert Figure 5 here]

In Figure 6 I investigate how close to each other are the East Asian economies in technology space. First, with Korea as a reference point, both Taiwan and Singapore are very close to Korea; in fact they seem to be closer to Korea than Korea is to Japan. This reminds us of the prominence of the electronics industry in these economies and the close integration amongst these economies in that industry. Malaysia has moved much closer to Korea since the beginning of the millennium. Turning to the figure using Taiwan as the reference point, similar patterns emerge. Around 2001, Singapore is almost as close to Taiwan as the latter is to itself. Hu (2004) found that Charter Semiconductor, a semiconductor wafer foundry, contributed to the bulk of Singapore's USPTO patents. Taiwan's semiconductor industry leads the world in the wafer foundry sector. Therefore the similarity is not surprising. China and Hong Kong, on the other hand, seem to be closer to the US, Japan, and G5 than they are to Korea. Jaffe (1986) found evidence

[8] I group Britain, Canada, France, Germany and Italy into a single group and call it G5.

that American firms closer to each other in technology space are more likely to capture technology spillovers from each other. In the same spirit, the relative position of the East Asian economies in the technology space should influence the likelihood that they will learn from each other.

[Insert Figure 6 here]

3.3 Knowledge flow to and from East Asia

East Asia's success with bridging the gap of innovation with developed countries is in part built upon knowledge spillover and explicit and intentional technology transfer from the latter. Such knowledge diffusion has occurred through multiple channels such as international trade, foreign direct investment, and technology licensing. Hobday (1995) demonstrated how the production process in the electronics industry was fragmented and distributed amongst East Asian countries and how technology diffuses as the production processes in different countries are integrated through trade, investment and licensing. Mathews and Cho (2000) focused on the semiconductor industry in East Asia and painted a vivid picture of how East Asian countries joined the semiconductor value chain at points that are compatible with their comparative advantage and moved up the value chain in a process suffused with R&D and technology diffusion from the developed countries, particularly US and Japan.

Figures 7 to 9 plot the raw shares of citations made by East Asian inventors by the countries of the cited patents, i.e., US, Japan, East Asia excluding home country, home country (compatriot), G5, and rest of the world (ROW). All self-citations have been excluded, i.e., if the assignees of the citing patent and the cited one are the same, I do not consider the citation an incidence of knowledge diffusion. A similar figure is drawn for the US and Japan to provide a reference point.

The US clearly dominates as the primary source of knowledge diffusion for all countries and accounts for between 40 and 60 percent of total citations made by East Asian patents with the exception of Thailand, for whom the share of US citations was nearly 75% in 2004. This is not surprising given the extraordinary innovative capability of the US and the fact that I am using USPTO patents. There are two implications of the latter: there are more US patents due to the home bias; the patent examiners are more familiar with USPTO patents. Nevertheless, the relative importance of the US as a source of knowledge diffusion is declining in the cases of Korea and Japan and not increasing for the rest of the East Asian economies except for Thailand.

[Insert Figures 7-9 here]

While Japan had been filling the space left by the US particularly in the decade following the mid 1980s, what has been remarkable is the increasing importance of East Asia as a source of knowledge diffusion for countries in the region. This is most striking in the case of Taiwan, for whom East Asian citations (including compatriot citations) have far exceeded in importance G5 and ROW citations and approached Japanese citations. This is also true with Korea, although the magnitude is smaller. In Hong Kong, Singapore and China, East Asian citations have caught up with G5 citations by 2004. The patterns for Malaysia and Thailand are less clear.

When we distinguish compatriot citations from non-compatriot citations, a dichotomy jumps out. For Korea and particularly Taiwan, most of the East Asian citations have been made to compatriot patents. In sharp contrast, for all the other East Asian economies, non-compatriot East Asian citations dominate. This dichotomy shown in Figures 7 to 9 indicates that regionalization of knowledge flow is driven by both localization of knowledge flow and international knowledge diffusion, most likely from Korea and Taiwan to the rest of East Asia.

While raw citation shares are informative, we need to be careful in using them to draw reference about knowledge diffusion. As I demonstrate in the Appendix, raw citation share can be interpreted as the probability of country i citing country j conditional on the citing patent being from country i. The ratio of two raw citation shares can be decomposed into two parts:

$$\frac{CS_{ij}}{CS_{il}} = \frac{CF_{ij}}{CF_{il}}\frac{N_j}{N_l} \tag{3}$$

That is, the share of citations that country i makes to country j relative to that of the citations it makes to country l is determined by two factors, citation frequency and the overall level of patenting activity. The former, which I will discuss in detail in the next section, measures the probability of a patent from the citing country citing a patent from the cited country. In other words, the U.S. can be a more important source of knowledge diffusion to Singapore than Japan does, as measured by the left hand side of equation (3), because Singapore patents cite U.S. patents (CF_{SGUS}) more intensively than they cite Japanese patents (CF_{SGJP}) at the individual level, or there are more U.S. patents (N_{US})than there are Japanese patents to be cited (N_{JP}), or both. What I have discussed in this section is therefore a combination these two forces. The next section separates out the effect of citation frequency.

4 Estimating a model of international knowledge diffusion

4.1 The model

To investigate the intensity of knowledge flow in East Asia and beyond, I estimate the following double exponential knowledge diffusion model[9]:

$$CF_{iT,jtg} = (1 + TD_{iT,jtg})\alpha(ij, T, t, g)e^{1-\beta_1(T-t)}(1 - e^{-\beta_2(T-t)}) + \epsilon_{iT,jtg} \qquad (4)$$

where i and j denote citing and cited countries respectively; citing patents are granted in year T and cited patents in year t; g is one of the six main technological fields. The left hand side is the citation frequency of patents of country i granted in year T citing country j's patents that are granted in year t in technological area g. It is computed as: $CF_{iT,jtg} = \dfrac{C_{iT,jtg}}{N_{iT} * N_{jtg}}$, the number of cites scaled by the numbers of potentially citing and citable patents. As I show in the appendix, it measures the empirical frequency of a patent from the group defined by iT citing a patent from the group with the characteristics of jtg.

The probability that a patent is cited by another patent depends on among other things, the likelihood that the cited patent comes to the knowledge of the inventor of the citing patent and the relevance of the knowledge embodied in the cited patent to the citing patent. The former increases with the lag between the grant dates of the

[9]The model was first proposed and estimated in Caballero and Jaffe (1993) and was later estimated in Jaffe and Trajtenberg (1998) and Hu and Jaffe (2003)

citing and cited patents $(T - t)$ - the longer the cited patent has been around, the more likely it becomes known to the inventor of the citing patent, whereas the latter diminishes with the lag. As new knowledge emerges and/or as the wide adoption of the old knowledge reduces the economic rent accruable to the proprietary knowledge embodied in the cited patent, the likelihood that the cited patent remains relevant and prior art to a potential citing patent is reduced. The double exponential model in (4) captures these two processes with β_1 measuring the speed of obsolescence and β_2 the speed of diffusion.

The first term of the right hand side of equation (4) contains the technology distance between the citing patents and the cited patents. The technology distance variable used here is similar to the technology proximity variable defined in (2):

$$TD_{iT,jtg} = V_{iT}' V_{jtg} \tag{5}$$

The closer the potentially citing patent is to the potentially cited patent in the technology space, the easier it is for the citing patent to capture knowledge spillover from the cited patent and therefore the likelihood of citation increases. Finally, $\alpha(ij, T, t, g)$ represents a number of fixed effects I am interested in estimating:

$$\alpha(ij, T, t, g) = e^{\sum_i \sum_j \alpha_{ij} D_{ij} + \sum_T \alpha_T D_T + \sum_t \alpha_t D_t + \sum_g \alpha_g D_g} \tag{6}$$

For each set of fixed effects, one reference case is left out in the estimation. The citing-cited country pair specific effect is estimated with the α_{ij}'s. For example, with US citing US as the reference group, α_{TWUS} would measure how much more intensively Taiwan cites the US relative to the US cites itself. If the coefficient is estimated to be say 0.5, then it would imply that Taiwan cites the US half as frequently as the US does. The citation frequency may also vary with the grant year of the citing patents; and this is captured by α_T's. With both the effects of citing year and citation lag included in equation (4), I am not able to estimate a full set of cited year effects of α_t's. Instead I group the cited year t's into groups and estimate the group effects. Lastly, I also allow the average citation frequencies of the six main technology fields to differ.

Instead of estimating all the country pair effects in my citation database, which would lead to an explosion of the number of parameters to be estimated and overtaxing the data's identifying capability, I choose to be selective in the number of citing and cited countries to model. For cited countries, I include US, Japan, G5, Korea and Taiwan in view of their dominance in patent numbers and as a source of citations. All seven East Asian economies and US and Japan are included as citing countries, the latter for comparison and benchmarking purposes. Table 3 reports summary statistics for the main variables.

[Insert Table 3 here]

4.2 Results and discussion

4.2.1 Is there regionalization of knowledge diffusion in East Asia?

While plotting the shares of citations by source country/region in Figures 7-9 shows that East Asia is emerging as a source of knowledge diffusion, estimating the knowledge diffusion model in (4) will enable us to address the various analytical concerns that encompass simple citation shares. I estimate the diffusion model in two variations and report the results in Table 4. The difference between models 1 and 2 is that the latter allows the citing-cited country pair effect to be different before and after 1995. Given my main interest in the intensity of knowledge diffusion between countries and space constraint, I have omitted the coefficients of α_T's and α_t's from Table 4 and will not comment on them. For the fixed effect estimates, I have computed the marginal effects (e^{α}) in the last column of each model for ease of interpretation.

All of the coefficients in column (1) of Table 4 are precisely estimated and significant at the 1 percent significance level except the technology field effect for mechanical patents. Starting with the technology field effects. Drugs and medical patents are the least cited patents, whereas citation in the computers and communications field is the most intensive. Compared with the reference group of chemical patents, patents in the computers and communications field are 80 percent more likely to be cited.

The estimate of the effect of technology distance confirms that being close to each other in technology space intensifies knowledge diffusion between two countries so much so that two patents being in the same technology class are 47 times more likely to cite each other than otherwise. This effect is somewhat smaller than the effect found in the literature, but still quite significant.

The estimates of the decay and diffusion parameters and the technological field effects are similar to what earlier studies obtained. For example, the estimate of β_1 is about 0.21, which implies a modal lag of five years. The estimate of β_2 confirms the effect of knowledge diffusion on the likelihood of a patent being cited. I will focus the discussion that follows on the estimates of the citing-cited country pair fixed effects using the marginal effects reported in Table 4. It is useful to bear in mind that the reference group for column (1) is "US citing US", the effect of which is normalized to unity.

The results with respect to the citing pattern of US and Japanese patents are broadly consistent with earlier findings with some interesting exceptions. Both countries cite their own patents more often than they cite others'. The US cites G5 slightly more intensively than it cites Japan, but the US is cited more often by Japan than is G5. What is somewhat surprising is that Korea has become such an important source of knowledge diffusion for Japan that Japan cites Korea at 44.1 percent the frequency the US cites itself. This is almost as intensively as Japan cites the US! In contrast, the US derives more knowledge diffusion from Japan and G5 than from Korea and Taiwan.

Turning to the citing behavior of Korea and Taiwanese inventors, Korea reciprocates Japan's preference of citing Korean patents by citing Japan much more frequently than it cites the US. On the other hand, Taiwan seems to draw equally on the knowledge pools of Japan and US and at about a quarter of the intensity of US citing US. The knowledge diffusion between Korea and Taiwan is so intensive that Taiwan cites Korea much more frequently than it cites Japan and Korea cites Taiwan as frequently as it cites Japan. Such intensity of knowledge diffusion between Japan, Korea and Taiwan, besides reaffirming the technological sophistication of Korea and Taiwan, shows that the increasing shares of citations that Korea and Taiwan make to East Asian patents are not just driven by compatriot citations, but also driven by cross-border (or perhaps cross-ocean) knowledge diffusion. The bidirectional pattern of knowledge diffusion is also consistent with what Jaffe and Trajtenberg (1998) found for G5 countries.

Singapore has proved to be the most eager in absorbing knowledge diffusion. The estimates for Singapore show that it cites the US at about 95 percent the frequency of the US citing itself. In other words, Singapore cites the US almost as frequently as the US cites itself. Even more remarkable is the knowledge flow from Taiwan to Singapore. The estimate of 1.630 implies that Singapore cites Taiwan almost twice as likely as Taiwan cites its own patents. The extraordinarily high intensity of knowledge flow from foreign countries to Singapore has yet to find a parallel in the literature. The pattern of the knowledge flow also defies simple characterization of localization, as Singapore cites the US more intensively and as intensively as it cites Japan and Korea respectively. Part of the explanation lies with the dominant and increasingly innovative presence of multinational corporations in Singapore and that foreign direct investment has been an agent of knowledge diffusion (Hu, 2004).

For both China and Malaysia, the frequency of patent citations made to Korean and Taiwanese patents dominates that of citations made to the US and Japan. Hong Kong on the other hand, cites the four sources with more or less equal intensity. Thailand is an outlier in the group - it cites the US much more often than the Asian economies. What this implies is that China and Malaysia, being on a lower rung of the technology ladder than Hong Kong is, are drawn closer to Korea and Taiwan than to the US and Japan in terms of citation frequency. This reminds us of the complementarity between knowledge flow/technology transfer and R&D. The relative low level of innovative activity in China and Malaysia makes it easier for them to absorb the technologies from Korea and Taiwan, than those from the US and Japan, which are presumably more advanced and less applicable to the local environment. In contrast, the technological sophistication of Hong Kong enables it to learn from all source countries with equal ease. But without further investigation, this remains a conjecture.

Finally, with the exception again of Thailand, all of the East Asian patents cite G5 least frequently. This result completes a coherent picture of an East Asia regional system of knowledge flow, with Korea and Taiwan at the core of this system and close to each other; they are tightly connected to Singapore and surrounded further out by Hong Kong, China and Malaysia with Thailand at the outmost circle. This regional system of knowledge creation and diffusion then gravitates towards Japan and the US with only a loose link to Europe. Such a picture seems totally consistent with the roles of geography, language, trade and investment play in amplifying or dampening international knowledge diffusion.

4.2.2 Trends after 1995

There seem to have been structural changes in East Asia around the mid to late 1990s when USPTO patenting of the region considerably accelerated (Figure 1). To investigate whether the regionalization pattern of knowledge diffusion has been a more recent phenomenon, I re-estimate the diffusion model and allow the citing-cited country pair effect to be different before and after 1995. The choice of 1995 is motivated by the seeming structural change in patenting around that time. The infrequent patenting by China, Malaysia, and Thailand before 1995 does not allow for identification of such differentiation. But on the other hand, given that most of their patents have been granted in more recent years, I consider the estimates of these countries' citing patterns reported in the previous subsection to reflect mostly their recent citation behavior.

Columns under Model 2 of Table 4 report results from estimating the knowledge diffusion model when the post-1995 country pair effects are separately estimated. Country names followed by "95" refers to the post-1995 effect. I am primarily interested in whether Korea and Taiwan as the region's center of invention and innovation have become a more or less important source of knowledge diffusion. The identification problem discussed earlier permits the estimation of only the post-1995 coefficient of US, Japan, Korea, Taiwan, Hong Kong, and Singapore citing US, Japan, Korea and Taiwan. It is important to note that the reference group is now "US citing US prior to 1995."

Both Korea and Taiwan have cited each other more since 1995 than before it. Prior to 1995 Korean patents on average cited Taiwanese patents at slightly more than one third the frequency of US citing itself, but since 1995, they have been citing Taiwanese patents 64 percent more than US citing US over the same period of time. This seems to have come at the expanse of Korean patents citing less frequently other Korean patents since 1995. There has been a huge jump in the overall frequency of Taiwanese patents making citations after 1995. Other than a much higher tendency to cite compatriot patents, the Taiwanese patents have been citing Korean patents more than three times as likely as the US has been citing itself since 1995. The US patents also get cited 160 percent more by Taiwanese patents than by other US patents. Taiwan even cites Japan three times as frequently as Japan cites Japan in the post 1995 period. What accounts for this sudden change in the Taiwanese patents is interesting but unclear. It certainly calls for further research on it.

That the increased frequency at which Taiwanese patents are being cited may reflect a genuine increase in the technological and economic significance of these patents is further substantiated by the noticeable increase in the intensity of US and Japan citing Taiwan. Japan and the US are now citing Taiwan three and four times respectively as often as they cite their own patents. The intensity at which Korea has been cited by the US and Japan has also increased to a level that is equal to or higher than the US and Japan cite themselves, although the increase has been less dramatic than in Taiwan's case.

Singapore has experienced a substantial decline in the intensity at which it cites Japan, Korea and Taiwan, particularly the latter two. This is compensated by a modest increase in the frequency of Singapore citing the US. Hong Kong, in contrast, has had across the board increase in citation frequency since 1995. All the pre-1995 coefficients for Hong Kong are significantly negative so that the marginal effect is below unity but all the post-1995 coefficients are statistically indistinguishable from zero implying the marginal effect to be indistinguishable from one. This suggests that Korea and Taiwan have changed from the least cited to as often cited as the US and Japan. This difference between Singapore and Hong Kong could signify Singapore's moving up the technology ladder - by citing the US more intensively - and pulling ahead of Hong Kong in technological innovation. But again more research is needed before any conclusion can be drawn.

5 Concluding remarks

East Asia is emerging as a new hub of technological innovation, with Korea and Taiwan leading the pack and joining the ranks of world class inventors. With the increasing amount of knowledge created in the region, opportunity expands for cross-border knowledge diffusion within East Asia. The commonality in language, history, and culture and the extensive economic integration of the region only heighten the expectation that with lower barriers to knowledge diffusion, East Asian economies should be learning from each other more than they did in the past and more than they are learning from the rest of the world.

This study subjects this conjecture to empirical test. Using citations made by USPTO granted patents to other USPTO patents as an indicator of knowledge flow and estimating a model of international knowledge diffusion, I find strong evidence corroborating the hypothesis of increasing regionalization of knowledge flow in East Asia.

There is intensive knowledge flow between East Asia's leading innovators: Korea and Taiwan cite each other more intensively than they cite Japan and the US. Such bidirectional knowledge flow has become even more frequent since the mid 1990s. Both Korea and Taiwan are citing each other much more frequently than before and more frequently than the US and Japan cite themselves. In the meantime Korea and Taiwan are also being cited much more intensively by the US and Japan. Particularly striking is the increased intensity at which Taiwanese patents have been cited.

Korea and Taiwan are not just a source of inspiration to each other, with the exception of Thailand, all of the East Asian economies that I examine, Hong Kong, Singapore, China, and Malaysia, cite Korea and Taiwan at least as intensively at the individual patent level as they cite the US and Japan. G5 countries, which include Britain, Canada, France, Germany and Italy, have been the least frequently cited source of knowledge for East Asia.

Together the empirical results reveal an interesting and integrated East Asian regional innovation system, with Taiwan and Korea at the core, both of which are tightly connected to Singapore, surrounded by China, Hong Kong, and Malaysia, and with

Thailand at the outmost circle. Knowledge flows from the core to the periphery. And in the space of knowledge diffusion, the system as a whole gravitates towards Japan and the US, and away from Europe. In the meantime as the system gains a critical mass, it also attracts Japan and the US to itself.

The findings complement and contribute to the existing literature on international knowledge diffusion by corroborating that language, culture, history and economic integration bring countries closer in the technology sphere and accelerates the flow of ideas and innovation, which in turn spreads the fruits of economic growth and development.

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Figure 1: Number of USPTO patents granted

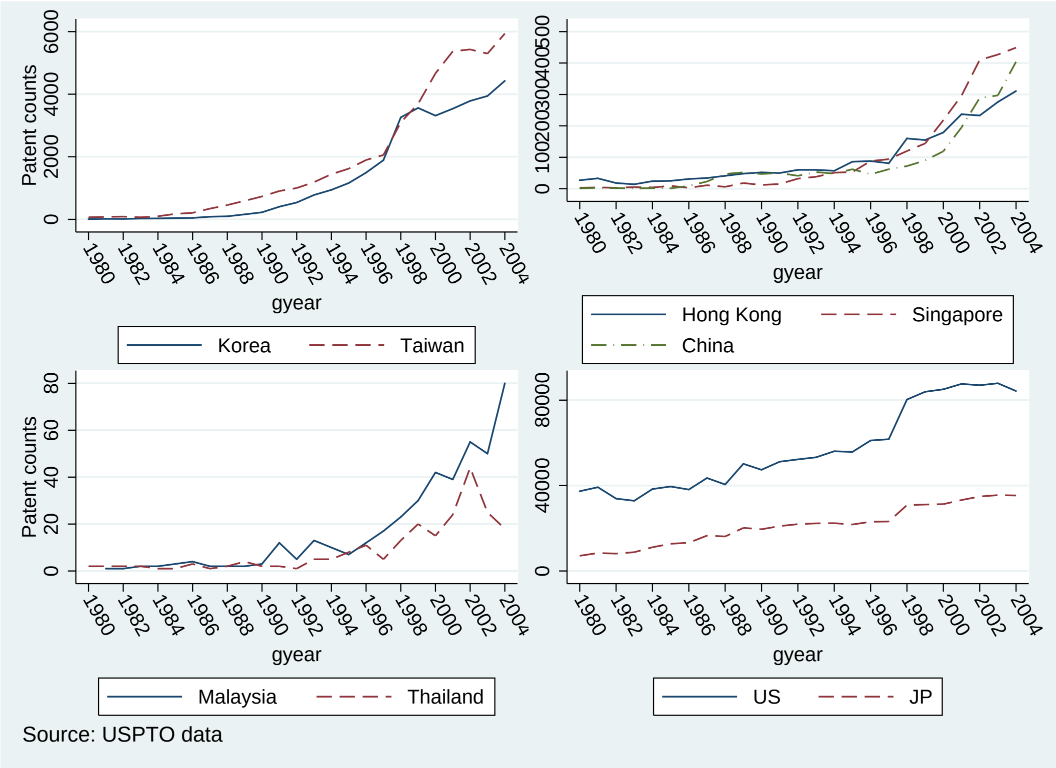

Figure 2: Technology class distribution of patents (1)

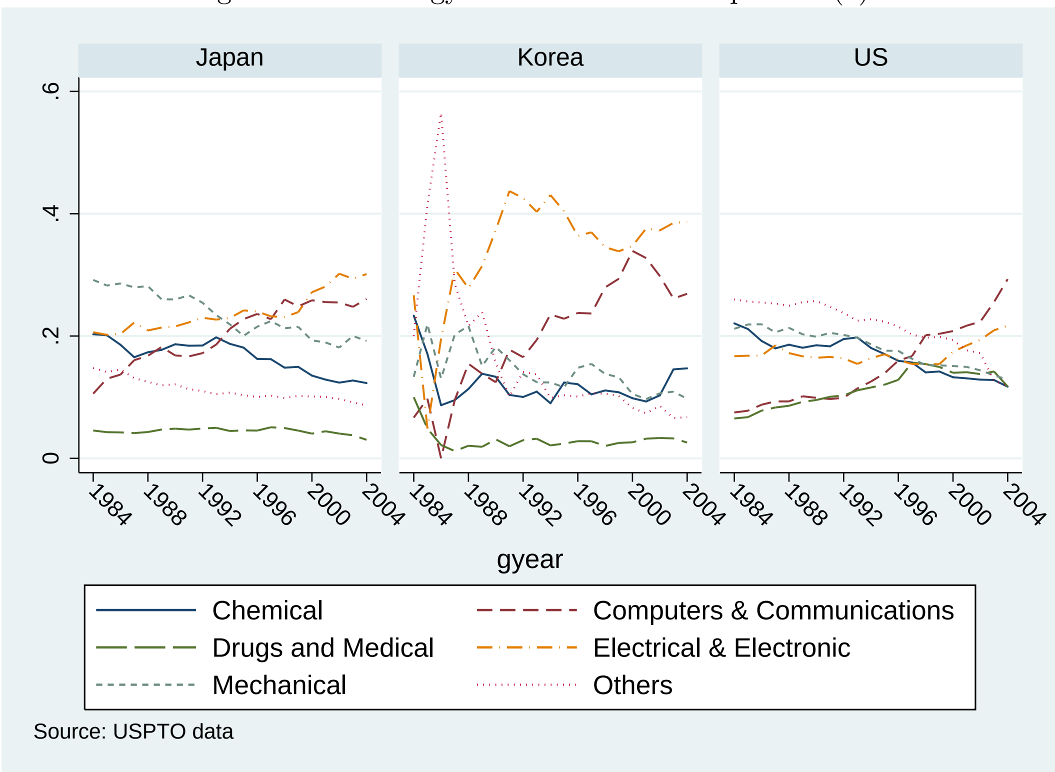

Figure 3: Technology class distribution of patents (2)

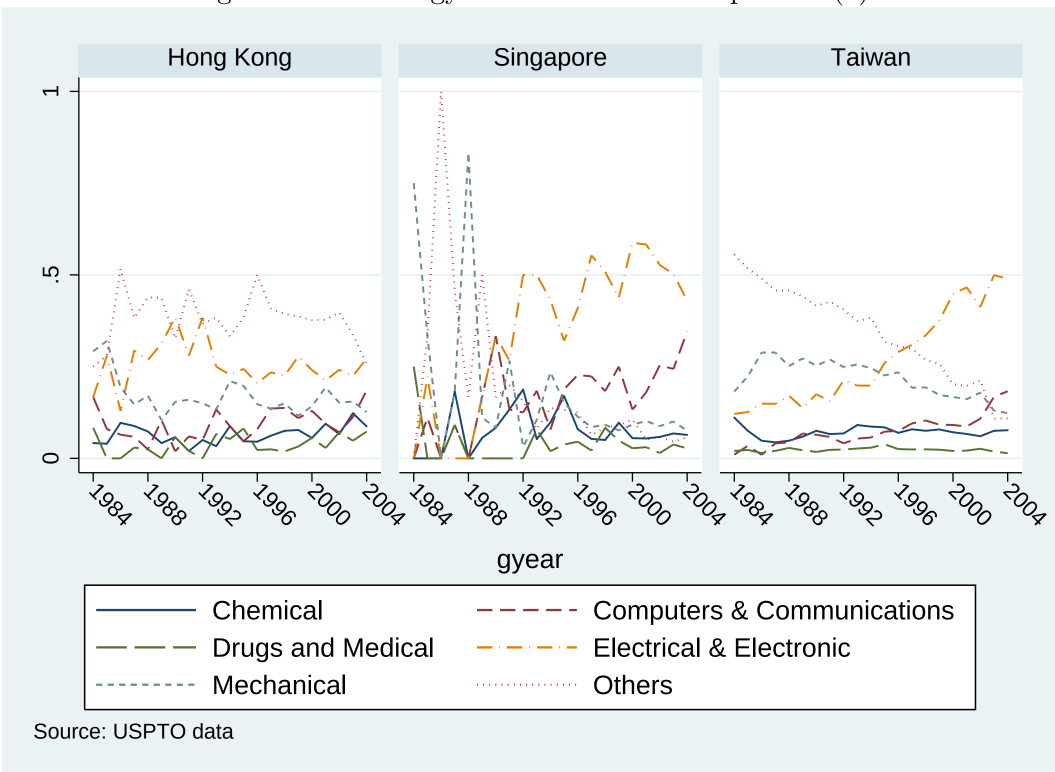

Figure 4: Technology class distribution of patents (3)

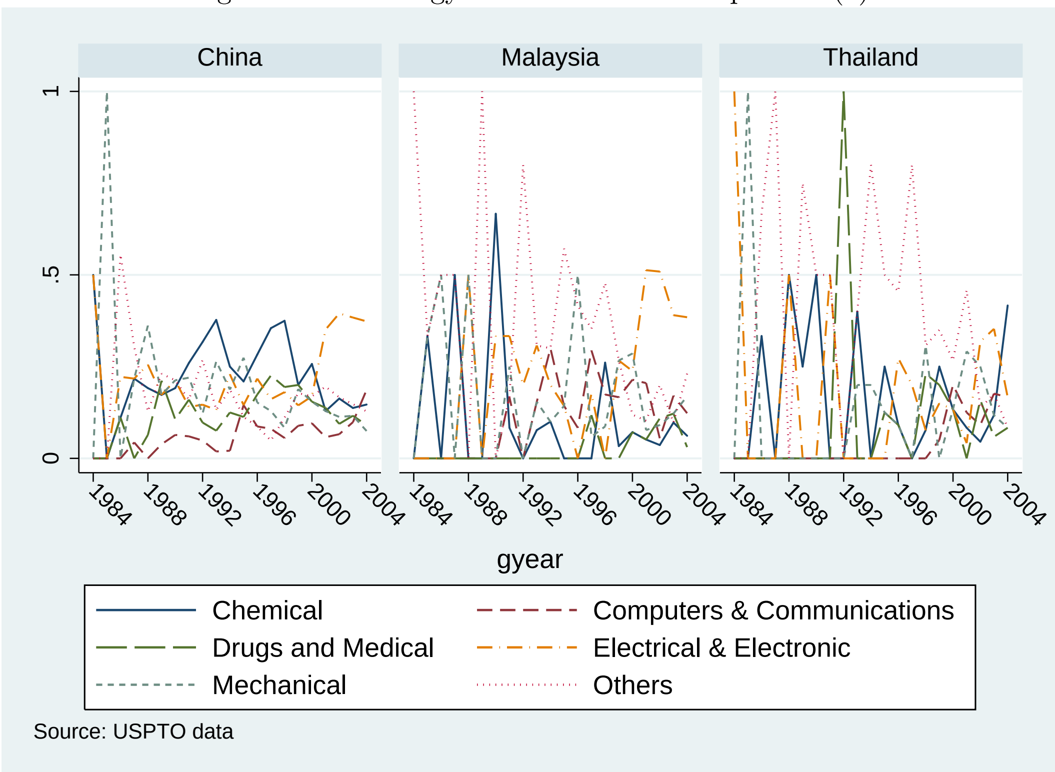

Figure 5: Technology Proximity: East Asia with US, Japan and G5

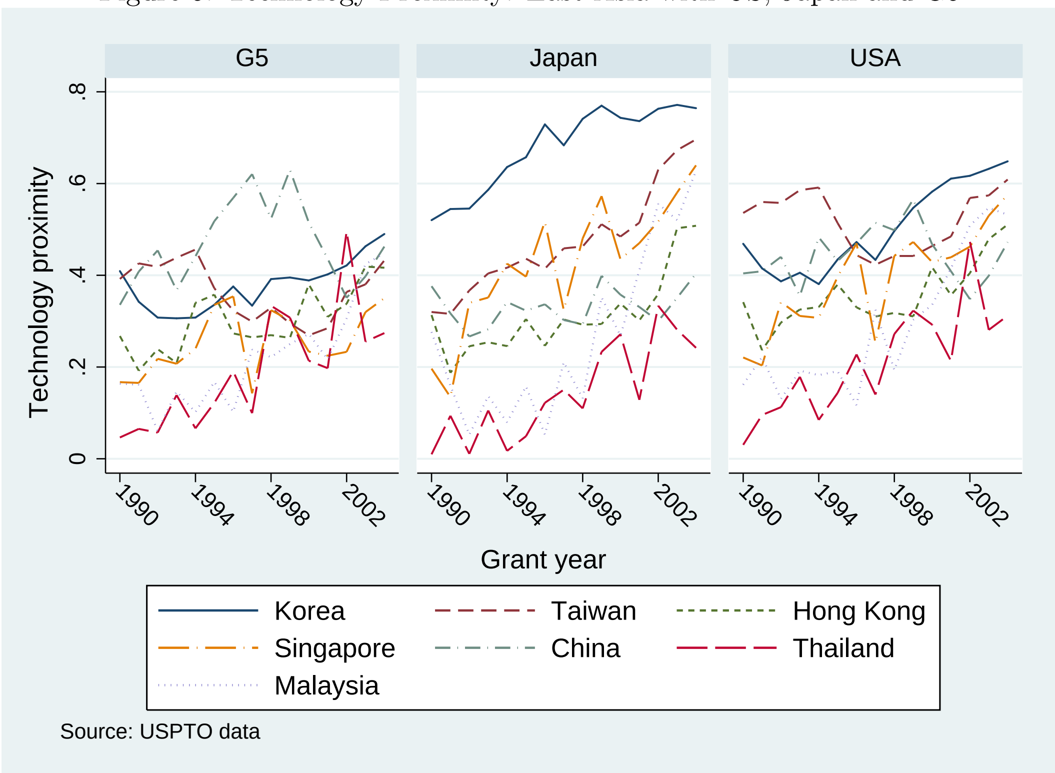

Figure 6: Technology Proximity: East Asia with Korea and Taiwan

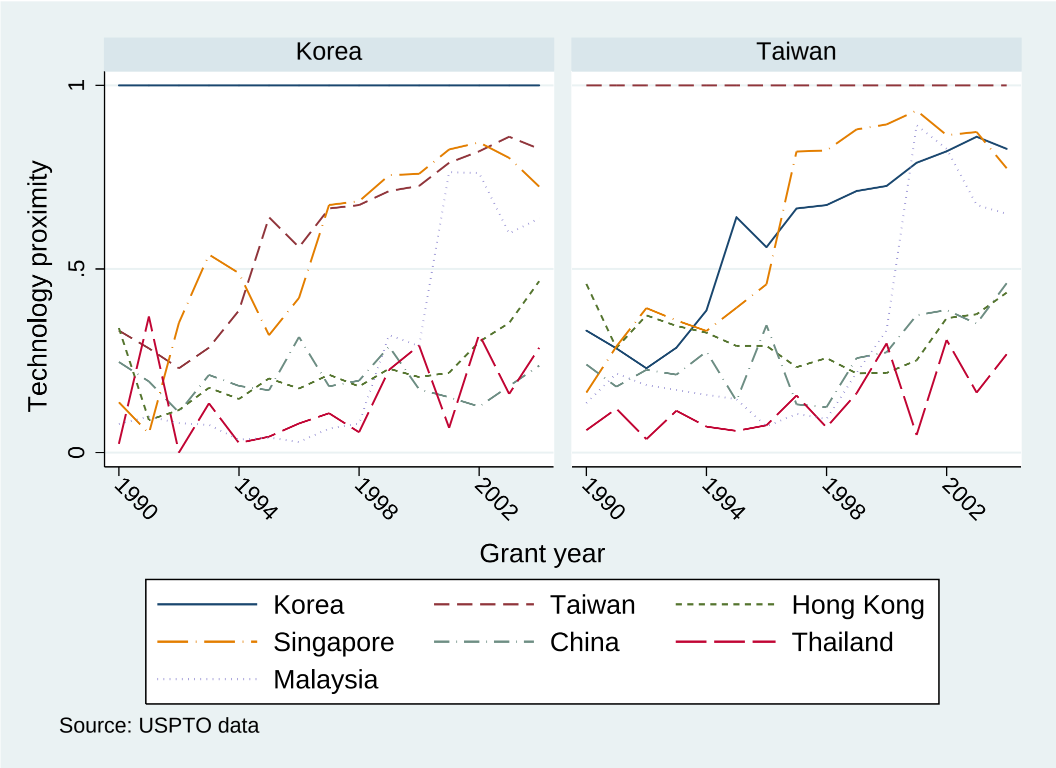

Figure 7: Shares of raw citations by source (1)

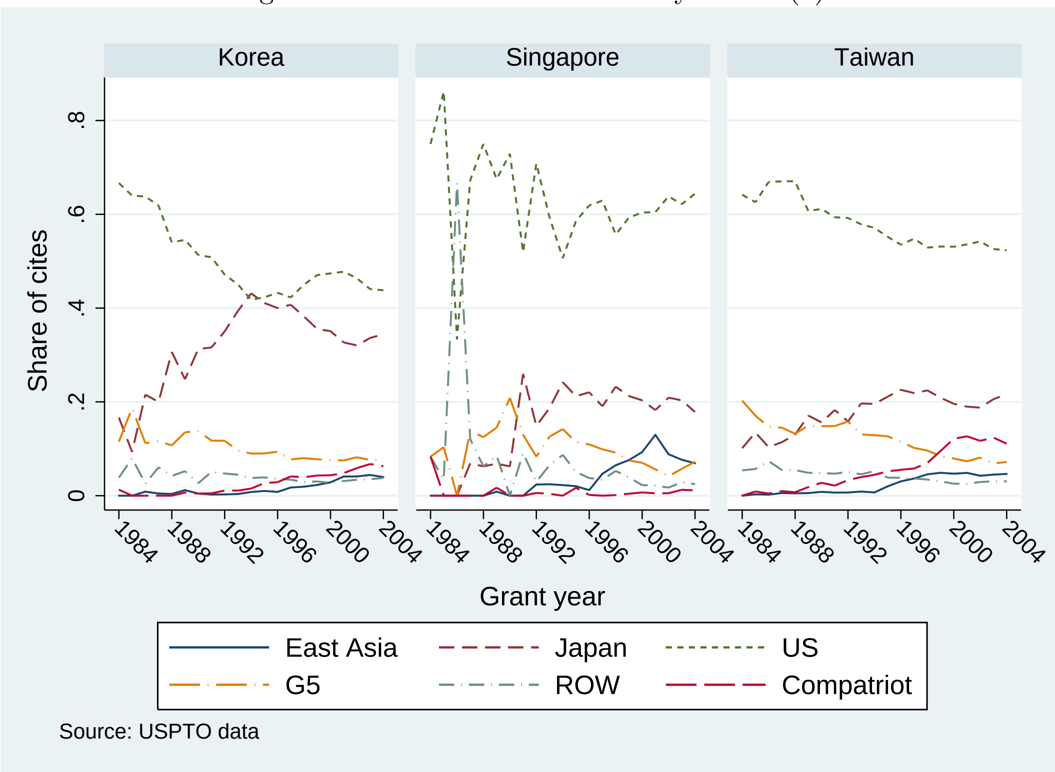

Figure 8: Shares of raw citations by source (2)

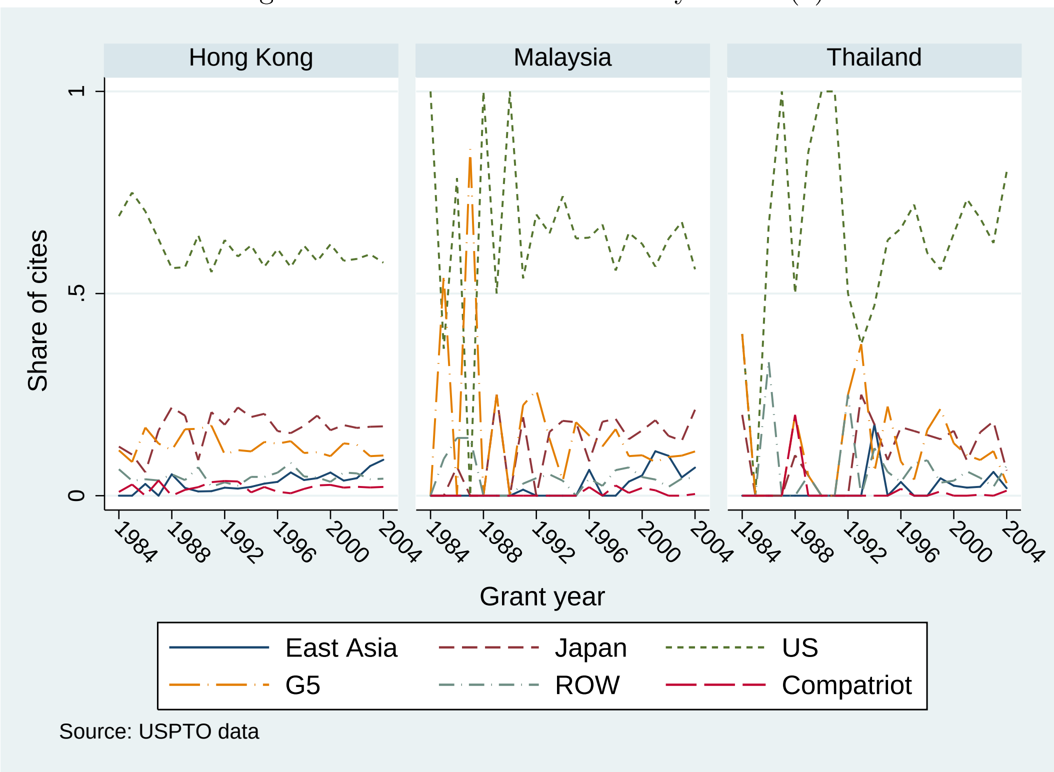

Figure 9: Shares of raw citations by source (3)

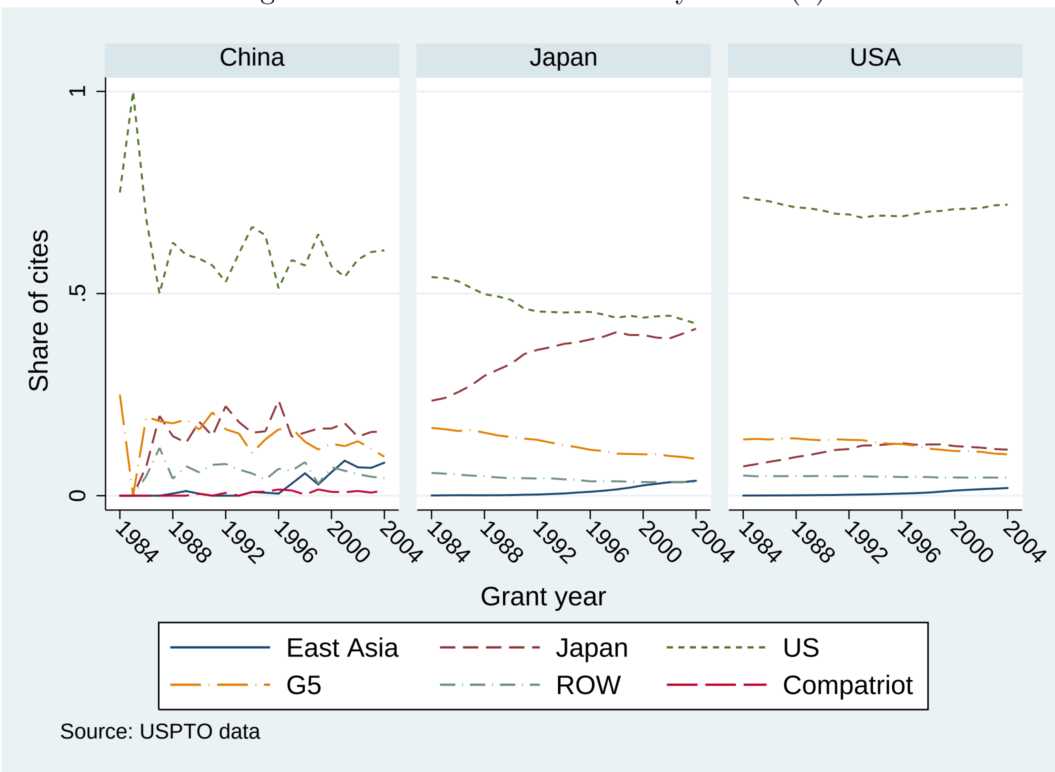

Table 1: Originality of patents

Country	Chemical	Computers & Communications	Drugs & Medical	Electrical & Electronic	Mechanical	Others
			1991-1995			
China	0.568	0.542	0.327	0.356	0.557	0.460
Hong Kong	0.603	0.625	0.551	0.448	0.397	0.371
Korea	0.551	0.432	0.469	0.401	0.420	0.423
Malaysia	0.850	0.544	n.a.	0.550	0.429	0.353
Singapore	0.629	0.493	0.503	0.360	0.603	0.478
Thailand	0.877	n.a.	0.552	0	0.794	0.071
Taiwan	0.540	0.472	0.352	0.369	0.411	0.412
Japan	0.529	0.461	0.470	0.460	0.445	0.465
USA	0.595	0.525	0.491	0.499	0.516	0.500
			2000-2004			
China	0.555	0.510	0.463	0.303	0.475	0.442
Hong Kong	0.571	0.480	0.477	0.492	0.455	0.404
Korea	0.514	0.454	0.466	0.485	0.474	0.462
Malaysia	0.690	0.567	0.606	0.492	0.630	0.461
Singapore	0.646	0.497	0.407	0.489	0.592	0.503
Thailand	0.574	0.796	0.390	0.685	0.719	0.449
Taiwan	0.541	0.478	0.367	0.421	0.452	0.425
Japan	0.561	0.497	0.465	0.501	0.457	0.507
USA	0.639	0.574	0.519	0.555	0.545	0.531

Table 2: Generality of East Asian patents

Country	Chemical	Computers & Communications	Drugs & Medical	Electrical & Electronic	Mechanical	Others
			1991-1995			
China	0.538	0.769	0.421	0.544	0.575	0.565
Hong Kong	0.583	0.621	0.525	0.479	0.493	0.471
Korea	0.610	0.500	0.384	0.509	0.487	0.476
Malaysia	0.85	0.681	n.a.	0.478	0.544	0.235
Singapore	0.532	0.508	0.543	0.511	0.6	0.558
Thailand	0.747	n.a.	0.686	0.7	0.377	0.574
Taiwan	0.539	0.550	0.366	0.466	0.466	0.430
Japan	0.602	0.522	0.478	0.540	0.494	0.531
USA	0.639	0.601	0.476	0.576	0.554	0.529
			2000-2004			
China	0.445	0.414	0.468	0.409	0.412	0.433
Hong Kong	0.488	0.523	0.28	0.539	0.416	0.425
Korea	0.490	0.465	0.387	0.484	0.480	0.411
Malaysia	0.500	0.650	0.717	0.373	0.822	0.111
Singapore	0.555	0.526	0.533	0.445	0.472	0.592
Thailand	1	0.730	0	0.680	0.083	0.333
Taiwan	0.489	0.464	0.289	0.418	0.365	0.375
Japan	0.550	0.480	0.422	0.502	0.459	0.499
USA	0.615	0.570	0.440	0.538	0.515	0.487

Table 3: Summary statistics

Variable	Mean	Std. Dev.	Min.	Max.	N
$Ncites$	114.817	597.48	0	28443	92685
$Npats_{iT}$	12355.376	22658.708	1	87685	92685
$Npats_{jtg}$	2788.411	3369.634	1	19446	92685
$CF(\times 10^5)$	0.242	1.768	0	260.417	92685
TP	0.544	0.264	0.001	1	92685
$Lag(T-t)$	10.562	6.95	1	29	92685

Table 4: Knowledge diffusion model estimation

	Model 1			Model 2		
	Coeff.	SE	e^{α}	Coeff.	SE	e^{α}
TD	47.142**	2.473		69.095**	4.068	
β_1	0.212**	0.002		0.211**	0.001	
$\beta_2(\times 10^6)$	1.010**	0.161		0.694**	0.100	
Com. & Comm.	0.586**	0.009	1.796	0.578**	0.009	1.782
Drugs & Med.	-1.078**	0.019	0.340	-1.193**	0.018	0.303
Electri. & Electron.	0.243**	0.010	1.275	0.218**	0.010	1.244
Mechanical	-0.006	0.012	0.994	0.032**	0.011	1.032
Others	-0.442**	0.013	0.643	-0.420**	0.013	0.657
US citing						
Japan	-0.561**	0.009	0.571	-0.225**	0.016	0.798
Korea	-0.960**	0.030	0.383	-1.076**	0.158	0.341
Taiwan	-1.227**	0.035	0.293	-2.600**	0.442	0.074
G5	-0.529**	0.010	0.589	-0.266**	0.015	0.766
Korea95				0.404*	0.162	1.497
Taiwan95				1.749**	0.443	5.747
US95				0.374**	0.018	1.453
Japan95				-0.100**	0.023	0.905
Japan citing						
US	-0.782**	0.011	0.457	-0.251**	0.016	0.778
Japan	-0.223**	0.009	0.800	0.396**	0.012	1.486
Korea	-0.819**	0.027	0.441	-0.416**	0.086	0.660
Taiwan	-1.453**	0.058	0.234	-1.682**	0.309	0.186
G5	-1.001**	0.018	0.367	-0.729**	0.021	0.482
Korea95				-0.176	0.091	0.838
Taiwan95				0.523	0.315	1.686
US95				-0.421**	0.026	0.656
Japan95				-0.588**	0.019	0.555
Korea citing						
US	-0.77**	0.021	0.463	-0.585**	0.060	0.557
Japan	-0.352**	0.014	0.703	0.145**	0.028	1.156
Korea	0.146**	0.016	1.157	0.995**	0.037	2.705
Taiwan	-0.379**	0.027	0.685	-1.010**	0.336	0.364
G5	-1.256**	0.048	0.285	-0.983**	0.049	0.374
Korea95				-0.675**	0.041	0.509
Taiwan95				0.868**	0.337	2.382
US95				0.095	0.065	1.100
Japan95				-0.310**	0.034	0.733
Taiwan citing						
US	-1.351**	0.033	0.259	-2.215**	0.194	0.109
Japan	-1.381**	0.039	0.251	-1.693**	0.175	0.184
Korea	-0.347**	0.025	0.706	-1.658**	0.505	0.191
Taiwan	-0.188**	0.019	0.829	-2.588**	0.475	0.075
G5	-2.130**	0.110	0.119	-1.874**	0.108	0.154

Korea95				1.569**	0.505	4.800
Taiwan95				2.762**	0.475	15.836
US95				1.318**	0.197	3.735
Japan95				0.625**	0.179	1.868
			Singapore citing			
US	-0.055**	0.020	0.946	0.057	0.069	1.059
Japan	-0.507**	0.032	0.602	0.146	0.079	1.157
Korea	-0.070*	0.033	0.933	1.751**	0.063	5.759
Taiwan	0.489**	0.020	1.630	1.858**	0.041	6.409
G5	-0.907**	0.071	0.404	-0.630**	0.070	0.532
Korea95				-1.648**	0.071	0.192
Taiwan95				-1.200**	0.046	0.301
US95				0.175*	0.072	1.191
Japan95				-0.449**	0.087	0.638
			Hong Kong citing			
US	-0.793**	0.046	0.452	-0.539**	0.086	0.583
Japan	-0.902**	0.058	0.406	-0.492**	0.100	0.611
Korea	-0.861**	0.125	0.423	-1.926	1.303	0.146
Taiwan	-0.918**	0.115	0.399	-1.026**	0.322	0.358
G5	-1.149**	0.09	0.317	-0.876**	0.088	0.416
Korea95				1.395	1.308	4.033
Taiwan95				0.397	0.344	1.487
US95				0.025	0.101	1.026
Japan95				-0.211	0.121	0.810
			China citing			
US	-1.015**	0.058	0.362	-0.743**	0.058	0.476
Japan	-1.178**	0.082	0.308	-0.912**	0.081	0.402
Korea	-0.824**	0.137	0.438	-0.564**	0.135	0.569
Taiwan	-0.903**	0.113	0.406	-0.667**	0.111	0.513
G5	-1.312**	0.103	0.269	-1.045**	0.101	0.352
			Malaysia citing			
US	-0.83**	0.067	0.436	-0.583**	0.067	0.558
Japan	-1.126**	0.109	0.324	-0.901**	0.108	0.406
Korea	-0.631**	0.113	0.532	-0.397**	0.109	0.672
Taiwan	-0.562**	0.077	0.570	-0.368**	0.076	0.692
G5	-1.624**	0.211	0.197	-1.394**	0.208	0.248
			Thailand citing			
US	-0.410**	0.057	0.664	-0.167**	0.058	0.846
Japan	-1.106**	0.144	0.331	-0.862**	0.142	0.423
Korea	-1.311**	0.330	0.270	-1.094**	0.323	0.335
Taiwan	-2.299**	0.626	0.100	-2.146**	0.627	0.117
G5	-1.175**	0.172	0.309	-0.938**	0.169	0.391
N		92,685			92,685	
Aj. R^2		0.99			0.99	

* - significant at 5% level; ** -significant at 1% level

APPENDIX

A note on raw citation share, citation frequency, and the relationship between them

Raw citation share

Suppose that the USPTO patents are classified into M groups. The group can be defined by the patents' nationality, grant year, or technological field or a combination of these characteristics. Raw citation share is the proportion of the citations that group i's patents have made to patents from group j out of all the citations the former has made, i.e.,

$$CS_{ij} = \frac{C_{ij}}{\sum_{k=1}^{M} C_{ik}} \tag{A-1}$$

Where the first subscript denotes citing group and the second subscript represents the group cited and C_{ij} is the number of cites made by group i's patents to those of group j. This is essentially the empirical equivalent of the following conditional probability:

$$f(citing = i, cited = j | citing = i) = \frac{f(citing = i, cited = j)}{\sum_{k}^{M} f(citing = i, cited = k)} \tag{A-2}$$

$f(i, j)$ is the (unconditional) probability of observing i citing j, which can be expressed as:

$$f(citing = i, cited = j) = g(i)g(j)h(i, j) \tag{A-3}$$

If a patent is randomly drawn from the patent population as the citing patent and cited patent respectively, $g(i)$ represents the probability of the citing patent coming from group i; likewise, $g(j)$ is the probability that the cited patent belongs to group j. The (conditional) probability that the patent from group i will cite the patent from group j is $h(i, j)$. In other words, given a potentially citing patent from i and a potentially cited patent from j, the probability that the former will cite the latter is $h(i, j)$. Substituting (A-3) in A-2) obtains:

$$f(citing = i, cited = j | citing = i) = \frac{g(i)g(j)h(i, j)}{\sum_{k=1}^{M} g(i)g(k)h(i, k)} \tag{A-4}$$

Let the size of the population of patents be N so that $g(i) = \frac{N_i}{N}$. Therefore the empirical equivalent of (A-4) is:

$$\begin{aligned} \widehat{f}(citing = i, cited = j | citing = i) &= \frac{\frac{N_i}{N}\frac{N_j}{N}\widehat{h}(i, j)}{\sum_{k=1}^{M} \frac{N_i}{N}\frac{N_k}{N}\widehat{h}(i, k)} \\ &= \frac{N_i N_j \widehat{h}(i, j)}{\sum_{k=1}^{M} N_i N_k \widehat{h}(i, k)} \end{aligned} \tag{A-5}$$

Given $\widehat{h}(i, j)$ and that there are $N_i N_j$ pairs of (i, j), the average number of citations from group i to group j is:

$$C_{ij} = N_i N_j \widehat{h}(i,j) \tag{A-6}$$

Substituting (A-6) in (A-5) yields (A-1).

Citation frequency

Citation frequency is defined as the empirical frequency of a patent from group i citing one from group j:

$$CF_{ij} = \frac{C_{ij}}{N_i N_j} \tag{A-7}$$

It is easy to see that CF_{ij} is just the sample equivalent of $\widehat{h}(i,j)$ (A-6), i.e., the probability of a randomly drawn patent from group i citing a randomly drawn patent from group j. Replacing $\widehat{h}(i,j)$ with CF_{ij} in (A-6) and substitute (A-6) in (A-1):

$$CS_{ij} = \frac{CF_{ij} N_i N_j}{\sum_{k=1} CF_{ik} N_i N_k} \tag{A-8}$$

which can be simplified to:

$$CS_{ij} = \frac{CF_{ij} N_j}{\sum_{k=1} CF_{ik} N_k} \tag{A-9}$$

Using raw citation share to gauge the importance of a cited country as a source of knowledge flow to a citing country relative to another cited country, we can take the ratio of two CS's:

$$\frac{CS_{ij}}{CS_{il}} = \frac{CF_{ij}}{CF_{il}} \frac{N_j}{N_l} \tag{A-10}$$

Equation (A-10) indicates that group j's importance as a source of knowledge flow to group i relative to that of group l to group i is determined by the relative citation frequency and the relative patent counts of groups j and l. Group i may derive a larger proportion of its citations from group j because group i patents cite group j patents more intensively at the individual level than they cite group l patents and/or there are more group j patents to be cited than are group l patents.