Knowledge Sources of Innovation in a Small Open Economy: The Case of Singapore

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Abstract

By tracing the flows of patent citation of prior patents and scientific journal articles, we investigate the sources of knowledge for innovation output in Singapore, a small, highly open economy that has traditionally been significantly dependent on foreign multinational corporations (MNCs). We found that the local production of new knowledge by indigenous Singaporean firms depends disproportionately on *technological* knowledge produced by MNCs with operational presence in Singapore and *scientific* knowledge generated by foreign universities. Locally produced new knowledge by indigenous firms and local universities constitute an insignificant, albeit rapidly growing, source for innovation in Singapore.

JEL Codes: 033, 031, 053

Keywords: innovation system, patent citation, Singapore, knowledge sources

1. Introduction

It is well established that a firm's innovation is partially dependent on R&D and knowledge flows from other firms and industries. An important empirical finding by Jaffe (1986) and Acs et al. (1992, 1994) is that R&D investment by private corporations and universities spills over to other third party firms, who may then exploit this R&D spillover in their own innovative activities. The body of work on R&D spillovers has developed significantly, as reviewed by Griliches (1992). Economic theorists have at the same time incorporated knowledge spillovers as a determinant of aggregate economic growth in the new class of endogenous growth models, pioneered by Romer (1986, 1990). More recently, literature on knowledge recombination has shown that organizations innovate through combining new and existing knowledge, including knowledge from external sources (Kogut and Zander, 1992; Song et al., 2001).

The existence of spillovers led to researchers studying the role of geography and the spatial dimension in the firm innovation process (Jaffe, 1989; Krugman, 1991; Feldman, 1994). Studies of American firms by Jaffe et al. (1993 and Audretsch and Feldman (1996), among others, empirically established the existence of geographic localization of R&D; ie knowledge spillovers are most likely exploited by firms in the geographic vicinity of the firm from which the knowledge originated. The geographic localization of knowledge spillovers is by now an accepted fact in the USA, and evidence to support the hypothesis has also been found in large countries such as Japan (Branstetter, 2001; Goto and Nagata, 1997), France (Piergiovanni and Santarelli, 2001), Germany (Herrigel, 1993) and Italy (Piergiovanni et al., 1997). There have also been a number of studies on geographic localization of knowledge in specific industries, such as the semi-conductor sector (Sorensen and Stuart, 2000; Almeida, 1996). However, there is no equivalent empirical literature on knowledge flows and sources of knowledge for innovation in smaller countries.

Early empirical studies on knowledge spillovers have typically used data on R&D expenditure and were focused on identifying where spillovers go. Jaffe et al. (1993) pioneered the use of patent citations data to trace the flow of knowledge. Other authors, such as Frost (2001) and Almeida (1996) have adopted this approach of using patents citation to study knowledge flows and spillovers.

Another approach is to use publications citation data. This has been notably accomplished in the USA using the Small Business Administration's Innovation Data Base (SBIDB). The SBIDB has been used in studies on the geography of innovation by Acs et al. (1992, 1994), Feldman (1994) and Audretsch and Feldmand (1996).

Many studies on knowledge spillovers have focused on the destination of outgoing knowledge; establishing that there are geographic bounds to the "reach" of spillovers. The flipside approach is to examine the recipient firms and the knowledge sources that are included in their search process when seeking to expand their knowledge stocks. Using this approach, Stuart and Podolny (1996) and Rosenkopf and Almeida (2003) have found that firms' search for new knowledge is geographically bounded to its immediate vicinity.

2. Knowledge sources for Innovation in Small, Open Economies

In this paper, we present findings on the knowledge sources of innovation by indigenous firms in Singapore by tracing the citations made by patents invented in Singapore. Singapore represents a very interesting case example of a small and highly open economy that traditionally has depended heavily on direct foreign investment by global MNCs. In the light of increasing globalization and the growing presence of foreign MNCs in developing countries, the potential role of foreign firms as a source of knowledge for innovation in the host country needs to be given greater attention. Because of the significant presence of foreign MNCs in her national innovation system, Singapore thus offers a relatively advanced case for studying the role of foreign MNCs as a knowledge source for innovation for local firms.

There has been little research on patenting activities in Singapore, due in part to the low level of patenting activity in Singapore in the past. While Singapore has been steadily increasing her R&D intensity since the early-1980s, it is really only from the mid-1990s that the pace of technological innovation leading to intellectual property started to accelerate. As can be seen from Table 1, Singapore's R&D expenditure to GDP ratio rose steadily from less than 0.3% in 1980 and less than 1% in 1990 to 2.15% by 2003, which already exceeds the level of many OECD countries. But the level of patenting activity, as measured by patents awarded by the US Patent and Trademark Office (USPTO) with at least one Singapore Inventor, only started to become significant from the mid-1990s: Of the cumulative total of 3027 patents granted by the US Patents and Trademarks Office (USPTO) to Singapore-based inventors at the end of 2003, 1871, or more than 60%, were granted in the 3 years after 2000.

Studying sources of knowledge in a small, open newly industrializing economy such as Singapore is a notable departure from other studies that have typically focused on geographical units within large advanced nations. In contrast to the empirical conclusions from large nations, we expect that the knowledge sources for small nations would be less geographically bounded. In addition, the dominant presence of foreign MNCs in a newly industrialized economy like Singapore would also present an interesting contrast to studies on other small advanced economies that typically have large home-grown technology-based firms, such as Finland and Sweden. Also using patents citation data, Hu (2004) had found that the R&D activities of MNCs in Singapore facilitate the flow of knowledge from MNCs headquarters outside Singapore to inventors in Singapore

The focus of this paper is on the pattern of knowledge sources for Singaporean organizations and how this has changed over time. We primarily examine two aspect of citations pattern: the ownership pattern reflected by the type of organizations that are cited (whether they are local companies, local universities/ PRICs, foreign MNCs with subsidiaries in Singapore or other foreign sources) and the geographic origins of cited knowledge. We trace the change in citation pattern by comparing citations across two time periods: 1976-1995 and 1996-2001. The late 1990s witnessed the beginning of high-tech entrepreneurial start-up activities in Singapore, similar to the Silicon Valley model. In particular spin-offs from universities and public R&D institutions were increasing in frequency. There was a shift towards longer term basic research and higher incentives to innovate, resulting in a surge in the number of Singapore-invented patents. We anticipate that this deepening of R&D activities in Singapore would be reflected in a shift towards greater dependence on locally produced knowledge outputs.

The paper is organized as follows. In the next section, we briefly review the methodology for using patent citation data as a means to trace knowledge flows in a national innovation

system. In Section 3, we present the profile and recent growth trends of patenting activities in Singapore, showing the growth in patenting activity by local private sector firms and local universities and PRIs. In Section 4, the main section of our paper, we present our key findings derived from applying the patents citation "matching" approach of Jaffe et al. (1993) and the publications citation approach (Acs et al., 1992) to patents invented Singapore.

3. Methodology

The study is based on a careful analysis of citations to patents and scientific publications contained within patents. Citations within these patents to external sources offer an indication of how important various sources of knowledge are to Singaporean firms' creation of new IP. The research methodology leverages a computerized US patent database (http://patents.nus.edu) that the authors have contributed to establishing in, as well as the Webofscience bibliographic database. Using these data sources allows us a lens through which to observe knowledge flows among the different constituents of Singapore's national innovation system.

a) Citing Patents

We have constructed a database of patents granted between 1976 and 2001 by the US Patent and Trademark Office (USPTO) that are invented by Singapore-resident inventors and owned by a "Singapore-related" organization. A patent is treated as Singapore-invented as long as one of its inventors was resident in Singapore at the time of the patent application.

From this list of Singapore-invented patents, we identified the patents that are "Singapore-related", based on the characteristics of the assignees. These are the "citing patents" in our research design. For each citing patent, we determine that it is Singapore-related if it is assigned to one of four possible types of organizations: (a) a local Singapore company, (b) a Singapore-based subsidiary of a foreign company, (c) a foreign-based company (usually a parent or headquarter company) that is part of a multinational (MNC) corporate group that has presence in Singapore, or (d) a Singaporean University, Public Research Institute (PRIs) or Government organization[1]. As our concern is to understand the knowledge flows to Singapore-related organizations, we have excluded patents that are assigned to individuals and to foreign organizations that do not have any presence in Singapore. Cases of the latter are relatively rare, with only 64 patents identified as belonging to organizations with no presence in Singapore. In total, we identified 1,423 citing patents that are Singapore-related. Of these, 128 were design patents, 1 was a reissued patent and the other 1,294 patents were utility patents.

Although there is a clear legal distinction between (b) and (c) (patent ownership being assigned to the local subsidiary of a foreign entity in the former and to a foreign entity in the latter), we suspect that the difference may not be that clear cut in practice and may be caused more by differences in corporate strategy or accounting policy of the foreign firm concerned.

In instances where a patent has more than one assignee, we classified the ownership of the patent according to its first named assignee. In the interest of completeness, we also maintain a separate classification of such patents as either "joint foreign and local private sector

[1] To determine if a company is locally or foreign owned, and whether a foreign company has a subsidiary in Singapore, we consulted sources such as the Accounting and Corporate Regulatory Authority of Singapore (formerly the Registry of Companies and Businesses), the Singapore 1000 directory and online search engines.

ownership" or "joint local public and private sector ownership".[2]

b) Cited Patents

Each citing patent cites a list of other patents that represent the "prior arts" upon which the innovation as embodied in the citing patent is built. We compiled detailed information on these cited patents paying particular attention to their geographic origins and whether the assignee are from foreign firms, local firms, universities or PRIs. We have categorized the geographic, technological and organizational characteristics of these cited patents according to their first-named assignees. For comparability, we have similarly categorized the assignees of cited patents as belonging to one of the four groups defining the assignees of citing patents.

Detailed information on the cited patents is drawn from the NUS patent database that contains complete details on all USPTO patents granted after January 1st 1976. As such, we were not able to compile information on the cited patents that were granted prior to this date. These early patents form a relatively small proportion of the total cited patents. Of the 11,264 patents that were cited by the 1,423 citing patents, only 914 (or 8.1%) were granted prior to 1976.

Using these data on both citing and cited patents, we constructed pairs of citing-cited patents which allow us to match and compare the characteristics of the citing technology and the cited source of knowledge.

c) Technological Classification

Every citing and cited patent is classified into one of 6 technological categories, using the NBER classification scheme developed by Hall, Jaffe and Tratjenberg (2001). These 6 categories are aggregated from 36 subcategories that each encompasses a number of the 3-digit patent classes in the US Patent Classification (USPC) scheme. Using this NBER approach, design patents are not classified as they are not categorized under the USPC classes.

d) Cited Journal Articles.

A citing patent may also cite a list of journal articles. In the scientometrics literature, one approach to measurement of science and technology flows is to distinguish between *papyrocentric* science and *papyrophobic* technology (Price, 1965). Science is publication directed while technology leads to patents rather than publications (Meyer, 2002). In this sense, cited patents represent sources of technological know-how, while cited publications represent sources of scientific know-how.

For each journal article that is cited by the citing patents, we conducted a search on the Web of Science database, comprising among others, the *Science Citation Index Expanded*, the *Social Science Citation Index*, the *Arts and Humanities Citation Index*, *Index Chemicus* and *Current Chemical Reactions*. While a number of cited articles would be excluded from our

[2] There were no instances of patents jointly owned by foreign private sector firms and local public sector institutions or vice versa.

analysis because the Web of Science is not exhaustive, it represents the widest available coverage of high-impact scientific journals.

We compiled detailed information on the authors of these cited journal articles, paying particular attention to their organizational affiliation. The geographic origin of the cited article is determined by the location of the organization to which the article's author is affiliated. We also identify if the organization is a private sector entity or a university, public institute or other government-related organization. In the cases of joint-authorship, the organizational affiliation of the first-named author is used. In total, there were 230 citing patents that cited 1,003 journal articles listed in the Web of Science database.

4. Profile of Singapore-Invented Patents

4.1 Overall Trends in Patenting Activities in Singapore

Figure 1 shows that Singapore invented patents are on an upward trend, with notable increase in the rate of patenting since 1996. In the three years 2001 to 2003, the number of Singapore invented patents was higher than the cumulative total granted in the previous 25 years. Very few patents were granted prior to the mid 1980s, after which there was an increase in the number of MNCs establishing R&D activities in Singapore. Up to the mid 1990s, foreign assignees dominated patenting activity in Singapore. The deepening of local R&D activities in the late 1990s saw a reversal of this trend in the period 1996-2003.

Table 2 contrasts the composition of Singapore invented patents in the two time periods of interest, 1976-95 and 1996-2001. As can be seen, the share of patents assigned to local Singapore companies increased from 21.5% to 40.2%, in tandem with a decline in the share of foreign companies from 56.7% to 43.7%. There is also a healthy increase in the rate of patenting in local Universities and PRICs.

Notwithstanding the increase in patenting by local organizations, Table 3 shows that the presence of foreign firms continue to be significant among the largest patent owners in Singapore, accounting for 14 out of the top 20 patent owning organizations at the end of 2001. As late as 1995, the top 5 patent owners in Singapore were all foreign firms. However, by the end of 2001, The top and third largest owners of patents had become Singaporean entities – a local company (Chartered Semiconductor, with 346 patents) and a local university (National University of Singapore, with 66). Reflecting the dominance of patenting by large organizations in Singapore, the top 20 patent owners accounted for 57.8% of all patented invention in Singapore in 2001.

4.2 Characteristics of Citing Patents

Table 4 presents an overview of the citing patents in our analysis sample. Of the total of 1423 citing patents, more than half are in the electronics and electrical (35%) and computers and communications (16%) categories respectively, reflecting the heavy focus on electronics manufacturing and information technology in Singapore's industry development strategy in the 1990's.

On average, each patent cited 7.3 other patents. The propensity to cite other patents was highest for patent holders that are Singapore subsidiaries of foreign MNCs, and lowest for

local universities/ PRICs/ government organizations.

The fifth column of numbers show the propensity of patents to cite other patents owned by the same assignee organization as the citing patents. This is a measure of self-reliance for technological knowledge. On average, 9.5% of patents cited by each patent is owned by the same assignee that owns the citing patent. The propensity to self-cite is seen to be highest amongst patents owned by foreign MNCs with local subsidiaries. On average, 16.2% of the patents cited by each Singapore invented patent owned by these foreign MNCs are self-citations. This may reflect the deeper technology base on MNC firms as they have a longer history of patenting and therefore, own higher numbers of cumulative patents.

The fourth column of numbers shows a measure of the *citing intensity of local patents*. On average, only 1.7% of patents that are cited by any one citing patent are from Singapore. A patent is considered to be "from Singapore" if it is assigned to a local Singapore company, a local university/ PRIC/ government organization or a local subsidiary of a foreign company. This suggests that the dependence on local sources of knowledge is minimal. Even if we include cited patents owned by foreign firms with subsidiary operations in Singapore, the increased share of local knowledge (2.6%) remains small. The citing intensity of local patents is noticeably higher among the local organizations, both local private sector companies (3.6%) and local public sector organizations and universities (3.4%). By contrast, only 0.1% of patents cited by foreign MNCs with Singapore subsidiaries are owned by Singaporean organizations, while the corresponding figure was 0.7% for Singapore-based subsidiaries of foreign companies.

The findings summarized in Table 4 represent preliminary evidence of how knowledge sources differ for the different groups of inventing organizations. Dependence on locally produced knowledge appears to be higher for local organizations, although the level of dependence is still quite low. Foreign MNCs appear to rely on internally generated knowledge to a much larger extent than other organizations. In the next part of the paper, we attempt to confirm these preliminary conclusions by looking at citing intensity that is measured by the relative frequencies of citation pairs.

5. Main Findings

5.1 Sources of Technological Knowledge: Citations to Patents

a) Analysis of Patent Citations by Type of Citing Patent

As earlier described, the citations flow data is organized by pairs of citing-cited patents, with a total of 10350 pairs originating from 1423 citing patents. Each citing patent is categorized into one of four groups of organizational type based on its first assignee: 1) Local Singapore company, 2) Local subsidiary of a foreign MNC, 3) foreign MNC with local subsidiary, 4) Local university/ PRIC/government organization. The same sectors are used for the cited patents, with the addition of two sectors: 5) Foreign university/ PRIC/ government organization and 6) Foreign company without subsidiaries in Singapore.

Table 5 shows the matrix of patent citation flows to and from the different assignee types. This is represented graphically in Figure 2, where the width of the arrows indicate the number of citations in the relevant direction. As seen from both Table 5 and Figure 2, the greatest

sources of knowledge for patents owned by all types of assignees are foreign companies with local subsidiaries. The flow of knowledge from foreign MNCs to local organizations is particularly notable, with 2513 citations made by local companies and 348 citations made by local universities and public sector organizations. We also observe a high degree of reliance on sources of knowledge outside of Singapore, in particular foreign companies that do not have any presence in Singapore. 1155 of the citations made by local Singapore companies are owned by such foreign companies, representing 27.4% of citations.

The reliance on knowledge from Singapore-based organizations is only significant among Singaporean organizations. Only about 3% of the 4,230 citations made by local organizations are to patents owned by local organizations. In contrast the number of local citations made by foreign companies is less than a handful out of over 5,000 citations. These findings confirm that the reliance on Singapore produced knowledge is more significant among Singapore organizations.

In Table 6, we investigate if the pattern of ownership of cited patents has changed over time, with particular interest in the sources of knowledge for local organizations. For Singapore owned companies, there is a large increase in the share of citations to foreign MNCs with subsidiaries in Singapore. At the same time, the share of citations made to local companies and local universities/ PRICs has also increased slightly. Correspondingly, the reliance on foreign companies without any Singapore presence has decreased significantly.

In the case of Singaporean universities/PRICs/government organizations, there is also a similar increased dependence on knowledge from foreign companies with local subsidiaries. While local companies did not contribute any knowledge in the period 1976-1995, they accounted for 1.5% of cited patents in the period 1996-2001. Citations to both local and foreign universities and PRICs had also increased in this period.

From these findings, we can conclude that there has been an increase in the use of local knowledge sources by local organizations, in particular knowledge that are produced by foreign MNCs with local presence. While the increase in citations to local companies and universities/PRICs is not as pronounced, it nevertheless suggests a trend towards greater reliance on indigenous knowledge.

Additional analysis of the sources of knowledge by different technology classes of the citing patent suggests that the above broad picture holds, suggesting that technology specific influences are relatively minor.

b) Geographic Origins of Cited Patents

A clear pattern of dominance of North America emerges from an analysis of the geographic location of inventions cited by Singapore patents (Table 7), with shares ranging from 48.7% for local subsidiaries of foreign firms to over 60% for foreign firms with operation in Singapore. Japanese patents are the next most cited, followed by patents from European countries. It is interesting to note, however, that indigenous firms exhibited a very high propensity to cite patents from Taiwan (10.7%, vs. 0.3% to 3.7% for other organizational types), due largely to the high level of patenting by local firms in the semiconductor and electronics field, where Taiwan had a high share of the world total patent counts. Japanese patents were most highly cited in the mechanical fields, while European patents were most frequently cited in the chemical field.

Comparing patenting in the two time periods 1976-95 vs. 1996-2001, we found significant changes in pattern of geographic location of knowledge sources. For local companies, Japan and Europe as a source of knowledge declined, while that of US, Korea and Taiwan increased. The increase in Taiwan was most dramatic, from a mere 1.5% before 1996 to 11.6% after 1996.

Amongst the local universities/ PRICs and government organizations, Taiwan similarly emerges as an important source of knowledge, contributing 4.3% of citations, whereas Taiwanese patents were not cited at all prior to 1996. There is also an increase in citations to Singapore and Japanese owned patents, while European owned patents declined in citations received.

The emergence of Taiwan as a source of knowledge for local organizations is in strong contrast to the trends seen among foreign firms, where the reliance on Japanese patents is seen to be growing, while that of Europe declined.

5.2 Sources of Scientific Knowledge: Citations to Journal Publications

a) Analysis of Publication Citations by Type of Citing Patent

Similar to the citing-cited patents pairs, the publications citation flow data are organized by pairs of citing patent – cited article. There are a total of 230 citing patents making citations to 1003 journal articles listed in the Web of Science. Using the same organizational sectors as for patent citations, Table 8 and Figure 3 show the flow of publications citations from citing patent to cited articles, for the different organizational types. Unlike patents citations, we found that the bulk (60%) of publication citations are made to foreign universities and overseas public sector organizations, with another 9.5% going to local universities/PRICs. This not only reflects the more important role of universities and public research institutes as sources of scientific knowledge for invention, but also encouragingly, a greater share of local universities as scientific knowledge sources to invention in Singapore, as opposed to technological knowledge, where the local universities contributed only 0.2% of patent citation. While patents by the local universities, as expected, exhibited the highest propensity to cite scientific journal articles produced by the local universities themselves (21.1%), foreign firms also showed higher propensity to cite locally produced scientific knowledge than locally produced technological knowledge as well. Local firms, however, had higher propensity to cite locally produced patents than locally authored journal articles.

Another interesting observation from Table 8 and Figure 3 is that, in contrast to patent citations, there is a proportionately greater share of scientific knowledge sources coming from foreign companies that have no operation in Singapore vs. those that have. While more than two-thirds of cited patents owned by foreign firms are from foreign firms that have operation in Singapore, more than half of cited journals published by authors with foreign firm affiliation are from foreign firms with no presence in Singapore.

Unlike the case of patent citations, where local technological knowledge is gaining in importance over time, Table 9 shows that the share of citations to scientific articles authored by local organizations had actually fallen in the period after 1995, suggesting that innovation activities in Singapore were becoming more dependent on foreign sources of scientific knowledge in recent years. Although there is an increase in the propensity of local

universities/PRICs to cite locally produced scientific knowledge (from 15.4% to 21.73%), this shift was not sufficiently large to offset the overall decline in local scientific article citation among local firms and foreign firms with subsidiary operations in Singapore.

b) Geographic Origins of Cited Publications

As expected, scientific publications by authors from North America are the most cited by all type of organizations owning the citing patents (Table 10). Compared to patent citations, journal articles from Europe are more frequently heavily cited, especially by local organizations, while Japan as a source of scientific knowledge appears to be much lower than as a technology source.

An examination of the changes in the pattern of geographic origins of cited articles over time also reveals interesting differences from cited patents (Table 11). While Europe as a source of cited patents declined over time as observed earlier, there was a notable increase in the share of Europe as source of cited journals, especially by local Singapore companies. The share of locally authored publications showed a modest aggregate increase, the result of two opposing trends: While local universities increased their propensity to cite locally authored articles, the trend is opposite for local and foreign firms.

6. Discussion and Conclusion

The above preliminary findings will be further expanded with more detailed statistical testing in a revised version of this paper. Despite the tentative nature of our findings, a number of tentative observations can nevertheless be highlighted at this stage. Firstly, by examining the patent citation flows for the entire stock of patents generated in an economy, we were able to develop a *systemic* view of *sources* and *flows* of one important type of knowledge in a national innovation system – knowledge as codified in patents and journal publications. It is true that there are other important sources and flows of knowledge used in innovation activities that our methodology does not cover, for example, tacit knowledge embodied in people that are transferred through collaboration networks or the movement of people from one organizational sector to another, and knowledge embodied in software, equipment and systems. However, since knowledge as codified in patents and scientific articles that are actually cited by a patented invention represents the most proximate and accurate measure of the antecedent knowledge inputs upon which the new invention is developed, we believe that our methodological approach does provide a valuable window to observe the working of an entire national innovation system in terms of the pattern of innovation activities among different organizational sectors and the knowledge flows between them, at a point in time as well as changes over time.

By applying such a systemic approach, we were able to confirm the important role that foreign firms play in the national innovation system of a small, open newly industrialized economy like Singapore. Not only do foreign firms contribute a significant share of the innovation activities in the host country (as measured by their share of patenting output in Singapore), but that they appear to generate significant knowledge spillover that contribute to further innovation activities in the future (as measured by patent citations). In addition, we were able to document the relatively low contribution of local universities and public research institutes as technological knowledge sources for the innovating activities of both local and foreign firms. We were also able to trace changes over time as Singapore increases her innovating intensity. Thus, although prior research (e.g. Hu 2004) has investigated the

knowledge spillover impact of foreign firms in Singapore using similar patent citation tracing method, its partial focus on one organizational sector limits a more comprehensive understanding of the entire national innovation system. Overall, our characterization of the knowledge sources and flows in Singapore's national innovation system may by representative of other newly industrialized economies adopting a similar open-economy, foreign investment-leveraging approach.

Secondly, while most prior research focused on the use of patent citation data, we were able to combined data on citation of patents as well as scientific journals from citing patents to provide a more holistic picture of the pattern of sources and flows of knowledge in a national innovation system. By combining information on *scientific* knowledge (proxied by journal article citations) as well as *technological* knowledge (proxied by patent citations), this more comprehensive approach allows us to develop a number of new insights. In particular, we found that not only were the relative importance of various organization types (local firms, local universities and foreign firms) different for scientific vs. technological knowledge, but that their pattern of change over time may vary as well.

Thirdly, we believe that our proposed systemic approach can potentially provide a common methodological tool for international comparative research on how national innovation systems differ among countries. By comparing and contrasting differences in the structure of knowledge sources and flows of national innovation systems, we can begin to develop a better understanding of common factors that influence national innovation system characteristics (e.g. size of domestic economy, degree of openness to foreign investment and trades, stage of economic development, etc.), and how and why they exhibit different innovation performance. For example, while countries like Ireland may share some of the features we found in Singapore's innovation pattern due to her similar strong reliance on R&D by foreign firms, countries like Finland and Sweden are likely to exhibit quite different patterns, due to the presence of large, technologically advanced domestic firms which could serve as important sources of technological knowledge for other domestic firms. The more advanced development of the university and public research system in these more advanced countries may also suggest a stronger scientific knowledge role than was observed in our study of Singapore.

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Table 1 Growth of R&D and patenting in Singapore, 1976-2003

Year	GERD (S$ m)	GERD/GDP (%)	RSEs	RSE/10,000 labour force	USPTO Patents
1978	37.80	0.21	818	8.4	3
1981	81.00	0.26	1,193	10.6	5
1984	214.30	0.54	2,401	18.4	4
1987	374.70	0.86	3,361	25.3	16
1990	571.70	0.85	4,329	27.7	28
1991	756.80	1.01	5,218	33.6	21
1992	949.50	1.17	6,454	39.8	41
1993	998.20	1.06	6,629	40.5	61
1994	1,174.98	1.09	7,086	41.9	79
1995	1,366.55	1.15	8,340	47.7	81
1996	1,792.14	1.38	10,153	56.3	124
1997	2,104.56	1.49	11,302	60.2	132
1998	2,492.26	1.82	12,655	65.5	181
1999	2,656.30	1.90	13,817	69.9	207
2000	3,009.52	1.88	14,483	66.1	299
2001	3,232.68	2.10	15,366	72.5	387
2002	3,404.66	2.15	15,654	73.5	533
2003	3,424.47	2.15	17,074	79.4	564
	Compound average growth rate per annum (%)				
1978-1990	25.4		14.9		
1990-1995	19.0		14.0		
1995-2000	17.1		11.7		
2000-2003	4.4		5.6		
1995-2003	12.2		9.4		

Source: National Survey of R&D Expenditure and Manpower (various years), Science Council of Singapore (prior to 1990); National Survey of R&D in Singapore (various years), National Science & Technology Board (for 1990-2000) and Agency for Science, Technology & Research (2001 to 2003)

Table 2 Share of Singapore Patenting [1] by Assignee Categories (1976-2001)

Type of Assignee	*1976-1995*	*%*	*1996-2001*	*%*	*TOTAL*	*%*
Singapore Assignee	178	41.7	*713*	53.6	891	25.4
1.Individuals	71	16.6	88	6.6	159	4.5
2.Companies	92	21.5	534	40.2	626	17.8
3.Universities and PRICs	15	3.5	91	6.8	106	3.0
Foreign Assignee	249	58.3	*617*	46.4	866	24.6
1. Individuals	4	0.9	5	0.4	9	0.3
2.Companies	242	56.7	581	43.7	823	23.4
3.Universities and PRICs	3	0.7	31	2.3	34	1.0
Total	427	*100*	*1330*	*100*	*3514*	*100*

Note1: Patents where at least one inventor is a Singaporean
Source: Database of the U.S. Patent and Trademark Office (USPTO) (various years)

Table 3 Top 20 Owners of Singapore Patents[1], Cumulative 1976-2001

No.	Company	Type of Organisation	Country	No. of patents 1976-2001
1	Chartered Semiconductor Manufacturing	Local Company	Singapore	346
2	Hewlett-Packard Company	MNC with Sub	United States	95
3	National University of Singapore	Local University	Singapore	79
4	Motorola, Inc.	MNC with Sub	United States	77
5	Texas Instruments	MNC with Sub	United States	77
6	Tritech Microelectronics International	Local Company	Singapore	56
7	Molex Incorporated	MNC with Sub	United States	34
8	Matsushita Electric Industrial Company	MNC with Sub	Japan	31
9	Seagate Technology	MNC with Sub	United States	29
10	Institute of Microelectronics	Local PRIC	Singapore	28
11	U.S. Philips Corporation	MNC with Sub	United States	27
12	STMicroelectronics	MNC with Sub	Frace/Italy	24
13	Thomson Consumer Electronics, S.A.	MNC with Sub	France	18
14	Black & Decker, Inc	MNC with Sub	United States	17
15	Nestec S.A.	MNC with Sub	Switzerland	15
16	Advanced Micro Devices	MNC with Sub	United States	13
17	Lucent Technologies	MNC with Sub	United States	13
18	Berg Technology	MNC with Sub	United States	12
19	Creative Technology	Local Company	Singapore	12
20	ST Assembly Test Services	Local Company	Singapore	12

[1]Patents where at least one inventor is a Singaporean. Includes patents which are jointly assigned.
Source: Database of the U.S. Patent and Trademark Office (USPTO) (various years)

Table 4 Profile of Citing Patents, 1976-2001

	Number of Patents	Age of Patent	Average Number of Citations Made to Other Patents (granted after 1976)	Proportion of Cited Patents that are from Singapore	Proportion of Cited Patents that are Self Citations
ALL	**1423**	**6.25**	**7.27**	**0.017**	**0.095**
Local Singapore Company	549	5.62	7.64	0.036	0.032
Local Singapore Subsidiary of Foreign MNC	48	5.27	8.75	0.007	0.008
Foreign MNC with local subsidiary	711	6.97	7.21	0.001	0.162
Local University / PRIC / Government	115	5.15	5.34	0.034	0.015

Table 5 Ownership of Cited Patents by Ownership of Citing Patents, 1976-2001

Ownership of Cited Patent	Ownership of Citing Patent: Local Singapore Company	Local Singapore Subsidiary of Foreign MNC	Foreign MNC with local subsidiary	Local University / PRIC / Government	ALL
Counts					
No assignee	269	40	331	36	676
Local Pte Sector Company	141	0	0	8	149
Local Subsidiary of Foreign MNC	0	4	2	0	6
Foreign MNC with local subsidiary (figure in brackets refers to patents with at least one Singapore inventor)	2513 (1)	222 (0)	3328 (91)	348 (2)	6411 (94)
Local Uni/ PRIC/ Gov	5	0	1	10	16
Foreign Uni/ PRIC/ Gov	129	5	61	55	250
Foreign Company without subsidiary in Singapore	1155	115	1411	161	2842
TOTAL	4212	386	5134	618	10350
% Distribution					
No assignee	6.39	10.36	6.45	5.83	6.53
Local Pte Sector Company	3.35	0.00	0.00	1.29	1.44
Local Subsidiary of Foreign MNC	0.00	1.04	0.04	0.00	0.06
Foreign MNC with local subsidiary (figure in brackets refers to patents with at least one Singapore inventor)	59.66 (0.02)	57.51 (0.0)	64.82 (1.77)	56.31 (0.32)	61.94 (0.91)
Local Uni/ PRIC/ Gov	0.12	0.00	0.02	1.62	0.15
Foreign Uni/ PRIC/ Gov	3.06	1.30	1.19	8.90	2.42
Foreign Company without subsidiary in Singapore	27.42	29.79	27.48	26.05	27.46
TOTAL	100	100	100	100	100

Table 6 Trends in Ownership of Cited Patents by Ownership of Citing Patents, 1976-2001

Citing Assignee is	1976-1995	1996-2001	Total
Local Singapore Company			
No assignee	15.94	5.41	6.39
Local Pte Sector Company	2.83	3.40	3.35
Foreign MNC with local subsidiary (figure in brackets refers to patents with at least one Singapore inventor)	45.50 (0.00)	61.10 (0.03)	59.66 (0.02)
Local Uni/ PRIC/ Gov		0.13	0.12
Foreign Uni/ PRIC/ Gov	1.03	3.27	3.06
Foreign Company without subsidiary in Singapore	34.70	26.68	27.42
TOTAL	100	100	100
Local Subsidiary of Foreign MNC			
No assignee	20.00	8.23	10.36
Local Subsidiary of Foreign MNC	2.86	0.63	1.04
Foreign MNC with local subsidiary (figure in brackets refers to patents with at least one Singapore inventor)	50.00 (0.00)	59.18 (0.00)	57.51 (0.00)
Foreign Uni/ PRIC/ Gov		1.58	1.30
Foreign Company without subsidiary in Singapore	27.14	30.38	29.79
TOTAL	100	100	100
Foreign MNC with local subsidiary			
No assignee	4.12	7.09	6.45
Local Pte Sector Company			
Local Subsidiary of Foreign MNC		0.05	0.04
Foreign MNC with local subsidiary (figure in brackets refers to patents with at least one Singapore inventor)	67.03 (1.70)	64.21 (1.79)	64.82 (1.77)
Local Uni/ PRIC/ Gov		0.02	0.02
Foreign Uni/ PRIC/ Gov	0.72	1.32	1.19
Foreign Company without subsidiary in Singapore	28.14	27.30	27.48
TOTAL	100	100	100
Local University / PRIC / Government			
No assignee	12.20	4.85	5.83
Local Pte Sector Company		1.49	1.29
Local Subsidiary of Foreign MNC			
Foreign MNC with local subsidiary (figure in brackets refers to patents with at least one Singapore inventor)	50.00 (0.00)	57.28 (0.37)	56.31 (0.32)
Local Uni/ PRIC/ Gov	1.22	1.68	1.62
Foreign Uni/ PRIC/ Gov	6.10	9.33	8.90
Foreign Company without subsidiary in Singapore	30.49	25.37	26.05
TOTAL	100	100	100
OVERALL			
No assignee	7.97	6.26	6.53
Local Pte Sector Company	0.66	1.59	1.44
Local Subsidiary of Foreign MNC	0.12	0.05	0.06
Foreign MNC with local subsidiary (figure in brackets refers to patents with at least one Singapore inventor)	60.41 (1.15)	62.23 (0.82)	61.94 (0.91)
Local Uni/ PRIC/ Gov	0.06	0.17	0.15
Foreign Uni/ PRIC/ Gov	1.03	2.68	2.42
Foreign Company without subsidiary in Singapore	29.75	27.02	27.46
TOTAL	100	100	100
Total Number of Patents Cited by			
Local Singapore Company	389	3823	4212
Local Singapore Subsidiary of Foreign MNC	70	316	386
Foreign MNC with local subsidiary	1116	4018	5134
Local University / PRIC / Goverment	82	536	618

Table 7 Geographic Origin of Cited Patents by Ownership of Citing Patent, 1976-2001

	Local Singapore Company	Local Singapore Subsidiary of Foreign MNC	Foreign MNC with local subsidiary	Local University / PRIC / Government	ALL
Number of Citing Patents	549	48	711	115	1423
Number of Cited Patents	4212	386	5134	618	10350
% of Self-Citations	3.1%	1.0%	14.3%	1.5%	8.5%
Origin of Cited Patent (% distribution)					
No Assignee	6.4	10.6	6.5	5.8	6.6
North America (USA and Canada)	54.7	48.7	60.6	58.6	57.7
Japan	17.4	21.5	21.2	17.2	19.4
Korea	3.1	0.5	1.5	1.5	2.1
Taiwan	10.7	0.3	0.8	3.7	5.0
Singapore	3.5	1.0	0.1	2.9	1.7
Europe	3.9	16.6	8.8	9.7	7.2
Others	0.3	0.8	0.6	0.6	0.5
TOTAL	*100.0*	*100.0*	*100.0*	*100.0*	*100.0*

Table 8 Trends in Geographic Origin of Cited Patents (1976-2001)

	1976-1995	1996-2001	Total
Citing Assignee is			
Local Singapore Company			
No Assignee	15.9	5.5	6.4
North America (USA and Canada)	48.8	55.3	54.7
Japan	21.6	16.9	17.4
Korea	0.5	3.3	3.1
Taiwan	1.5	11.6	10.7
Singapore	2.8	3.5	3.5
Europe	7.5	3.6	3.9
Others	1.3	0.2	0.3
Total	100.0	100.0	100.0
Local Subsidiary of Foreign MNC			
No Assignee	20.0	8.5	10.6
North America (USA and Canada)	42.9	50.0	48.7
Japan	1.4	25.9	21.5
Korea		0.6	0.5
Taiwan		0.3	0.3
Singapore	2.9	0.6	1.0
Europe	30.0	13.6	16.6
Others	2.9	0.3	0.8
Total	100.0	100.0	100.0
Foreign MNC with local subsidiary			
No Assignee	4.1	7.1	6.5
North America (USA and Canada)	67.3	58.8	60.6
Japan	15.3	22.8	21.2
Korea	1.2	1.5	1.5
Taiwan	0.4	0.9	0.8
Singapore		0.1	0.1
Europe	11.7	8.0	8.8
Others		0.7	0.6
Total	100.0	100.0	100.0
Local University / PRIC / Government			
No Assignee	12.2	4.9	5.8
North America (USA and Canada)	57.3	58.8	58.6
Japan	13.4	17.7	17.2
Korea	1.2	1.5	1.5
Taiwan		4.3	3.7
Singapore	1.2	3.2	2.9
Europe	14.6	9.0	9.7
Others		0.7	0.6
Total	100.0	100.0	100.0
% Self-Citations			
Local Singapore Company	2.3	3.2	3.1
Local Subsidiary of Foreign MNC	2.9	0.6	1.0
Foreign MNC with local subsidiary	19.6	12.8	14.3
Local University / PRIC / Government	1.2	1.5	1.5

Table 9 Organisational Origin of Cited Publications by Ownership of Citing Patents

Organisational Origin of Cited Articles	Ownership of Citing Patent				
	Local Singapore Company	Local Singapore Subsidiary of Foreign MNC	Foreign MNC with local subsidiary	Local University / PRIC / Government	ALL
Counts					
Local Singapore Company	1	0	0	0	1
Local Subsidiary of Foreign MNC	0	0	1	0	1
Local Uni/ PRIC/ Govt	5	1	5	84	95
Foreign MNC with Local Subsidiary	43	2	68	19	132
Foreign Uni/ PRIC/ Govt	173	12	178	238	601
Foreign Company without Local Subsidiary	58	1	56	58	173
TOTAL	280	16	308	399	1003
% Distribution					
Local Singapore Company	0.36				
Local Subsidiary of Foreign MNC	0.00		0.32		0.10
Local Uni/ PRIC/ Govt	1.79	6.25	1.62	21.05	9.48
Foreign MNC with Local Subsidiary	15.36	12.50	22.08	4.76	13.17
Foreign Uni/ PRIC/ Govt	61.79	75.00	57.79	59.65	59.98
Foreign Company without Local Subsidiary	20.71	6.25	18.18	14.54	17.27
TOTAL	100.0	100.0	100.0	100.0	100.0

Table 10 Trends in Organizational Origin of Cited Publications

	1976-1995	1996-2001	Total
Citing Assignee is			
Local Singapore Company			
Local Singapore Company	0	0.42	0.36
Local Subsidiary of Foreign MNC	0	0	0
Local Uni/ PRIC/ Govt	5.00	1.25	1.79
Foreign MNC with Local Subsidiary	15.00	15.42	15.36
Foreign Uni/ PRIC/ Govt	65.00	61.25	61.79
Foreign Company without Local Subsidiary	15.00	21.67	20.71
Total	100.00	100.00	100.00
Local Subsidiary of Foreign MNC			
Local Singapore Company	0	0	0
Local Subsidiary of Foreign MNC	0	0	0
Local Uni/ PRIC/ Govt	0	6.25	6.25
Foreign MNC with Local Subsidiary	0	12.50	12.50
Foreign Uni/ PRIC/ Govt	0	75.00	75.00
Foreign Company without Local Subsidiary	0	6.25	6.25
Total		100.00	100.00
Foreign MNC with local subsidiary			
Local Singapore Company	0	0	0
Local Subsidiary of Foreign MNC	0	0.41	0.32
Local Uni/ PRIC/ Govt	3.13	1.23	1.62
Foreign MNC with Local Subsidiary	20.31	22.54	22.08
Foreign Uni/ PRIC/ Govt	57.81	57.79	57.79
Foreign Company without Local Subsidiary	18.75	18.03	18.18
Total	100.00	100.00	100.00
Local University / PRIC / Government			
Local Singapore Company	0	0	0
Local Subsidiary of Foreign MNC	0	0	0
Local Uni/ PRIC/ Govt	15.38	21.67	21.05
Foreign MNC with Local Subsidiary	17.95	3.33	4.76
Foreign Uni/ PRIC/ Govt	58.97	59.72	59.65
Foreign Company without Local Subsidiary	7.69	15.28	14.54
Total	100.00	100.00	100.00
Overall			
Local Singapore Company		0.05	0.05
Local Subsidiary of Foreign MNC		0.05	0.05
Local Uni/ PRIC/ Govt	6.45	4.85	4.98
Foreign MNC with Local Subsidiary	18.06	10.56	11.13
Foreign Uni/ PRIC/ Govt	61.29	68.05	67.54
Foreign Company without Local Subsidiary	14.19	16.43	16.26
Total	100.00	100.00	100.00
Total Number of Articles Cited by			
Local Singapore Company	40	240	280
Local Singapore Subsidiary of Foreign MNC	0	16	16
Foreign MNC with local subsidiary	64	244	308
Local University / PRIC / Goverment	39	360	399

Table 11 Geographic Origin of Cited Publications by Ownership of Citing Patent

	Local Singapore Company	Local Singapore Subsidiary of Foreign MNC	Foreign MNC with local subsidiary	Local University / PRIC / Government	ALL
Number of Citing Patents	83	4	90	53	230
Number of Cited Articles	280	16	308	399	1003
Origin of Cited Article (% distribution)					
North America (USA and Canada)	66.4	75.0	66.3	43.1	57.3
Japan	6.8		9.1	8.5	8.1
Taiwan	0.7		2.3	1.3	1.4
Singapore	2.1	6.3	1.9	21.1	9.7
Europe	16.1	12.5	14.9	19.8	17.1
Others	7.9	6.3	5.5	6.3	6.5
TOTAL	*100.0*	*100.0*	*100.0*	*100.0*	*100.0*

Table 12 Trends in Geographic Origin of Cited Publications by Ownership of Citing Patent

	1976-1995	1996-2001	Total
Citing Patent Assignee is			
Local Singapore Company			
North America (USA and Canada)	67.50	66.25	66.43
Japan	7.50	6.67	6.79
Taiwan		0.83	0.71
Singapore	5.00	1.67	2.14
Europe	10.00	17.08	16.07
Others	10.00	7.50	7.86
Total	100.0	100.0	100.0
Local Subsidiary of Foreign MNC			
North America (USA and Canada)		75.00	75.00
Japan			
Taiwan			
Singapore		6.25	6.25
Europe		12.50	12.50
Others		6.25	6.25
Total		100.0	100.0
Foreign MNC with local subsidiary			
North America (USA and Canada)	65.63	66.39	66.23
Japan	7.81	9.43	9.09
Taiwan		2.87	2.27
Singapore	3.13	1.64	1.95
Europe	12.50	15.57	14.94
Others	10.94	4.10	5.52
Total	65.63	66.39	66.23
Local University / PRIC / Government			
North America (USA and Canada)	56.41	41.67	43.11
Japan		9.44	8.52
Taiwan		1.39	1.25
Singapore	15.38	21.67	21.05
Europe	17.95	20.00	19.80
Others	10.26	5.83	6.27
Total	100.0	100.0	100.0
Total Number of Articles Cited by			
Local Singapore Company	40	240	280
Local Singapore Subsidiary of Foreign MNC	0	16	16
Foreign MNC with local subsidiary	64	244	308
Local University / PRIC / Goverment	39	360	399

Figure 1: Trend in Singapore Invented Patents, 1976 – 2003

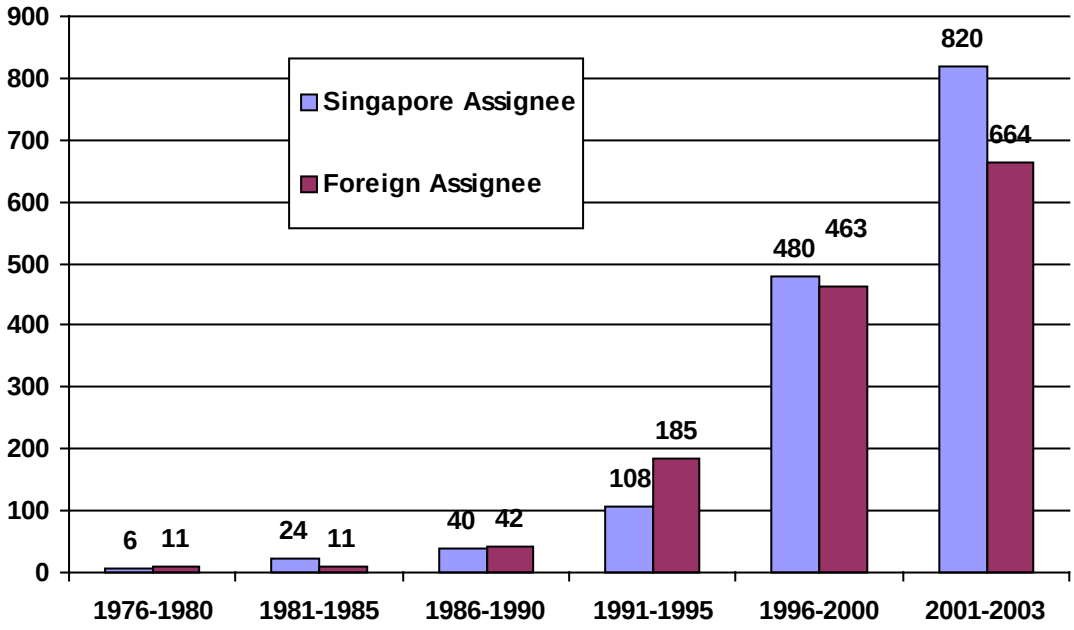
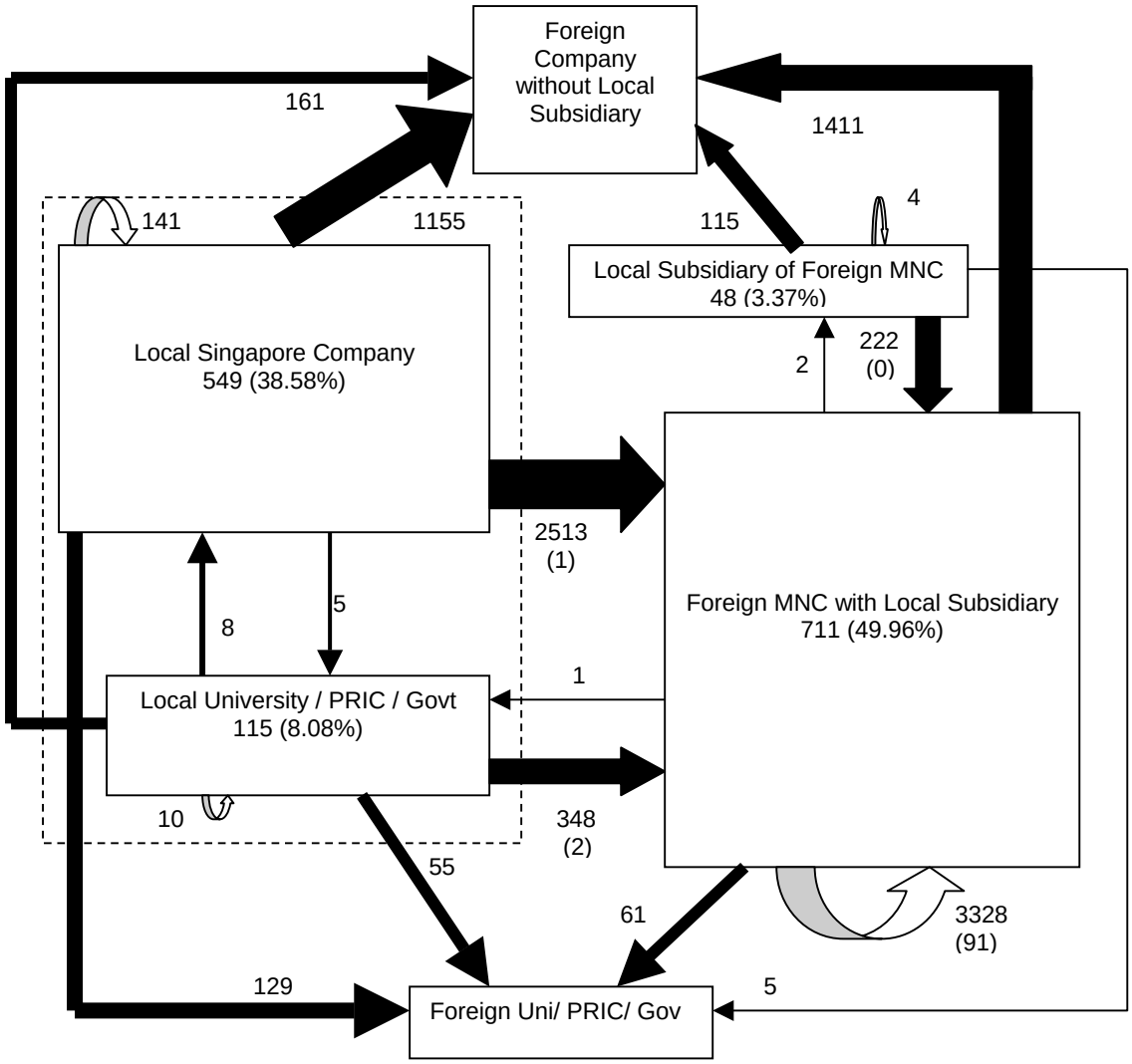


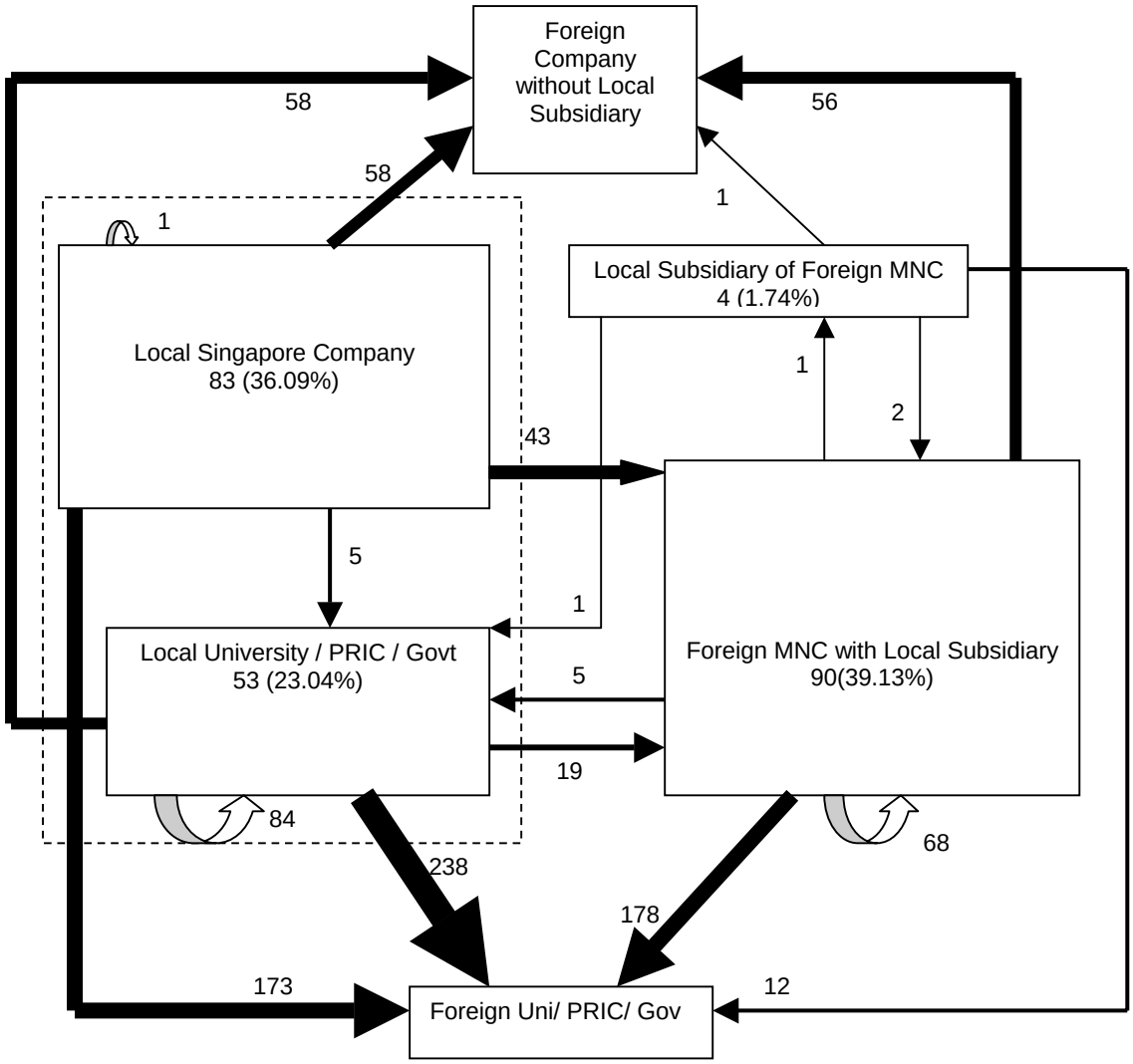
Figure 2: Patent Citation Flows for Singapore Invented Patents



Direction of arrows reflects the direction of citation flow from the citing patent to the cited patent. Numbers next to arrows indicate the number of citations made.

For citations to patents owned by Foreign MNCs with Local Subsidiaries, the figures in parentheses refer to the number of patents that have at least one inventor that was a Singapore resident at the time of the patent application.

Figure 3: Publication Citation Flows for Singapore Invented Patents



Direction of arrows reflects the direction of citation flow from the citing patent to the cited article. Numbers next to arrows indicate the number of citations made.