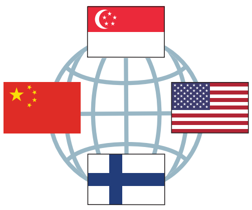
FEATURE ARTICLE

INNOVATION SPACE AND THE CUMULATIVE NATURE OF TECHNOLOGICAL PROGRESS:
A Case Study of Singapore

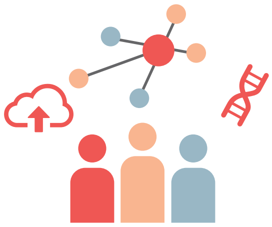
INTRODUCTION

Knowledge of their existing technological strengths and the adjacent technological areas that can leverage these strengths is important for economies seeking to upgrade their innovation capabilities. To enhance understanding in this area, a diagnostic tool called the "Innovation Space" was created to (i) analyse the technological capabilities of economies over time, (ii) benchmark the technological capabilities of economies against one another, (iii) assess economies' ability to build new technological capabilities based on their existing technological strengths, and (iv) identify opportunities for innovation collaborations between countries.

ANALYSE THE TECHNOLOGICAL CAPABILITIES OF ECONOMIES OVER TIME



BENCHMARK THE TECHNOLOGICAL CAPABILITIES OF ECONOMIES AGAINST ONE ANOTHER



ASSESS ECONOMIES' ABILITY TO BUILD NEW TECHNOLOGICAL CAPABILITIES BASED ON THEIR EXISTING TECHNOLOGICAL STRENGTHS

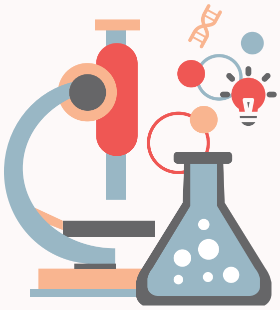
IDENTIFY OPPORTUNITIES FOR INNOVATION COLLABORATIONS BETWEEN COUNTRIES

SINGAPORE'S INNOVATION LANDSCAPE

In Singapore's case, we find that its areas of innovation through the years have complemented its economic needs and productive capabilities. Reflecting its progress in developing technological capabilities, Singapore has seen healthy growth in its patenting activity and forged stronger international innovation collaborations over the past decade. Its patents also generally have higher technological influence and are advancing from more recent technology.

CONCLUSION

Singapore's Research, Innovation and Enterprise plans and Industry Transformation Maps play important roles in deepening the linkages in its innovation ecosystem, strengthening the research-industry nexus, and growing its indigenous innovation capabilities. Such efforts will build on Singapore's existing competitive strengths and help to drive its progress towards a knowledge-based, innovation-driven and value-creating economy.



EXECUTIVE SUMMARY

- Knowledge of their existing technological strengths and the adjacent technological areas that can leverage these strengths is important for economies seeking to upgrade their innovation capabilities. To enhance understanding in this area, we create a diagnostic tool called the "Innovation Space" to (i) analyse the technological capabilities of economies over time, (ii) benchmark the technological capabilities of economies against one another, (iii) assess economies' ability to build new technological capabilities based on their existing technological strengths, and (iv) identify opportunities for innovation collaborations between countries.

- In Singapore's case, we find that its areas of innovation through the years have complemented its economic needs and productive capabilities. Reflecting its progress in developing technological capabilities, Singapore has seen healthy growth in its patenting activity and forged stronger international innovation collaborations over the past decade. Its patents also generally have higher technological influence and are advancing from more recent technology.

- Singapore's Research, Innovation and Enterprise plans and Industry Transformation Maps play important roles in deepening the linkages in its innovation ecosystem, strengthening the research-industry nexus, and growing its indigenous innovation capabilities. In the area of intellectual property (IP), Singapore's continued investments in patent analytics and tech forecasting capabilities will help to sharpen national research and development (R&D) and innovation decisions. The strengthening of IP management capabilities will also facilitate the translation of public-funded R&D into economic and societal outcomes. Such efforts will build on Singapore's existing competitive strengths and help to drive its progress towards a knowledge-based, innovation-driven and value-creating economy.

*The views expressed in this paper are solely those of the authors and do not necessarily reflect those of the Ministry of Trade and Industry (MTI), Agency for Science, Technology and Research (A*STAR), National Research Foundation (NRF), Intellectual Property Office of Singapore (IPOS) or the Government of Singapore.*[1]

1. INTRODUCTION

A country's economic competitiveness is driven and enabled by its productive capabilities, which include physical and institutional infrastructure, production capacity, as well as production, organisational, technological and innovation capabilities (see Andreoni et al., 2015). For advanced economies, building up innovation capabilities is important as such capabilities play a key role in pushing the technological frontiers, thereby helping the economies to sustain their long-term competitive advantage and economic growth.

Innovation is a cumulative process where history and the existing stock of knowledge are important in shaping future innovations (Furman & Stern, 2011; Lazonick & Mazzucato, 2013; Acemoglu et al., 2016). Path dependence in the development of technology means that the direction of innovation is shaped by past successes and failures (Rosenberg, 1976). By fostering a conducive ecosystem where innovators build on existing successful ideas and knowledge to develop new innovations, economies can better create a self-sustaining virtuous cycle of innovation.

1 *We would like to thank Ms Yong Yik Wei, A*STAR, NRF, IPOS, and the Economic Development Board for their useful suggestions and comments.*

Knowledge of their existing technological strengths and the adjacent technological areas that can leverage these strengths is important for economies seeking to upgrade their innovation capabilities. To enhance understanding in this area, we create a diagnostic tool called the "Innovation Space" to (i) analyse the technological capabilities of economies over time, (ii) benchmark the technological capabilities of economies against one another, (iii) assess economies' ability to build new technological capabilities based on their existing technological strengths, and (iv) identify opportunities for innovation collaborations between countries. In this article, we focus on the case study of Singapore.

The rest of the paper is organised as follows. Section 2 reviews the relevant literature that motivates this study. Section 3 describes the data source and methodology used to construct the Innovation Space. Section 4 presents Singapore's innovation landscape, while Section 5 applies the Innovation Space to Singapore's context. The final section concludes.

2. LITERATURE REVIEW

An economy's existing capabilities serve as a foundation for it to build new capabilities. Leveraging data on countries' exports, Hidalgo et al. (2007) pioneered the use of product space maps to cluster products with similar capabilities.[2] In a product space map, product relatedness was based on an output-based proximity measure where two products were in close proximity if they had a high probability of being jointly exported by countries with comparative advantages in both of them (for more details, see Hausmann & Klinger, 2006, 2007). In a similar vein, Zaccaria et al.'s (2014) taxonomy network highlighted that countries followed a sequential and systematic process of industrial upgrading, as they transformed their capabilities from "root" to new products. Collectively, this body of research suggests that complementary capabilities serve as the basis to develop adjacent industrial strengths (Hidalgo, 2018), and that structural change in an economy typically follows a diffusion process over a network of products (Hidalgo & Hausmann, 2008).

Similarly, technological and scientific progress is a cumulative process whereby new innovations build on the stock of past and existing knowledge. Analysing 1.8 million United States patents between 1975 and 1994, Acemoglu et al. (2016) created an "Innovation Network" that linked progress in technological fields to prior advances in upstream technological areas. The authors found that patenting in upstream technology fields had a strong predictive power on subsequent downstream innovations over the next decade. This would suggest that prior knowledge in adjacent or related fields serves as a base to build new technological strengths.

3. DATA AND METHODOLOGY

This study focuses on the early stage of the innovation process – inventiveness, as measured by patents.[3] Patents provide ex-ante incentives to innovate by (i) rewarding innovators with ex-post profits for successful innovations, and (ii) excluding imitators for a finite period of time.[4] The mandatory disclosure of the invention in a patent in exchange for legal protection has made the patent system one of the most effective tools for knowledge sharing and technology transfer.[5] At a country level, the quantity and quality of patents generated are widely acknowledged to be important drivers of economic growth and development (see Lee & Kim, 2009; Hasan & Tucci, 2010).

Our analyses of patents leverage PATSTAT, a global patent statistical database that contains bibliographical intellectual property (IP) rights data relating to more than 100 million patent documents from over 190 patent offices[6] in the world for the period of 1977 to 2016[7]. Bibliographical information on patent applications in the PATSTAT database includes citations to prior art (i.e., published patents that precede and are referenced by the current application) and the International Patent Classification (IPC) of the patent.

2 *See Hausmann et al. (2013) for a more recent formulation of product space maps.*

3 *As this study focuses on the early stage of the innovation process using patents data, it does not cover innovation that arises from (i) the commercialisation of novel products, (ii) new business methods and processes, (iii) internet-based or software applications that are not patentable, (iv) open source innovation, and (v) inventions that are trade secrets. Nonetheless, as noted by Lee (2013), patents remain an appropriate indicator to capture the proprietary and competitive dimensions of technological change, as they are direct outcomes of the inventive process (specifically inventions which are expected to have a commercial impact).*

4 *Patents mitigate the fundamental problem of appropriability, which is a concern for inventors as knowledge – an output of the innovation process – is an intangible asset and public good. Patents are also an important part of a firm's innovation strategy because they can be used (i) to obtain licensing revenue, (ii) as bargaining chips in negotiations, and/or (iii) as a defensive strategy to prevent lawsuits.*

5 *Based on a survey by the Organisation for Economic Co-operation and Development, 88 per cent of firms from the United States, Europe and Japan reported that the information disclosed in patents was useful in shaping and implementing their research & development (R&D) strategy (Lévêque & Ménière, 2006).*

6 *They include the five largest patent offices in the world – i.e., the United States Patent and Trademark Office (USPTO), European Patent Office (EPO), China National Intellectual Property Administration (CNIPA), Japan Patent Office (JPO) and Korean Intellectual Property Office (KIPO).*

7 *More recent data were excluded from the analysis as the study focuses on published patents, which typically have a lag of 18 months from the date of filing.*

We examine patents at the family-level where identical patents that are filed in different patent offices are grouped together. We focus on published patents[8], with the earliest filing year of the patents in a patent family chosen as the reference year as it is closest to the date of invention (see OECD, 2009). The inventor's country of residence is used as the reference country of the patent, rather than where the patent is filed or the inventor's nationality. In instances where a patent family has multiple inventors from different countries of residences, it will be counted separately for each country.[9]

In order to map the patents into technology fields, we utilise the IPC[10] of the patent, which classifies patents according to their technical function and field of application. Specifically, the IPCs are aggregated into 35 technology fields using an IPC-Technology concordance table [Exhibit 1].[11] As a patent may be associated with multiple IPCs, we follow Jaffe's (1986) approach to apportion the patent based on the IPC weight to avoid over counting.[12]

Exhibit 1: List of 35 IPC Technology Fields

Electrical Engineering	Chemistry		Mechanical Engineering
1. Electrical machinery, apparatus, energy	14. Organic fine chemistry	20. Materials, metallurgy	25. Handling
2. Audio-visual technology	15. Biotechnology	21. Surface technology, coating	26. Machine tools
3. Telecommunications	16 Pharmaceuticals	22. Micro-structure and nano-technology	27. Engines, pumps, turbines
4. Digital communication	17. Macromolecular chemistry, polymers	23. Chemical engineering	28. Textile and paper machines
5. Basic communication processes	18. Food chemistry	24. Environmental technology	29. Other special machines
6. Computer technology	19. Basic materials chemistry		30. Thermal processes and apparatus
7. IT methods for management			31. Mechanical elements
8. Semiconductors			32. Transport

Instruments		Other Fields
9. Optics	12. Control	33. Furniture, games
10. Measurement	13. Medical technology	34. Other consumer goods
11. Analysis of biological materials		35. Civil engineering

Source: Schmoch (2008)

To investigate connections between patents (and the technologies embedded within them), we focus on citations to prior art which are identified by the applicant or patent examiner. Patent citations can be backward (i.e., citations to previous patent documents) or forward (i.e., citations subsequently received by the patent), and are commonly used to measure knowledge flows (Jaffe et al., 1993, 2000), patent quality (Harhoff et al., 2003), and companies' strategic behaviour (Podolny et al., 1996).

Finally, to create the Innovation Space, we adopt and expand the approach that Acemoglu et al. (2016) used to construct their Innovation Network. First, we create a Global Innovation Network based on patent citations between 2007 and 2016, which reflect the Science and Technology (S&T) precedents in inventions, and the knowledge diffusion between different technology fields. To establish linkages between technology fields in the network, we compute a CiteFlow indicator using patent citations:

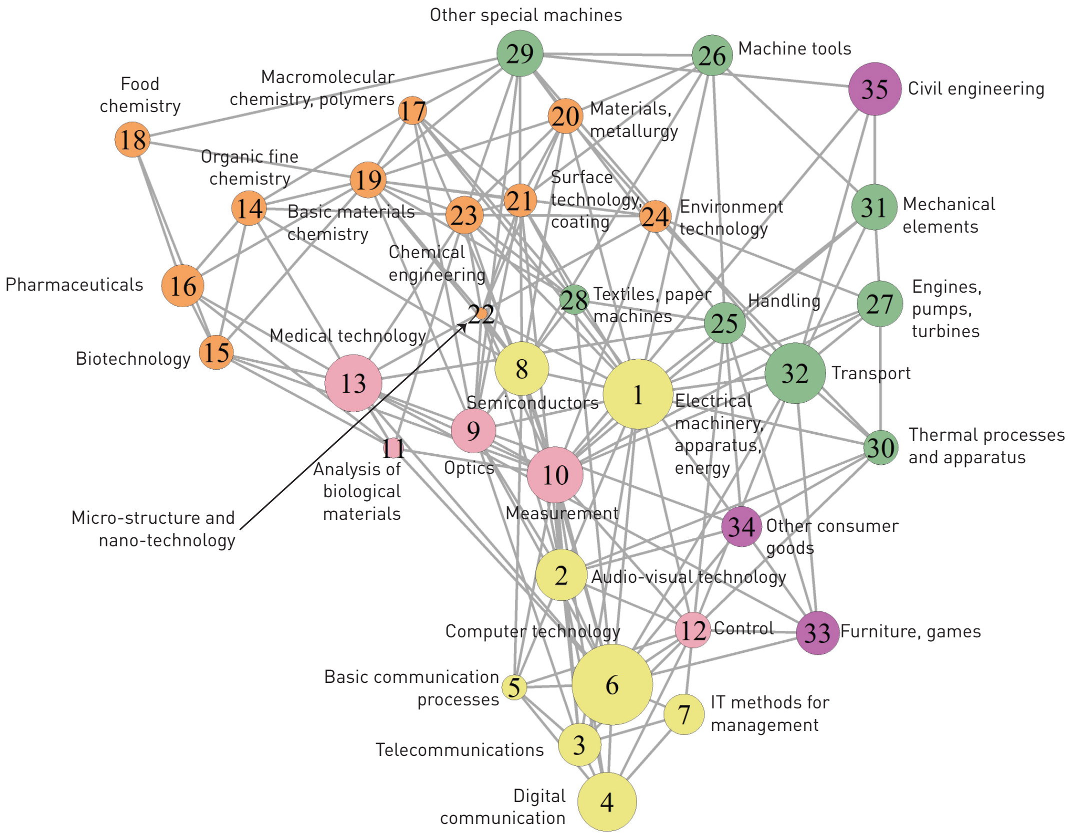
$$CiteFlow_{j\to k} = \frac{Citation_{j\to k}}{Citation_j}$$

8 *Published patents include patents that are eventually rejected for the certificate of grant. Patents that are filed but not yet published are excluded from the analysis. Patents are typically published within 18 months after filing, unless they are withdrawn before publication.*
9 *For instance, a patent family with five inventors (three residing in Germany, one in China and one in Singapore) will count as one observation in each of the three countries.*
10 *The IPC is an internationally-recognised, hierarchical patent classification system that is administered by the World Intellectual Property Organisation (WIPO).*
11 *The IPC classes are mapped to technology areas using the IPC-Technology concordance table (see Schmoch, 2008).*
12 *For instance, if a patent is associated with three IPCs under technology field A and two IPCs under technology field B, it will have a technology field weight of 0.6 in A and 0.4 in B.*

where $CiteFlow_{j \to k}$ is a 35x35 matrix that quantifies the rate at which patents in technology k cite patents in technology j. This indicator thus represents the flow of knowledge from prior technology j to technology k. We consider two technology fields to be more closely related if patents in one technology field have a higher propensity to cite patents in the other technology field (i.e., high CiteFlow).

In the Global Innovation Network, each node represents an IPC technology field, with the edge between any pair of technology fields quantified by CiteFlow [Exhibit 2]. As such, the closer the nodes, the more closely related are the technology fields represented by the nodes. The size of each node in the network is proportional to the share of a technology field's patenting activity in the world (i.e., larger nodes indicate higher global patenting activity), and the colours correspond to the five broad technology areas (i.e., Electrical Engineering, Instruments, Chemistry, Mechanical Engineering, and Other Fields) in the IPC-Technology concordance table.

Exhibit 2: Global Innovation Network, 2007-2016



Notes: The network is a directed graph, but has been plotted without arrows here. The nodes are positioned based on the best two-dimensional representation of the network.

Source: Authors' estimates

<u>Second</u>, we compute a country's Revealed Technological Advantage (RTA) to reflect the relative specialisation of the country in different technology fields:

$$RTA_{i,j,t} = \frac{P_{i,j,t}}{P_{world,j,t}} \Big/ \frac{\sum_j P_{i,j,t}}{\sum_j P_{world,j,t}}$$

where $P_{i,j,t}$ refers to the number of patents by country i in technology field j at time t. Broadly, RTA is computed as an economy's share of patents in a particular technology field in the world divided by its share of patents in the world across all technology fields.[13] The RTA is greater than one for technology fields that the economy is relatively more specialised in (i.e., it has relatively stronger capabilities in these technology fields). Conversely, RTA is less than or equal to one when the economy does not specialise in the technology field.

Third, we combine the Global Innovation Network (which maps the relationships between technology fields) and the RTA scores achieved by a country for each of the technology fields to construct the Innovation Space for that country. Specifically, RTA is used in the Innovation Space to identify the country's current technological strengths and capabilities (i.e., nodes with RTA > 1 are shaded as red, while RTA ≤ 1 are shaded as blue).

The Innovation Space builds on Acemoglu et al.'s (2016) innovation Network in three ways. First, the analysis spans beyond patents in the United States to patents in the world. This is important as knowledge and the process of knowledge diffusion are not confined within the geographical boundaries of individual countries. Second, it layers on the RTA indicator to reflect a country's technological strengths, in order to better identify opportunities through adjacencies in technology fields. Third, it captures relationships between patents (and their embedded technologies) in the more recent decade (i.e., 2007 to 2016), whereas Acemoglu et al.'s (2016) Innovation Network only focused on the period up to 1994. This is pertinent as the nature of technological progress and new advances in various technology fields (e.g., digital technology) have led to changes in the location of and linkages between technology fields in the network over the years (see Annex A).

4. SINGAPORE'S INNOVATION LANDSCAPE

As an advanced economy that has benefitted from catch-up growth in its earlier years, innovation will play an increasingly important role in Singapore's next phase of economic development.[14] Recognising the importance of innovation in sustaining Singapore's competitive edge and economic growth, Singapore's government has made significant investments in research and development (R&D) through its various S&T and Research, Innovation and Enterprise (RIE) plans (Teo et al., 2019).

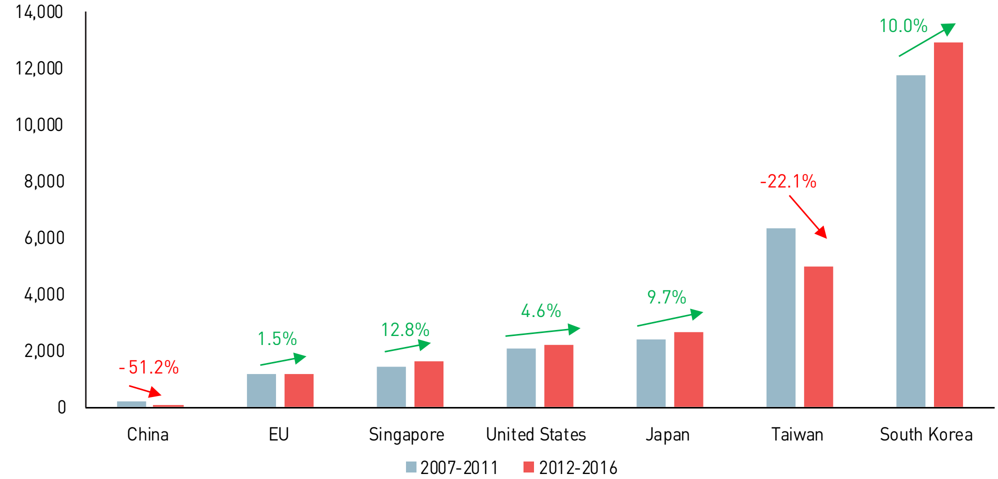
In this section, we describe the trends in Singapore's patenting activities vis-à-vis other economies to have a sense of the progress made in Singapore's innovation landscape, before presenting Singapore's Innovation Space in the next section. We make five key observations.

First, there are signs that Singapore's efforts in R&D are bearing fruit. Between the periods of 2007-2011 and 2012-2016, Singapore's patenting activity (i.e., the number of patent families published per million of total population) increased by 12.8 per cent, faster than that of the G3 economies (i.e., United States, Eurozone and Japan) and other East Asian economies (e.g., South Korea and Taiwan) [Exhibit 3].[15] Nonetheless, in absolute levels, Singapore's patenting activity in 2012-2016 remained below that of South Korea, Taiwan, Japan and the United States – economies with a longer history of innovation, suggesting that there is still room for Singapore to further raise its innovation capabilities.

13 The RTA is analytically equivalent to Balassa's (1965) revealed comparative advantage (RCA) indicator in international trade, which uses the exports of products/services instead of patents in technology fields.
14 According to the Global Innovation Index 2019 by Cornell University, INSEAD and WIPO, Singapore ranked eighth in the world and first in Asia (Dutta et al., 2019).
15 The growth in Singapore's patenting activity between the periods of 2007-2011 and 2012-2016 also compares favourably with that of other small advanced economies such as Israel (4.9 per cent), Switzerland (1.8 per cent) and Sweden (1.6 per cent).

Exhibit 3: Patenting Activity, 2007-2016

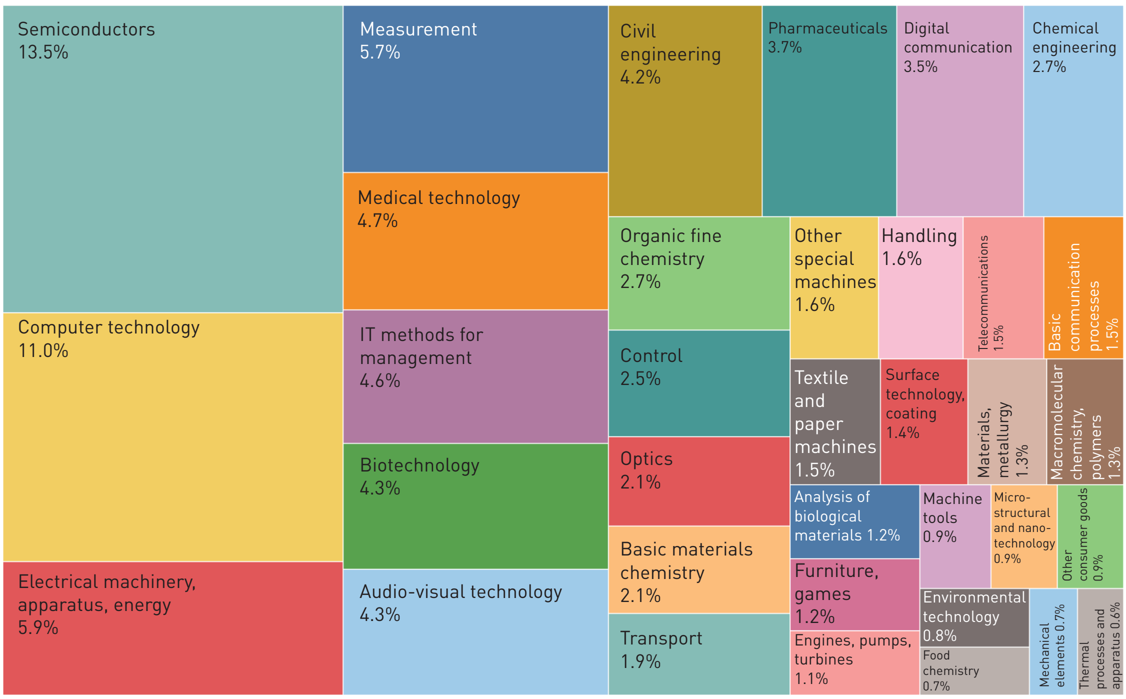
Number of Patent Families Published (per million of total population)



Source: PATSTAT, Authors' estimates

Second, Singapore's patenting activities have been in line with its capabilities in the manufacturing sector. In particular, given Singapore's strengths in the electronics industry, Singapore's patenting activities are tilted towards the technology fields of Semiconductors and Computer Technology [Exhibit 4]. This differs from global norms where patents are more evenly distributed across technology fields [Exhibit 5]. Based on Singapore's RTA Index for the period of 2012-2016, its relative technological strengths were mainly in the Electrical Engineering, Instruments and Chemistry areas, particularly Micro-structure and Nano-technology[16], Semiconductors, and Biotechnology [Exhibit 6].

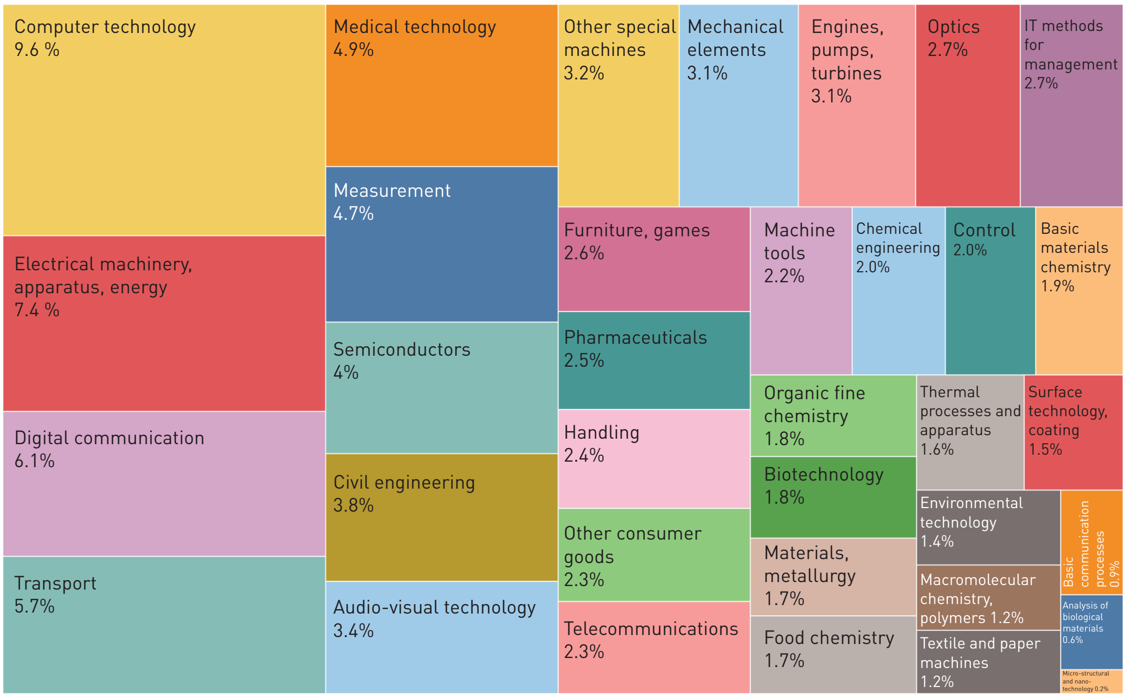
Exhibit 4: Share of Patenting Activity in Singapore, 2012-2016



Source: PATSTAT, Authors' estimates

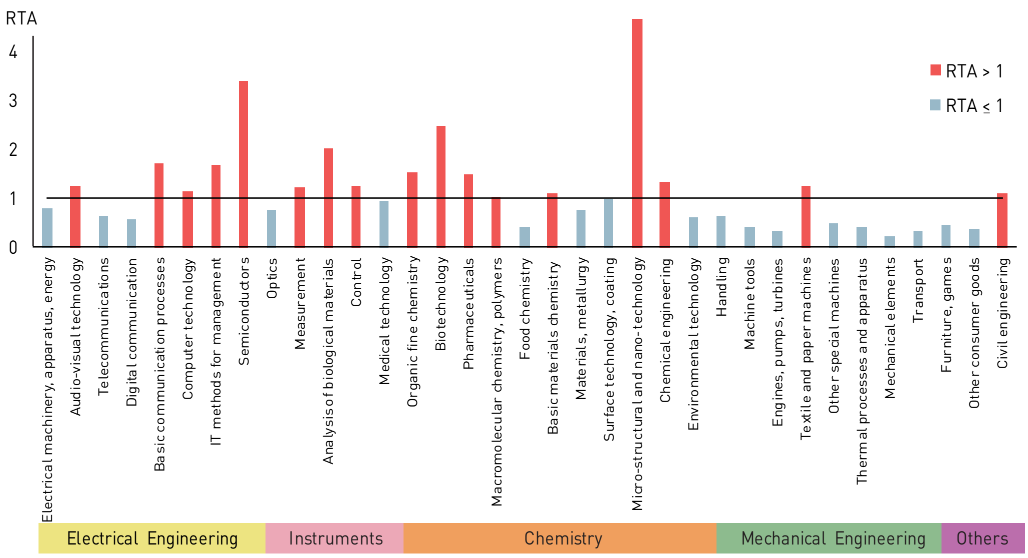
16 *Reflecting Singapore's strength in micro-structure and nano-technology, the Nanyang Technology University of Singapore ranks highly in the world for Material Science. It is ranked first in the U.S. News (2019) Best Universities Rankings 2019, and third in the 2019 Quacquarelli Symonds (2019) World University Rankings, behind the Massachusetts Institute of Technology and Stanford University, but above the University of Cambridge and Harvard University. See Boey (2016) and Venkatraman (2016) for more information on Singapore's developments in material sciences.*

Exhibit 5: Share of Patenting Activity in the World, 2012-2016



Source: PATSTAT, Authors' estimates

Exhibit 6: Singapore's RTA Index, 2012-2016



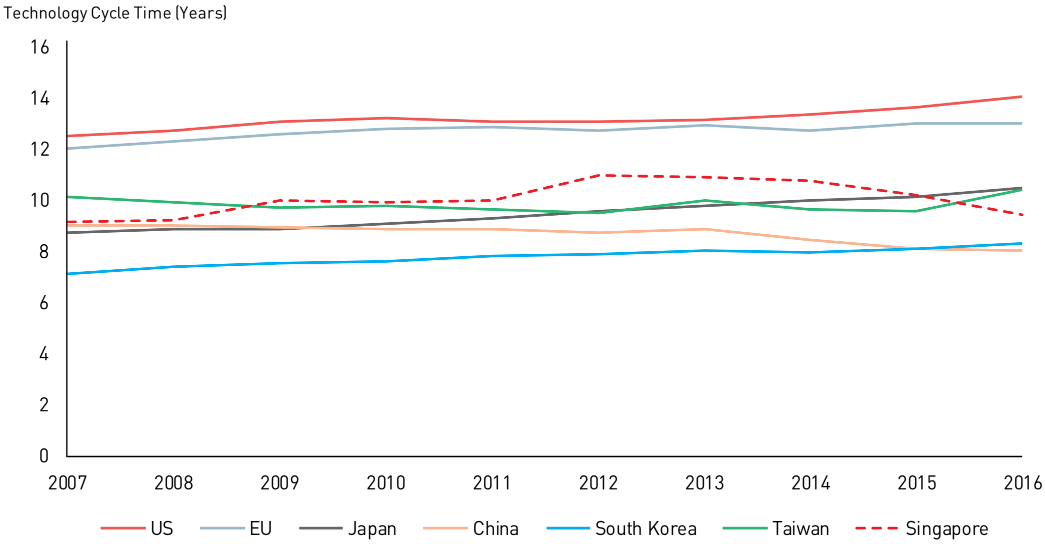
Source: Authors' estimates

<u>Third</u>, Singapore's speed of innovation, as measured by technology cycle time[17] (i.e., the average age of patents that a country's patents cite), is faster than that in the United States and European Union [Exhibit 7]. This is partly driven by Singapore's heavier focus in technology fields with shorter industry cycles (e.g., Semiconductors and Computer Technology).[18] Over the more recent period of 2012-2016, Singapore's technology cycle time has shortened further, indicating that its patents are increasingly advancing from more recent technology.

17 See Hall et al. (2002) for more details on technology cycle times.

18 Globally, the technology cycle times of Semiconductors (7.75 years) and Computer Technology (8.46 years) were faster compared to the average technology cycle time across the 35 IPCs (12.61 years) between 2007 and 2016. In Singapore, the technology cycle times of Semiconductors (7.48 years) and Computer Technology (7.54 years) were faster compared to global levels.

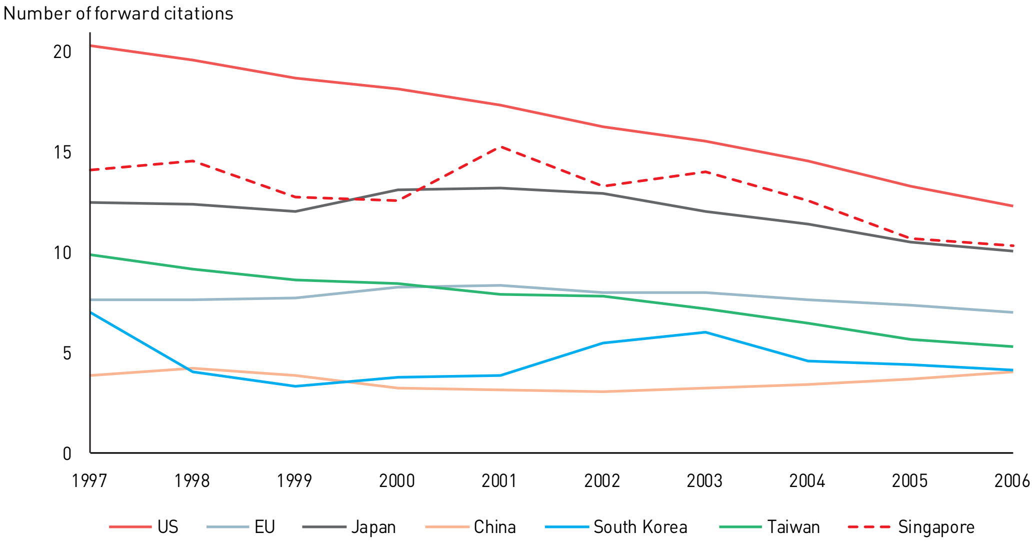
Exhibit 7: Technology Cycle Time, 2007-2016



Source: Authors' estimates

Fourth, reflecting high patent quality and technological influence, Singapore's patents are generally well-cited by other patents (i.e., high forward citation counts) [Exhibit 8].[19] Notably, Singapore's patent quality is better than South Korea's and Taiwan's, with its leading position largely due to innovations in its core areas of expertise such as Semiconductors.[20]

Exhibit 8: Patent Quality, 1997-2006



Note: The analysis was for the period 1997-2006 as forward citations were counted over a period of ten years after the publication date (i.e., 2007-2016).

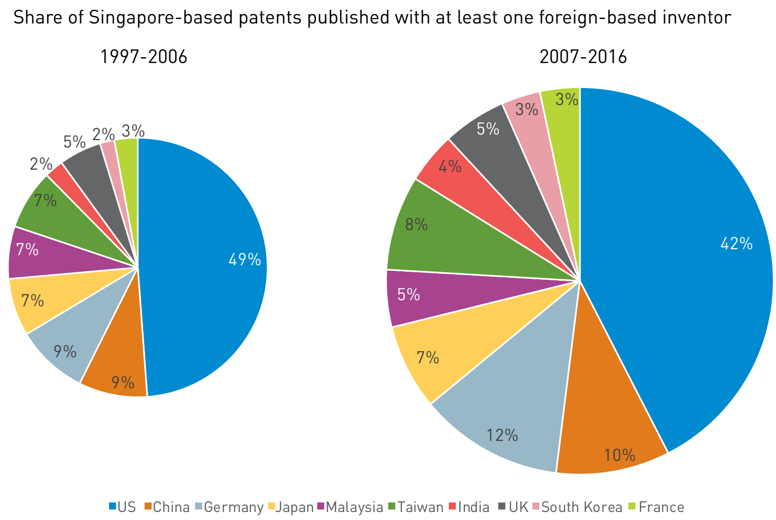
Source: Authors' estimates

Fifth, Singapore-based inventors have also made progress in international innovation collaboration efforts, with the number of patents with at least one foreign-based inventor more than doubling between 1997-2006 and 2007-2016 [Exhibit 9]. While the United States remained a key innovation partner, Singapore-based inventors had entered into more partnerships with inventors in China and Germany in the period of 2007-2016 compared to the earlier period of 1997-2006. These partnerships were mainly in the area of Semiconductors.

19 Patent quality is measured by the number of forward citations over ten years. Forward citations serve as a proxy of technological impact, as a revolutionary patent with greater technological influence attracts more citations (see Trajtenberg, 1990; Harhoff et al., 2003; Lanjouw & Schankerman, 2004).

20 Notably, Singapore's average ten-year forward citation counts for the period of 1997-2006 for Semiconductors was 16.67, significantly higher than the global average for patents in the same field (9.94).

Exhibit 9: Collaborations of Singapore-based Inventors, 1997-2016



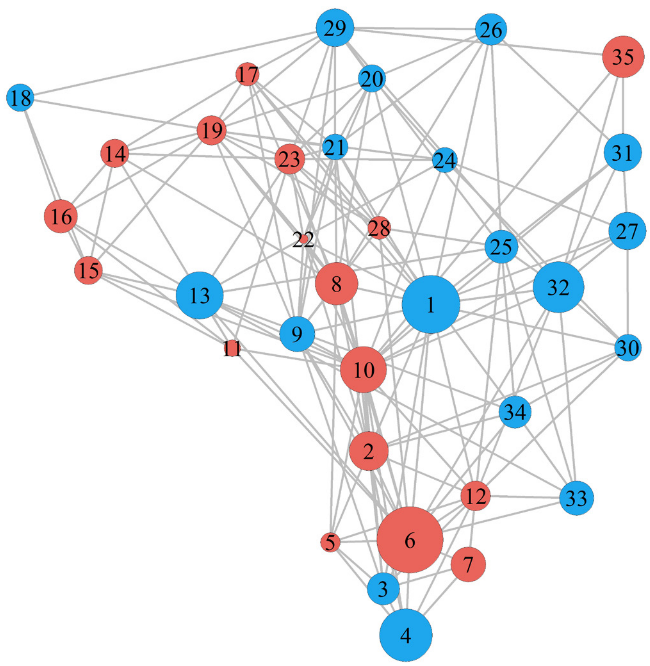
Source: Authors' estimates

5. INNOVATION SPACE – A CASE STUDY OF SINGAPORE

We next present the Innovation Space for Singapore, trace its evolution over time, and highlight possible policy takeaways.

Singapore's Innovation Space for the most recent period of 2012-2016 is shown in Exhibit 10. From the Innovation Space, we can observe that Singapore's technological strengths are largely clustered in the areas of Electrical Engineering, Chemistry and Instruments (see red nodes in Exhibit 10 that denote technology fields that have RTA > 1), which are in line with Singapore's industrial development and economic priorities.

Exhibit 10: Singapore's Innovation Space, 2012-2016

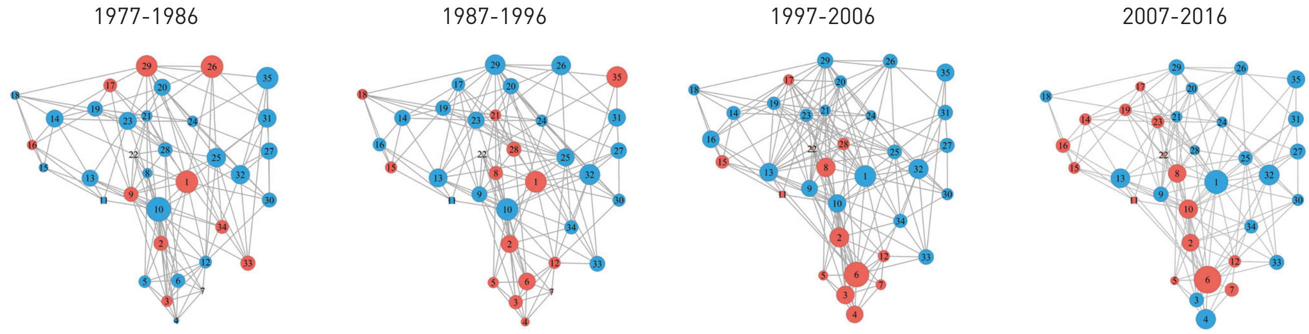


Note: Red nodes denote technology fields that Singapore has a revealed technological advantage in (i.e., RTA > 1).

Source: Authors' estimates

The development of Singapore's technological capabilities over time has, in fact, always been closely aligned with its economic priorities and industrial development strategies. To see this, we trace the evolution of Singapore's Innovation Space from 1977 to 2016 [Exhibit 11]. In its early phase of development (1977-1986), Singapore's technological capabilities were largely diffused, and included peripheral areas such as Furniture and Games (#33) and Other Consumer Goods (#34). As Singapore industrialised (1987-1996), it gained technological capabilities in new areas relating to the electronics industry, including Computer Technology (#6) and Semiconductors (#8). Between 1997 and 2006, Singapore consolidated its strengths in the electrical engineering cluster (#1-8), but also branched into Macromolecular Chemistry, Polymers (#17), supported by the opening of Jurong Island in 2000. With the growth of the chemicals and biomedical manufacturing clusters between 2007 and 2016, Singapore gained technological capabilities in Organic Fine Chemistry (#14), Pharmaceuticals (#16), Basic Materials Chemistry (#19) and Chemical Engineering (#23). The development of Singapore's information & communications sector also enabled it to nurture technological capabilities in Basic Communication Processes (#5) and IT Methods for Management (#7).

Exhibit 11: Evolution of Singapore's Innovation Space, 1977-2016



Note: The Innovation Space maps are constructed using ten-year periods. Red nodes denote technology fields that Singapore has a revealed technological advantage in (i.e., RTA > 1) for the period of analysis. The visualisations across the years use the 2007-2016 Global Innovation Network as the base network, with adjustments to the size of the node to reflect the technology field's share of global patenting activity in the period.

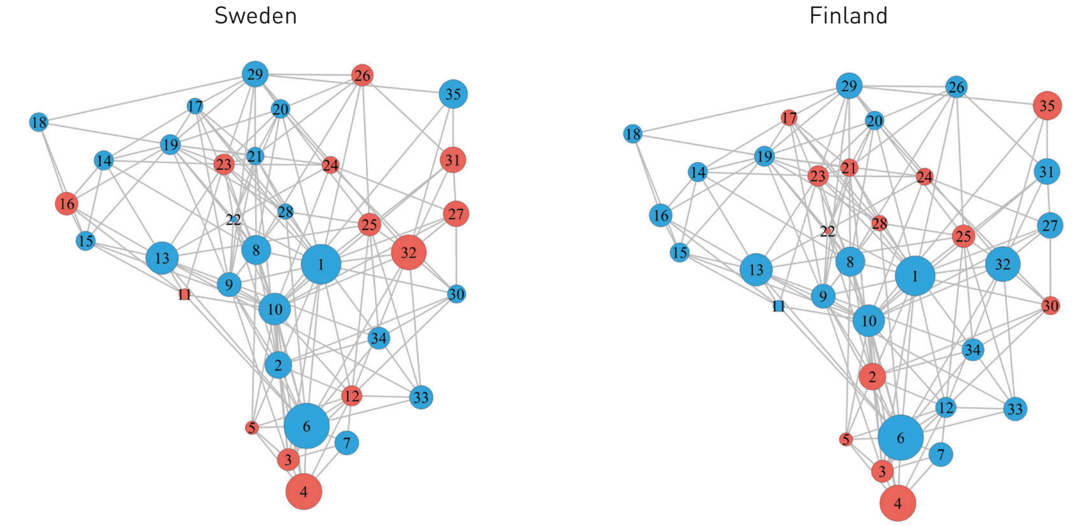
Source: Authors' estimates

Apart from allowing policymakers to trace the evolution of Singapore's technological capabilities over time, the Innovation Space can also shed light on adjacent technology fields that can leverage Singapore's existing technological strengths. For instance, based on the latest Innovation Space (2012-2016) for Singapore, there may be scope for Singapore to consider building capabilities in technology fields such as Medical Technology (#13), which is closely related to Analysis of Biological Materials (#11) and Biotechnology (#15), where Singapore's RTA is already above one.[21]

By comparing Singapore's Innovation Space with that of other economies, we can also identify potential areas of collaboration with these economies. For example, from the Innovation Space of small advanced economies such as Sweden and Finland [Exhibit 12], we can see that both Sweden and Finland have strengths in Telecommunications (#3) and Digital Communication (#4). Partnerships with Sweden and Finland may thus be mutually beneficial, as Singapore's technological strengths in Computer Technology (#6) and IT Methods for Management (#7) are complementary to Sweden/Finland's strengths in the related Telecommunications (#3) and Digital Communication (#4) technology fields. (We also present the Innovation Space for large economies like the United States and China in Annex B.)

21 Between the periods of 2007-2011 and 2012-2016, Singapore's patenting activity in Medical Technology rose by 19.8 per cent, higher than that for Taiwan (16.4 per cent), European Union (3.8 per cent) and United States (0.6 per cent). During this period, patenting activity in Medical Technology in South Korea and Japan also grew robustly, at 51.0 per cent and 47.6 per cent respectively.

Exhibit 12: Innovation Space for Sweden and Finland, 2012-2016



Source: Authors' estimates

6. CONCLUSION

Mission-oriented innovation policy plays a key role in advancing scientific discovery and transforming an economy's ability to create the next generation of products and services. To sustain a virtuous cycle of innovation, successful economies benefit from fostering a rich ecosystem that thrives on the accumulation of knowledge and synergies between related activities. In this regard, the Innovation Space provides a framework to analyse the innovation landscape, survey an economy's technological strengths and capabilities, and identify opportunities that leverage the economy's existing technological capabilities.

In Singapore's case, its areas of innovation have complemented its economic needs and productive capabilities, with strengths observed in technology fields that are related to the electronics, chemicals, biomedical manufacturing, and information & communications sectors. Reflecting its progress in developing technological capabilities, Singapore has seen healthy growth in its patenting activity and forged stronger international innovation collaborations over the past decade. Its patents also generally have higher technological influence (as measured by forward citations) and are advancing from more recent technology (as measured by its technology cycle time).

As an advanced economy that is approaching the technological frontiers in many sectors, Singapore will need to forge new paths of success by intensifying and diversifying its innovation capabilities. Against this backdrop, Singapore's RIE plans and Industry Transformation Maps will play important roles in deepening the linkages in its innovation ecosystem, strengthening the research-industry nexus, and growing its indigenous innovation capabilities. In the area of IP, Singapore's continued investments in patent analytics and tech forecasting capabilities will help to sharpen national R&D and innovation decisions. The strengthening of IP management capabilities will also facilitate the translation of public-funded R&D into economic and societal outcomes. Such efforts will build on Singapore's existing competitive strengths and help to drive its progress towards a knowledge-based, innovation-driven and value-creating economy.

Contributed by:

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REFERENCES

Acemoglu, D., Ukcigit, U., & Kerr, W. R. (2016). Innovation Network. Proceedings of the National Academy of Sciences, 113(41), 11483-11488.

Andreoni, A., Kuan, M. L., & Goya, D. (2015). Industrial Capabilities Indicators. Enhancing the Quality of Industrial Policies (EQuIP) Tool 9. Vienna: United Nations Industrial Development Organisation.

Balassa, B. (1965). Trade Liberalisation and "Revealed" Comparative Advantage. The Manchester School, 33(2), 99-123.

Boey, F. (2016). Historical Narrative Early Beginnings to Present. In F. Boey, B. V. Chowdari, & S. S. Venkatraman (Eds.), 50 Years of Materials Science in Singapore (pp. 1-20). Singapore: World Scientific.

Dutta, S., Lanvin, B., & Wunsch-Vincent, S. (Eds.). (2019). Global Innovation Index 2019: Creating Healthy Lives - The Future of Medical Innovation. Geneva: Cornell University, INSEAD and World Intellectual Property Organisation.

Furman, J. L., & Stern, S. (2011). Climbing Atop the Shoulders of Giants: The Impact of Institutions on Cumulative Research. The American Economic Review, 101(5), 1933-1963.

Hall, B. H., Jaffe, A. B., & Trajtenberg, M. (2002). The NBER Patent-Citations Data File: Lessons, Insights, and Methodological Tools. In A. B. Jaffe, & M. Trajtenberg (Eds.), Patents, Citations, and Innovations: A Window on the Knowledge Economy (pp. 403-460). Cambridge, MA: The MIT Press.

Harhoff, D., Scherer, F. M., & Vopel, K. (2003). Citations, Family Size, Opposition and the Value of Patent Rights. Research Policy, 32(8), 1343-1363.

Hasan, I., & Tucci, C. L. (2010). The Innovation-Economic Growth Nexus: Global Evidence. Research Policy, 39(10), 1264-1276.

Hausmann, R., & Klinger, B. (2006). Structural Transformation and Patterns of Comparative Advantage in the Product Space. Center for International Development (Harvard University) Working Paper No. 128. Cambridge, MA: Harvard University.

Hausmann, R., & Klinger, B. (2007). The Structure of the Product Space and the Evolution of Comparative Advantage. Center for International Development (Harvard University) Working Paper No. 146. Cambridge, MA: Harvard University.

Hausmann, R., Hidalgo, C. A., Bustos, S., Coscia, M., Simoes, A., & Yildirim, M. A. (2013). The Atlas of Economic Complexity: Mapping Paths to Prosperity. Cambridge, MA: MIT Press.

Hidalgo, C. A. (2018). Economic Complexity: From Useless to Keystone. Nature Physics, 14, 9-10.

Hidalgo, C. A., & Hausmann, R. (2008). A Network View of Economic Development. Developing Alternatives, 12(1), 5-10.

Hidalgo, C. A., Klinger, B., Barabási, A.-L., & Hausmann, R. (2007). The Product Space Conditions the Development of Nations. Science, 317(5837), 482-487.

Jaffe, A. B. (1986). Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value. The American Economic Review, 76(5), 984-1001.

Jaffe, A. B., Trajtenberg, M., & Fogarty, M. S. (2000). Knowledge Spillovers and Patent Citations: Evidence from A Survey of Inventors. The American Economic Review, 90(2), 215-218.

Jaffe, A. B., Trajtenberg, M., & Henderson, R. (1993). Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations. The Quarterly Journal of Economics, 108(3), 577-598.

Lanjouw, J. O., & Schankerman, M. (2004). Patent Quality and Research Productivity: Measuring Innovation with Multiple Indicators. The Economic Journal, 114(495), 441-465.

Lazonick, W., & Mazzucato, M. (2013). The Risk-Reward Nexus in the Innovation-Inequality Relationship: Who Takes the Risks? Who Gets the Rewards ? Industrial and Corporate Change, 22(4), 1093-1128.

Lee, K. (2013). Schumpeterian Analysis of Economic Catch-Up: Knowledge, Path-Creation, and the Middle-Income Trap. Cambridge: Cambridge University Press.

Lee, K., & Kim, B.-Y. (2009). Both Institutions and Policies Matter but Differently for Different Income Groups of Countries: Determinants of Long-Run Economic Growth Revisited. World Development, 37(3), 533-549.

Lévêque, F., & Ménière, Y. (2006). Patents and Innovation: Friends or Foes? CERNA Working Paper. Paris: MINES ParisTech.

OECD (Organisation for Economic Co-operation and Development). (2009). OECD Patent Statistics Manual. Paris: OECD Publishing.

Podolny, J. M., Stuart, T. E., & Hannan, M. T. (1996). Networks, Knowledge, and Niches: Competition in the Worldwide Semiconductor Industry, 1984-1991. American Journal of Sociology, 102(3), 659-689.

Quacquarelli Symonds. (2019). QS World University Rankings for Materials Sciences 2019. Retrieved 9 February, 2020, from QS World University Rankings: https://www.topuniversities.com/university-rankings/university-subject-rankings/2019/materials-sciences

Rosenberg, N. (1976). Perspectives on Technology. New York: Cambridge University Press.

Schmoch, U. (2008). Concept of a Technology Classification for Country Comparisons: Final Report to the World Intellectual Property Organisation (WIPO). Karlsruhe: Fraunhofer Institute for Systems and Innovation Research.

Teo, M., Loo, A., & Kuan, M. L. (2019). Returns to Research and Development (R&D) Among Firms in Singapore. Economic Survey of Singapore Third Quarter 2019, 42-50.

Trajtenberg, M. (1990). A Penny for Your Quotes: Patent Citations and the Value of Innovations. The RAND Journal of Economics, 21(1), 172-187.

U.S. News. (2019). Best Global Universities for Materials Science. Retrieved 9 February, 2020, from U.S. News & World Report: https://www.usnews.com/education/best-global-universities/materials-science?int=994b08

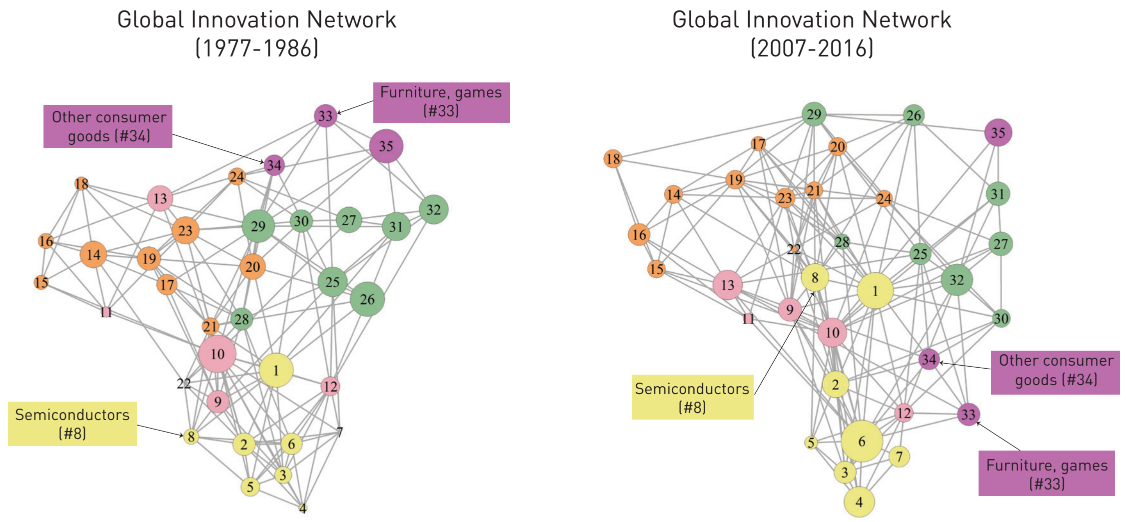
Venkatraman, S. S. (2016). "Singaporean" Materials Science: What Does the Future Hold? In F. Boey, B. V. Chowdari, & S. S. Venkatraman (Eds.), 50 Years of Materials Science in Singapore (pp. 225-228). Singapore: World Scientific.

Zaccaria, A., Cristelli, M., Tacchella, A., & Pietronero, L. (2014). How the Taxonomy of Products Drives the Economic Development of Countries. PLoS ONE, 9(12).

ANNEX A: GLOBAL INNOVATION NETWORK FOR 1977-1986 AND 2007-2016

The base Global Innovation Network in the article is for the period of 2007 to 2016, in order to reflect patent citations between technology fields in the more recent decade. A comparison with the Global Innovation Network for the period of 1977 to 1986 shows that (i) the network has grown denser over time as patents started to cite across technology fields more frequently (i.e., greater technology spillovers), (ii) the positioning of certain technology fields have changed as they increasingly cited new technological areas (e.g., furniture, games and other consumer goods have become more closely related to the electrical engineering cluster, and (iii) some technology fields (e.g., semiconductors) have started to occupy a more central location in the network [Exhibit A1].

Exhibit A1: Global Innovation Network, 1977-1986 and 2007-2016

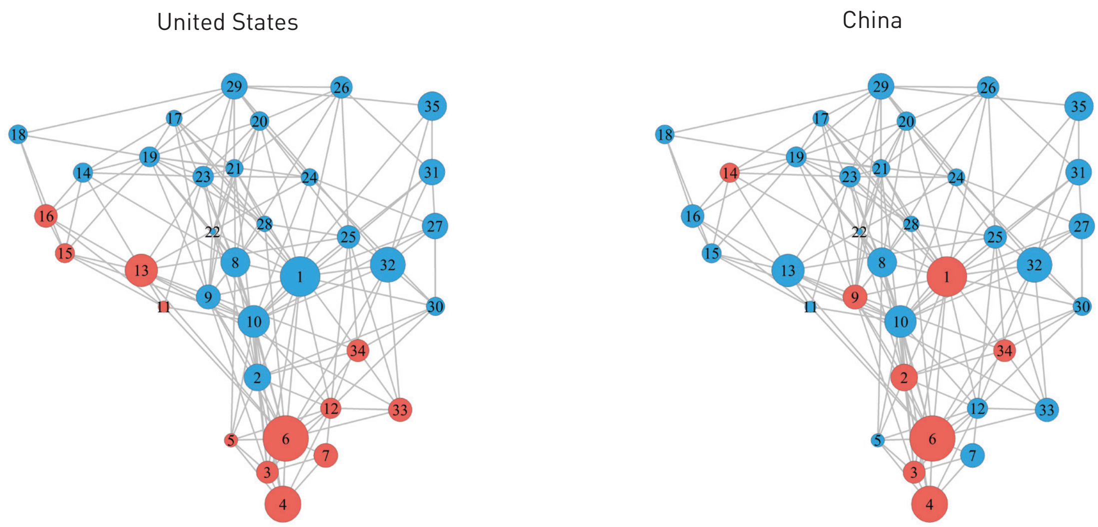


Source: Authors' estimates

ANNEX B: COMPARISON WITH INNOVATION SPACE OF OTHER COUNTRIES

Singapore's Innovation Space contrasts with that of the two largest economies in the world (i.e., United States and China) [Exhibit B1]. For the United States, its technological capabilities lie in two distinctive clusters – information & communications and biomedical technology, as it has stronger capabilities in technology fields such as Telecommunications (#3), Digital Communication (#4), Medical Technology (#13) and Biotechnology (#15). Similarly, China has built technological capabilities in the information & communications industry, which comprises Telecommunications (#3), Digital Communication (#4) and Computer Technology (#6).[22] However, compared to the United States, China possesses technological capabilities in Audio-visual Technology (#2), rather than Basic Communication Processes (#5) and IT Methods for Management (#7).

Exhibit B1: Innovation Space for United States and China, 2012-2016



Source: Authors' estimates

22 Between the periods of 2007-2011 and 2012-2016, Singapore's patenting activity in Medical Technology rose by 19.8 per cent, higher than that for Taiwan (16.4 per cent), European Union (3.8 per cent) and United States (0.6 per cent). During this period, patenting activity in Medical Technology in South Korea and Japan also grew robustly, at 51.0 per cent and 47.6 per cent respectively.