Are There Laws of Innovation? Part I: Introduction

by

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Are There Laws of Innovation? Part I: Introduction

Lawrence J. Lau and Yanyan Xiong[1]

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Abstract: One important indicator of national economic strength, in addition to real GDP, is its innovative capacity. Sustained investment in research and development (R&D) is essential for the occurrence of innovation in an economy. The stock of real R&D capital, defined as the cumulative past real expenditure on R&D, less depreciation of ten percent per year, is a useful summary measure of the current potential capacity of innovation. It is compared across the Group-of-Seven (G-7) Countries, the four East Asian Newly Industrialized Economies (EANIEs) and China on both an aggregate and a per capita basis. Indicators of success in innovation, such as the number of patent applications submitted and the number of patents granted, both domestically and abroad, each year, are also compared across the same set of economies. The real R&D capital stock can be shown to have a direct and positive causal relationship to the number of patents granted--the higher the level of the real R&D capital stock of an economy, the higher is the number of domestic and U.S. patents granted to it. Among R&D expenditures, different categories may be distinguished: basic research, applied research and development. The share of basic research in total R&D expenditures is also compared across the same set of economies, as "break-through" discoveries and innovations can only consistently occur in an economy with a strong foundation of basic research.

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One important indicator of national economic strength, in addition to real GDP, is its innovative capacity. Sustained investment in research and development (R&D) (and in human capital) is essential for the occurrence of innovation in an economy. There are, however, significant variations in the extent of investment in R&D across economies. In Chart 1, the ratios of R&D expenditure to GDP of the Group-of-Seven (G-7) countries (Canada, France, Germany, Italy, Japan, the United Kingdom and the United States), the four East Asian Newly Industrialized Economies (EANIEs) (Hong Kong, South Korea, Singapore and Taiwan), and China (Mainland)[2] are presented. From 1964 to 1990, R&D expenditure data are only available for West Germany. Thus, the R&D to GDP ratios and the quantities of real R&D capital stock of West Germany prior to 1991 are presented separately from those of the unified Germany, which are available since 1991.

The U.S. ratio started with a relatively low percentage, 1.36%, in 1953, but increased rapidly to 2.15% in 1957, partly as a reaction to the successful launch of the Sputnik satellite by the former Soviet Union. It has since held steady between 2.1% and 2.9% over the last half-a-century. The Chinese ratio started with a less than 0.1% in 1953, but increased rapidly to a peak of 2.57% in 1960, comparable to the U.S. ratio of the same year. Between 1963 and 1984, the Chinese ratio was higher than those of Canada, Italy and the four EANIEs. Then it plummeted below 1%, bottoming in 1996 at 0.57%. Since then it has been recovering steadily to reach 2.09% in 2014, once again surpassing the R&D expenditure to GDP ratios of Canada and Italy and that of the U.K., but still lagging significantly behind not only the developed economies of Germany, Japan and the U.S., but also the newly industrialized economies of South Korea and Taiwan. The Chinese ratio is targeted to reach 2.2% in 2015. The West German ratio was neck and neck with the U.S. ratio between 1975 and 1990. However, since German reunification in 1990, the unified German ratio was below the U.S. ratio until 2011, when it finally managed to catch up[3]. The Japanese ratio was 1.47% in 1963 and rose steadily to overtake the U.S. ratio in 1989, and has remained significantly higher than it ever since. More recently, the South Korean ratio caught up with the U.S. ratio in 2005 and surpassed the Japanese ratio in 2010. South Korea led the world with an R&D expenditure to

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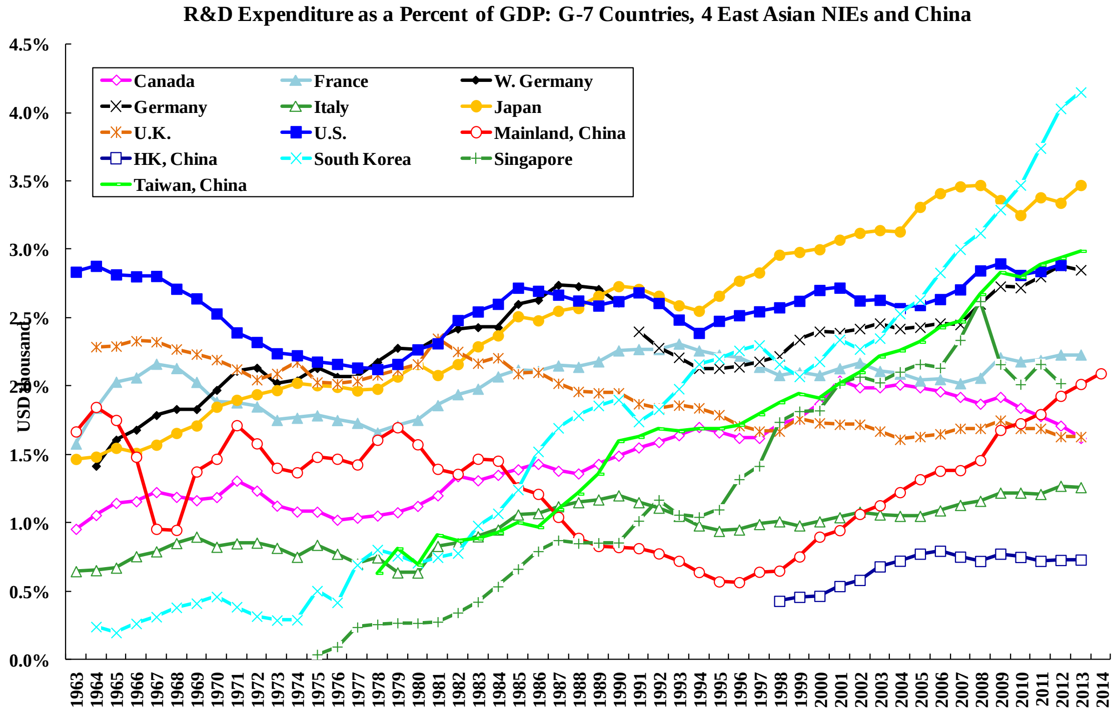
[2] In this study, data for China pertain to the Mainland of China only.

[3] In 2011, the U.S. ratio was 2.84 compared to Germany's 2.80; in 2012, the ratios were respectively 2.89 and 2.88, almost identical.

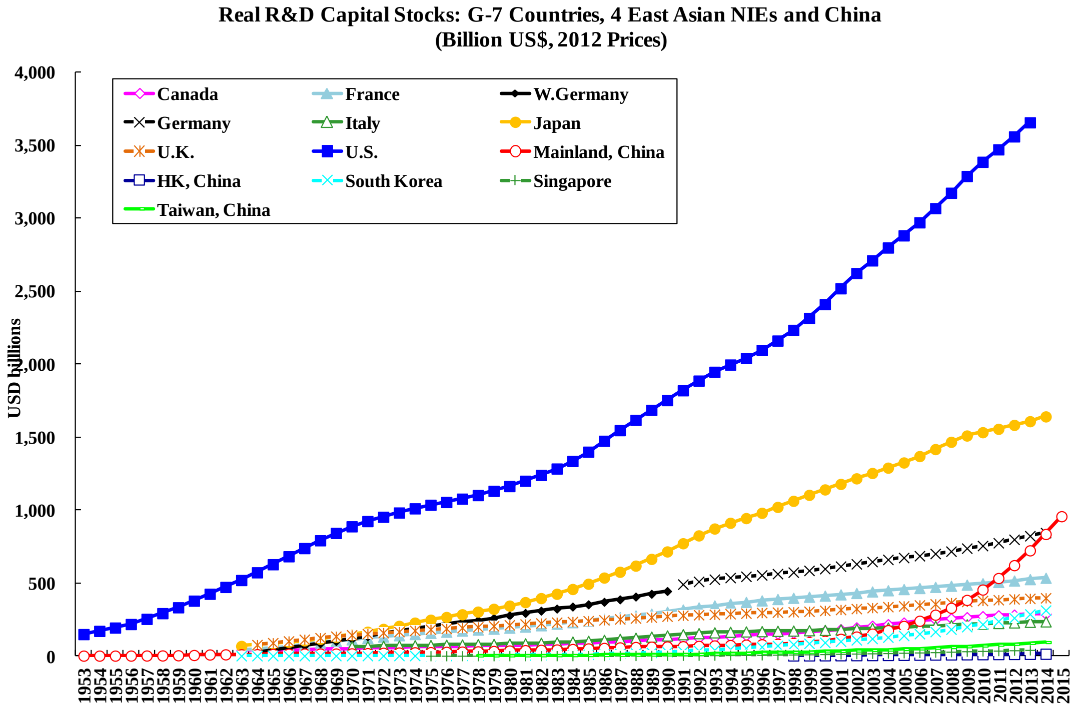
GDP ratio of 4.15% in 2013. In 2011, the Taiwan ratio also surpassed the U.S. ratio. Hong Kong, at less than 0.8%, has the lowest ratio of R&D expenditure to GDP among the economies in our study.

Chart 1: R&D Expenditure as a Percent of GDP:
G-7 Countries, 4 EANIES and China



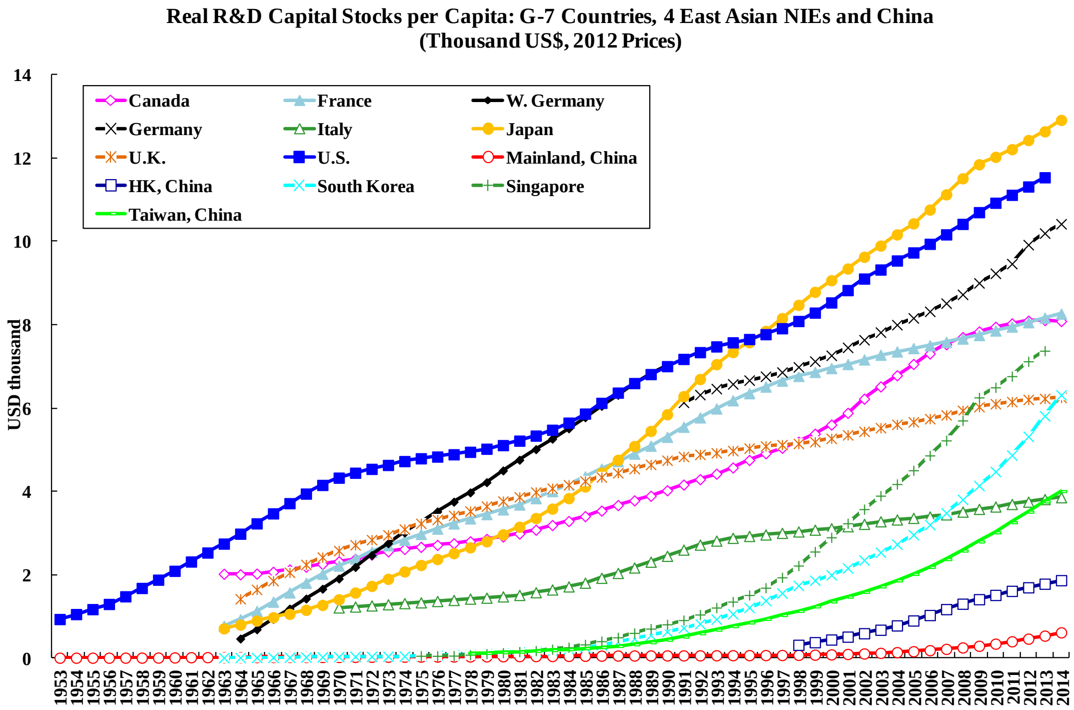
The stock of real R&D capital, defined as the cumulative past real expenditure on R&D, less depreciation of ten percent per year, is a useful summary measure of the current potential capacity of innovation, as it typically takes years of cumulative efforts before investment in R&D pays off in terms of new discoveries and inventions. The initial real R&D capital stocks at the beginning of the years for which data on R&D expenditure are first available are not known and have to be separately estimated for each economy. (The estimation procedure is described in Appendix I.) Given estimates of the initial real R&D capital stocks, and the time series of real R&D expenditures, time-series of the real R&D capital stocks can be estimated for all the economies in our study. In Chart 2, the real R&D capital stocks (in 2012 U.S. Dollars) of our set of economies at the beginning of each year are compared (again, only West German data are available between 1964 and 1990). At US$3.66 trillion in 2013, the U.S. is clearly the World leader in R&D capital stock, followed by Japan, with US$1.61 trillion. The Chinese R&D capital stock has been rising rapidly since the early 2000s because both its GDP and its R&D expenditure to GDP ratio have been growing. At US$722 billion in 2013, Chinese R&D capital stock has caught up with those of most countries and regions with the exceptions of the U.S., Japan and Germany (it is expected to surpass Germany in 2015). Hong Kong has the smallest R&D capital stock, US$12.8 billion in 2013, among all the economies included in this study.

Chart 2: Real R&D Capital Stocks: G-7 Countries, 4 EANIES and China (Billion US$, 2012 prices)



In Chart 3, we compare the R&D capital stocks per capita at the beginning of each year across the same set of economies. By this measure, the lead of the U.S. over other economies was consistent and large until it was overtaken by Japan in 1996. They were followed by Germany. (West Germany had a real R&D capital stock per capita comparable to that of the U.S. in the late 1980s.) The three EANIEs--Singapore, South Korea and Taiwan--had rapidly rising real R&D capital stocks per capita, but were still behind France and Canada in 2014. China has been and continues to be in the last place among this set of economies because of its large population. Even Hong Kong has a higher R&D capital stock per capita than China.

Chart 3: Real R&D Capital Stocks per Capita: G-7 Countries, 4 EANIES and China (Thousand US$, 2012 prices)



The objective of R&D activities is innovation. How should one assess the effectiveness of the R&D activities in each economy? How should one measure the degree of success in innovation of an economy? A number of indicators are possible: for example: the number of patent applications submitted, both domestically and abroad, each year, and the number of patents granted, either domestically or in another country or region, each year. The number of patent applications submitted by the citizens of a given country or region each year can be used as an indicator of the success of the country or region in innovation because a patent application is filed only if something new--a new design, a new product, a new procedure or a new process--is believed to have been discovered or invented. In Chart 4, the number of patent applications submitted domestically each year by domestic applicants in each of the economies under study is presented. The patents considered in this study are exclusively what are known as “invention patents”, the definitions of which are presented in Appendix II[4].

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[4] Data on patents used in this study are collected from World Intellectual Property Organization (WIPO),

Chart 4: Domestic Patent Applications Filed Annually:

G-7 Countries, 4 EANIEs and China

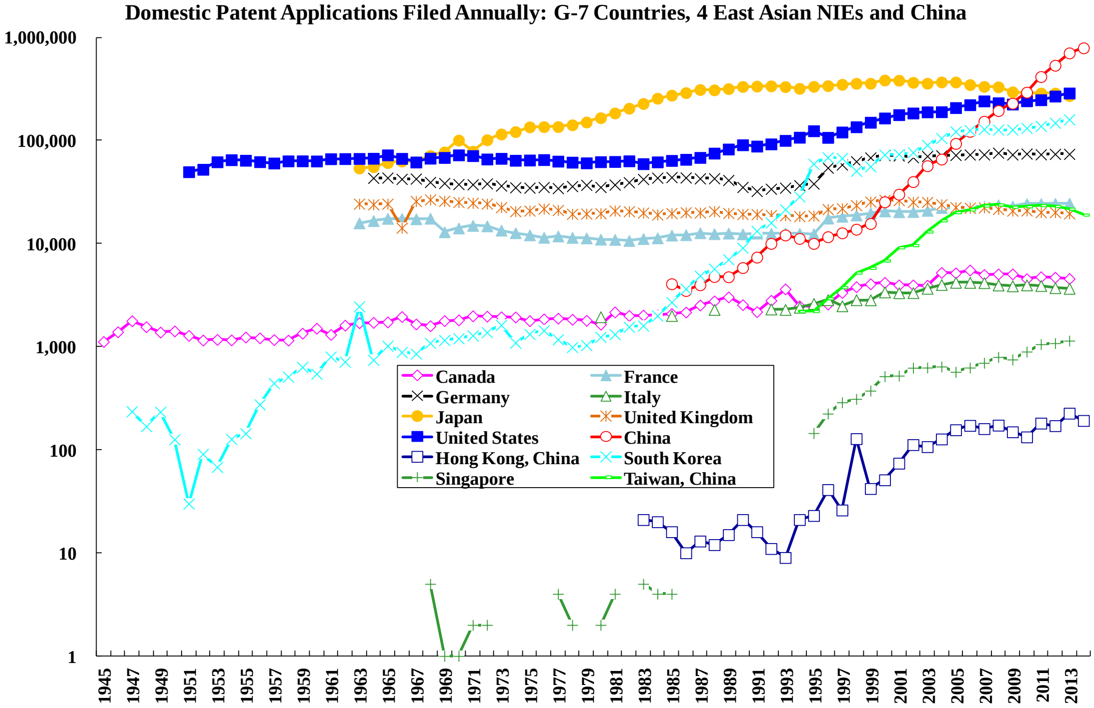


Chart 4 shows that the U.S. was the World leader in terms of the number of domestic patent applications submitted from the early 1950s to 1967. Between 1967 and 2009, Japan had the highest number of domestic patent applications in the World, until it fell behind China in 2010 (290,081 compared to 293,066). Japan also fell behind the United States in 2013 (271,731 compared to 287,831). Somewhat surprisingly, the number of domestic patent applications in China soared from 4,065 in 1985 to 790,000 in 2014, overtaking those of both the United States and Japan to become the highest in the World in 2010. Germany was in the third place in the World[5] until overtaken by South Korea in 1995; it was also surpassed by China in 2005. The newly industrialized economies of first South Korea and then Taiwan have also seen a rapid rise in their number of domestic patent applications.

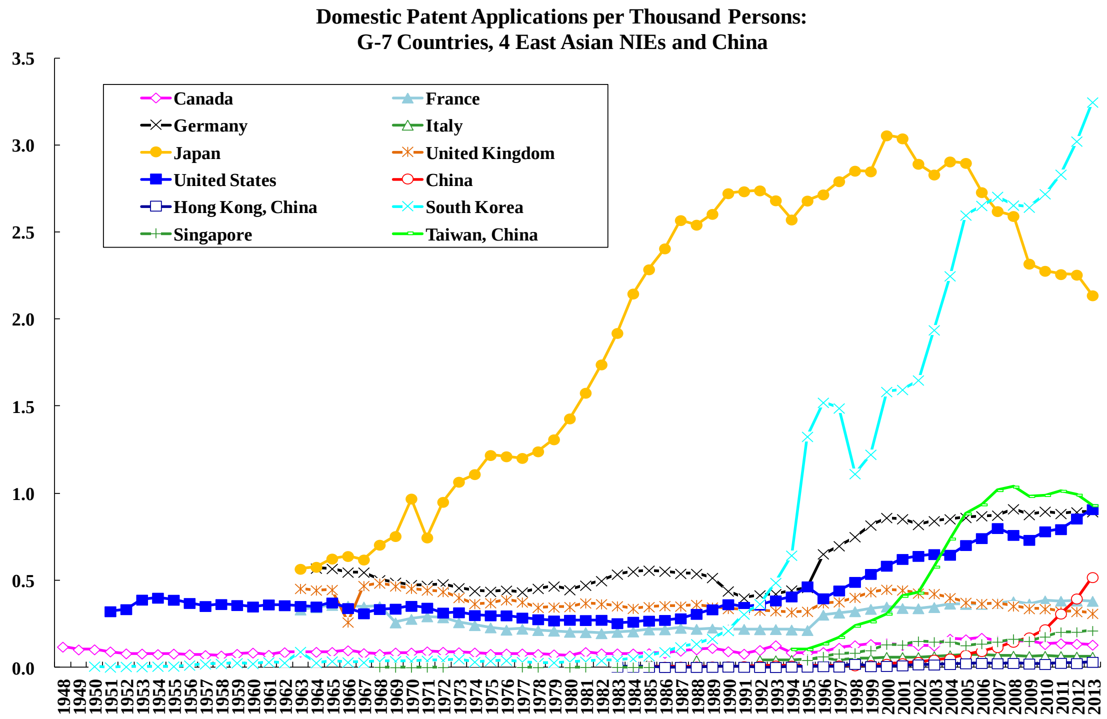
United States Patent and Trademark Office (USPTO), State Intellectual Property Office of the People's Republic of China (for Mainland China) and the Intellectual Property Office, Ministry of Economic Affairs, R.O.C (for Taiwan, China).

[5] Unlike R&D expenditure data, patent application and grant data are available for an unified Germany back to 1964. However, both the United States Patent and Trademark Office (USPTO) and the World Intellectual Property Organization (WIPO) publish data for an unified Germany only. Separate patent data for West Germany are not available.

However, for the smaller economies such as Hong Kong and Singapore, where the domestic markets are relatively limited in size, the numbers of domestic patent applications have remained low, with Singapore surpassing Hong Kong in the early 1990s. In fact, the numbers of the domestic patent applications of Hong Kong and Singapore are lower than the numbers of patent applications submitted by their citizens to foreign jurisdictions such as the U.S. There are several reasons for this phenomenon. First, since patent applications and their continued maintenance once granted are costly, especially in jurisdictions outside the country or region of the discoverer/inventor, they are filed only if they show significant promise of commercial potential and only in countries or regions with potentially large and hence profitable markets. The United States is a potentially large market for almost all economies in the World and a U.S. patent is much more valuable than a domestic patent for a discoverer/inventor in small economies. Second, for the small economies, their own domestic markets are not commercially important enough compared to the large foreign markets such as the United States to even warrant filing an application. This is especially the case if the discoverer/inventor is employed by the local subsidiary of a foreign, including U.S., corporation conducting its business globally. Thus, looking only at domestic patent applications and grants may not be sufficient--a comparison of the number of patent applications filed in the U.S. across economies may also reveal their relative success in innovation.

In order to adjust for the effect of the size of an economy, in Chart 5, the number of patent applications submitted domestically by domestic applicants divided by the total domestic population each year in each of the economies under study is presented.

Chart 5: Domestic Patent Applications Filed Annually per Thousand Persons: G-7 Countries, 4 EANIEs and China



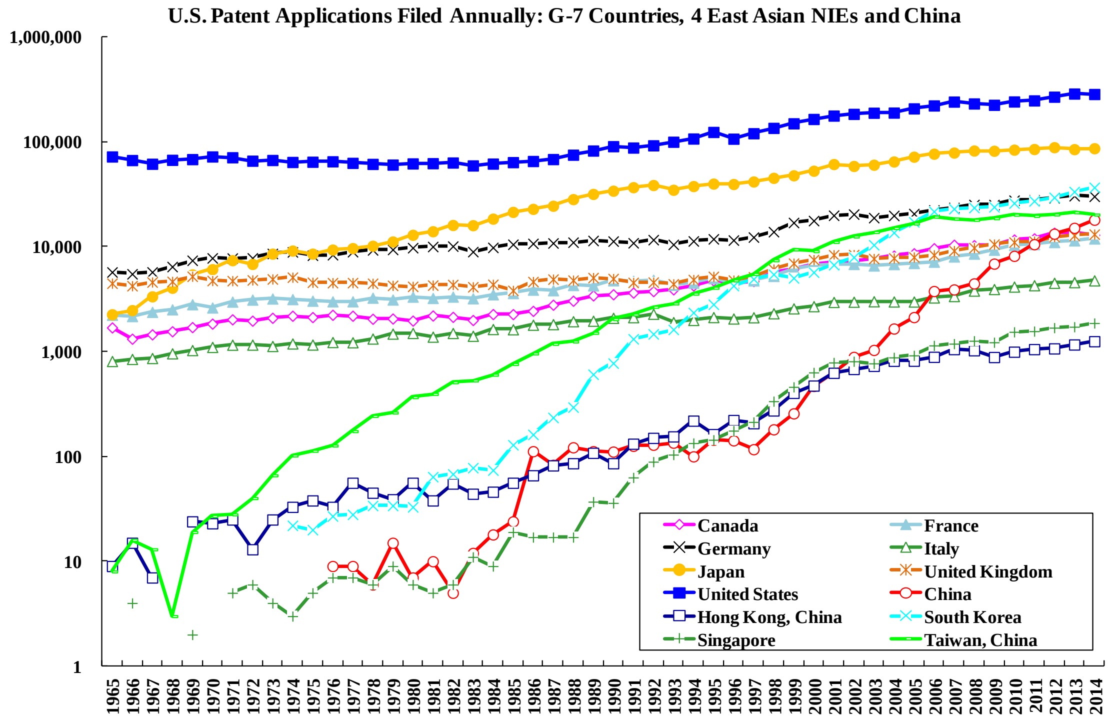
South Korea is currently the World leader in domestic patent applications per capita, with 3.25 applications per thousand. Japan had the highest number of domestic applications per capita since 1963, the first year for which Japanese data are available, until overtaken by South Korea in 2007. Germany was in second place until it was surpassed by South Korea in 1993. It was further overtaken by both Taiwan in 2005 and the U.S. in 2013. The U.S., which has always had a respectable number of domestic applications per capita, saw its domestic applications per capita more than tripled from 0.25 per thousand persons in 1983 to 0.90 per thousand persons in 2013. The number of domestic patent applications per thousand persons in China has also been rising rapidly since 1999 and reached 0.518 per thousand persons to rank sixth among our set of economies in 2013[6].

In Chart 6, the number of patent applications submitted in the U.S. each year by citizens of each of the country or region under study, including those of the U.S. itself, is presented. We choose the U.S. for all economies so that number of patent

6 There are, of course, other economies not represented in Chart 5; for example, Israel had a domestic patent applications per capita of 0.16 per thousand persons in 2013 but an U.S. patent applications per capita of 0.936 and 0.940 per thousand persons in 2013 and 2014 respectively.

applications and the number of patents granted are more comparable across the different economies and across time from the point of view of both the quality and quantity of the patents. In addition, as the largest market by value in the World, the U.S. attracts the most foreign patent applications.

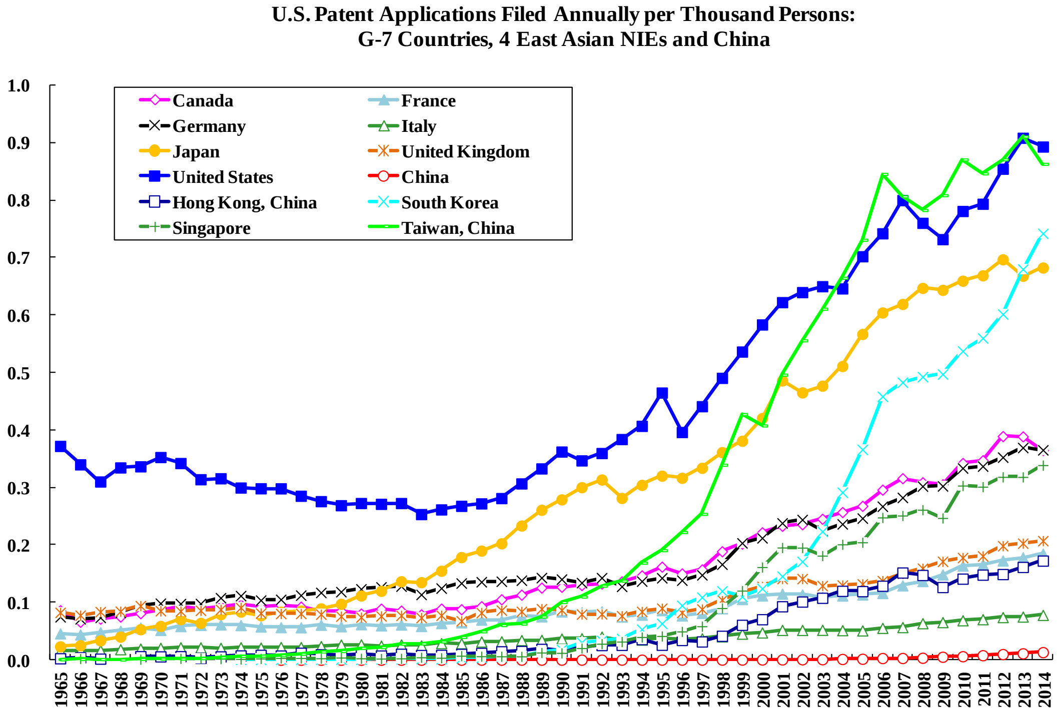
Chart 6: U.S. Patent Applications Filed Annually: G-7 Countries, 4 EANIEs and China



The U.S. is clearly the World's leader in terms of the number of patent applications filed in the U.S., followed by Japan. However, the numbers of applications from the newly industrialized economies of South Korea and Taiwan and lately from China respectively have also been increasing rapidly. Moreover, their numbers of applications have exceeded those from Canada, France, Italy and the U.K. As noted above, for small economies, the numbers of their U.S. patent applications may far exceed the numbers of their domestic applications.

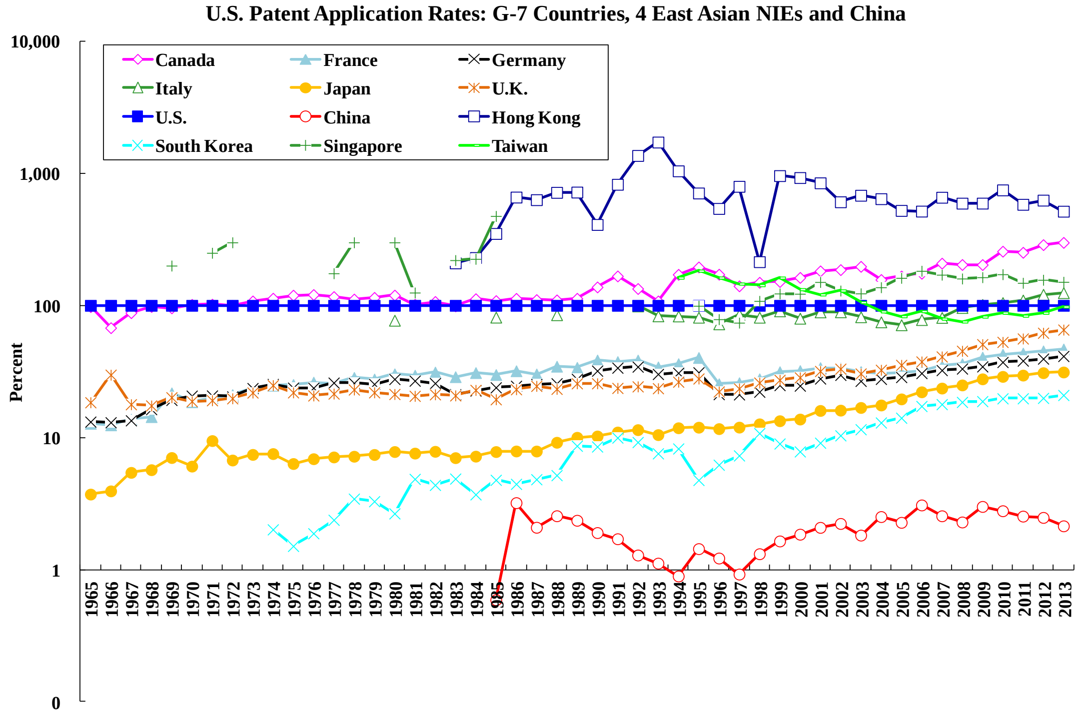
Again, in order to adjust for the effect of the size of the economy, in Chart 7, the number of U. S. patent applications submitted by the citizens of each country or region divided by its total domestic population each year is presented. The U.S. was the leader in the number of U.S. patent applications per capita until it was overtaken by Taiwan in 2004. It was able to recapture the lead in 2014. South Korea (0.680) overtook Japan (0.669) in 2013 to become the third highest in our set of economies. China has remained in the last place because of its large population.

Chart 7: U.S. Patent Applications Filed Annually per Thousand Persons G-7 Countries, 4 EANIEs and China



An interesting indicator is the U.S. patent application rate of each economy, defined as the ratio of the number of U.S. patent applications to the number of domestic patent applications. Given that patent applications and maintenance are costly, especially in a foreign jurisdiction, the U.S. patent application rate may provide information on the self-perceived quality of the discoveries and inventions that underlie the patent applications. However, for economies in which the U.S. patent application rate exceeds 100 percent, it is not going to be a good indicator of the self-perceived quality of the U.S. patent applications from these economies. The U.S. patent application rates of different economies are presented in Chart 8. It is clear that the U.S. patent application rates differ significantly across economies. The U.S. patent application rates of the smaller economies such as Canada, Hong Kong, Singapore and Taiwan all exceed 100 percent. The U.S. patent application rates of Italy have also exceeded 100 percent since 2009[7].

Chart 8: U.S. Patent Application Rates:
G-7 Countries, 4 EANIEs and China

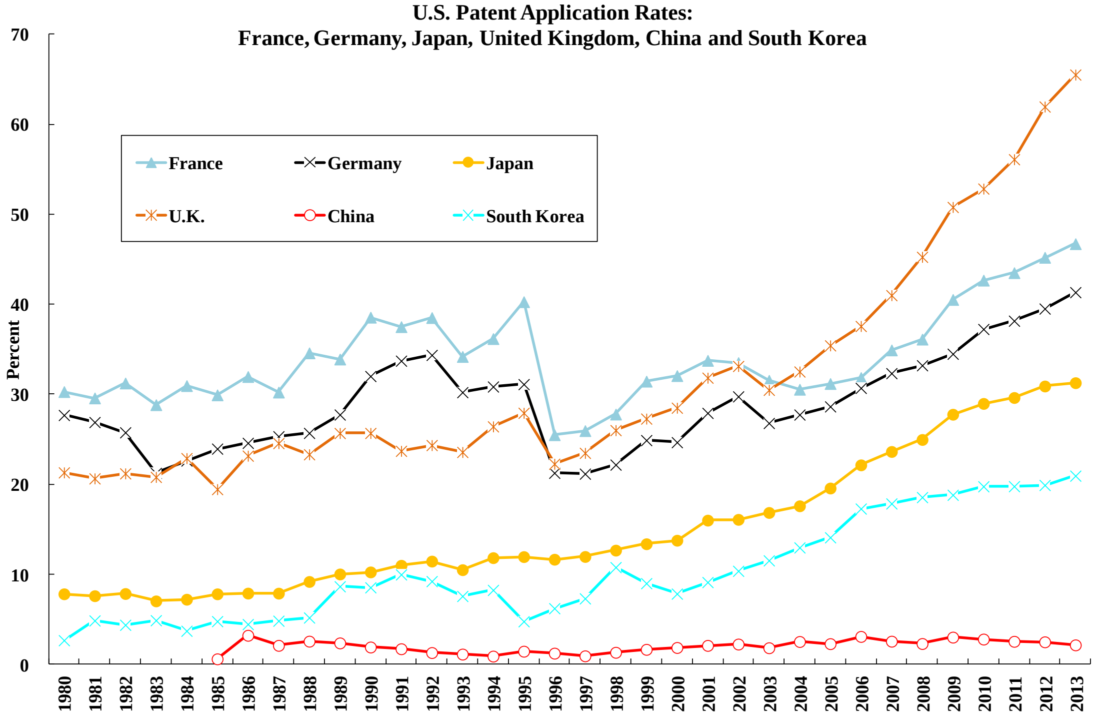


In Chart 9, we present the U.S. patent application rates of those economies with U.S. application rates less than or equal to 100 percent. For the U.S., its U.S. application rate is by definition 100 percent. The U.K. has the highest U.S. patent application rates among this group of economies, which excludes those economies with U.S. patent application rates exceeding 100 percent, of 65.5% in 2013. It was followed by France, with an application rate of 46.7% in 2013. The U.S. patent application rates of the other economies have on the whole been rising since the late 1990s, some more rapidly than the others, with the exception of China. China has by far the lowest U.S. patent application rates, with a rate of slightly over 2% in 2013.

[7] The data on domestic applications of Italy, collected from the World Intellectual Property Organization (WIPO), appear to have some problems. The data have been adjusted. The adjusted data have been used to calculate the U.S. application rates.

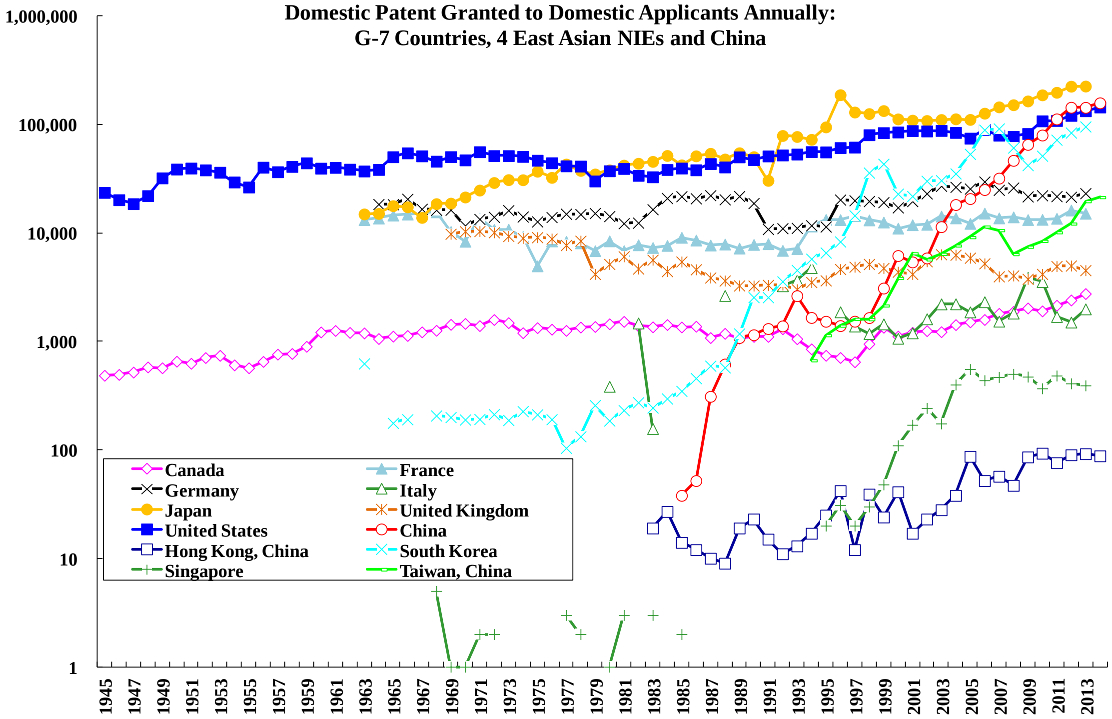
Chart 9: U.S. Patent Application Rates:

France, Germany, Japan, United Kingdom, China and South Korea



An alternative indicator of the degree of success in innovation is the number of patents granted, as opposed to the number of patent applications filed. In Chart 10, the number of patents granted domestically to domestic applicants by the relevant domestic patent authority each year for each of the economies under study is presented. Japan currently leads the World in terms of the number of domestic patents granted to domestic applicants, followed by China, the U.S. and South Korea. Germany, France and the U.K, which used to rank right after Japan and the U.S., have fallen behind in terms of the number of domestic patents granted. China's rise in the number of domestic patent grants has been especially rapid and it looks poised to have the highest number of domestic patent grants in the World in a few years, extrapolating from the current trend rate of growth of the number of its domestic patent applications and grants.

Chart 10: Domestic Patents Granted to Domestic Applicants Annually: G-7 Countries, 4 EANIEs and China



It is interesting to compare the domestic success rates of the domestic applications across economies. The success rate may be defined as the number of domestic patents granted to domestic applicants divided by the number of domestic applications submitted by domestic applicants, lagged one year[8]. The domestic success rates of the economies under study are presented in Chart 11, with the exception of those economies in which the number of U.S. applications exceeds the number of domestic applications in any period[9]. These rates vary significantly across economies and also show significant fluctuations over time. Currently Japan has the highest domestic patent success rate among our set of economies (almost 80 percent), followed by South Korea (65%) and France (62%), and China has the lowest (22 percent)[10], with the U.S. domestic patent success rate at approximately 50 percent, or one patent grant for every two patent applications.

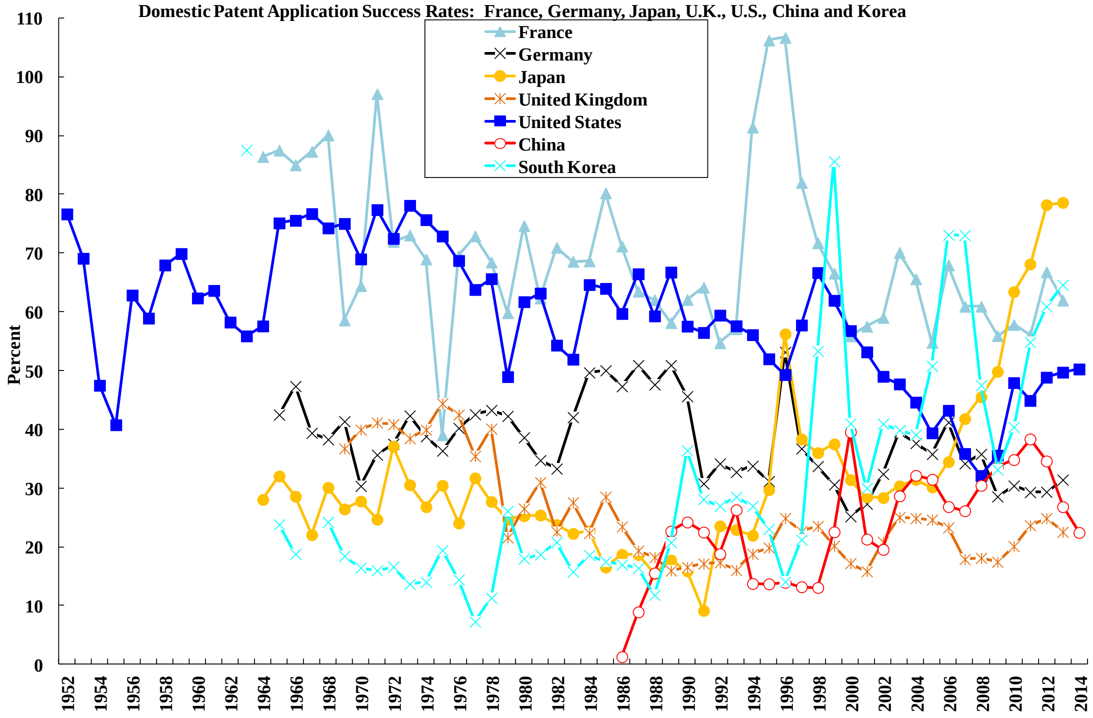
[8] One can also choose a two year lag for the number of domestic applications. It all depends on the time required for processing of patent applications by the relevant domestic patent authorities.

[9] The success rate may occasionally exceed 100%, as, for example in the case of France, because of variations in the time elapsed between the submission of patent applications and the award of patent grants.

[10] The U.K. had the lowest domestic patent success rate in 2013 but the Chinese domestic patent success rate for 2014 appeared likely to be lower than that of the U.K., data for which is not yet available.

Chart 11: Domestic Patent Application Success Rates:

France, Germany, Japan, United Kingdom, United States, China and South Korea

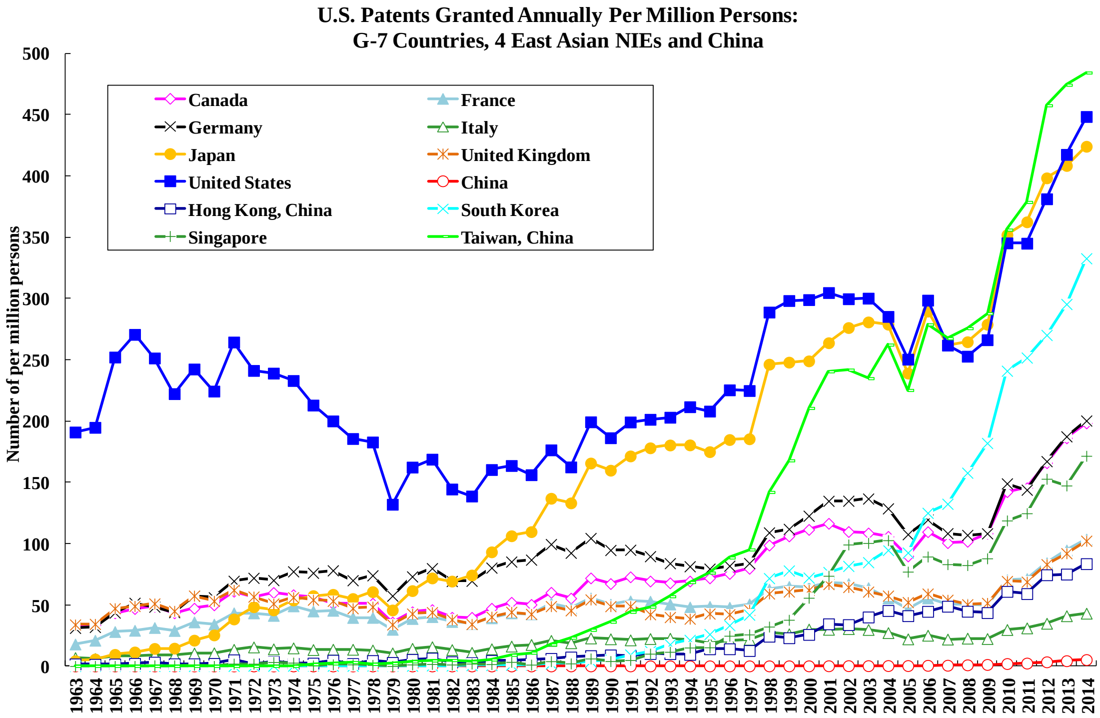


In Chart 12, the number of patents granted in the United States by the U.S. Patent and Trademark Office (USPTO) each year to applicants from different countries and regions, including the U.S. itself, is presented. The U.S. is the undisputed champion over the past fifty years, with more than 144,621 patents granted in 2014, followed by Japan, with 53,849 patents, and then Germany. Since these are patents granted in the U.S. by the USPTO, the U.S. may possibly have a home advantage; however, for all the other countries and regions, the comparison across them should be reasonably fair. The number of U.S. patents granted to Chinese applicants each year increased rapidly from single-digit levels before the mid-1980s to 7,236 patents in 2014. The number of U.S. patents granted to applicants from South Korea and Taiwan were respectively 16,469 and 11,332 in 2014, ahead of Canada, France, Italy and the U.K. as well as China (Mainland).

In Chart 13, the number of patents granted in the United States by the U.S. Patent and Trademark Office (USPTO) each year to the applicants from different countries and regions, including the U.S. itself, divided by the population of the respective countries and regions, are presented. On a per capita basis, the U.S. was the World champion until 2007, when it was overtaken by Taiwan and Japan.

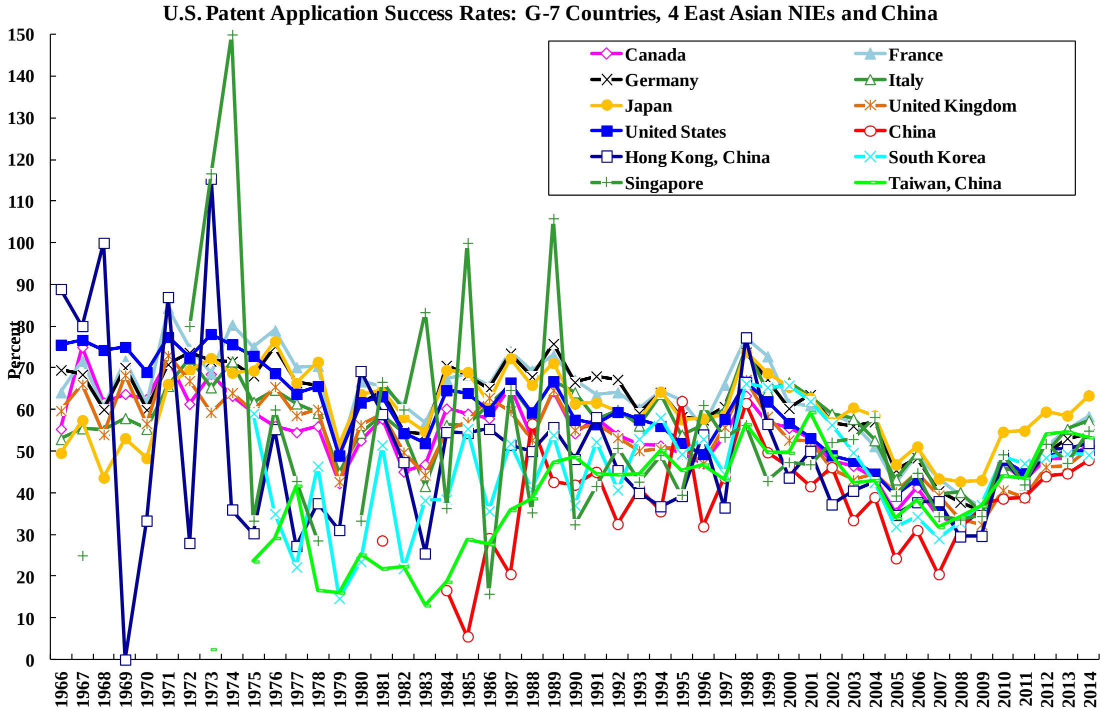
Taiwan is currently the leader, with 484 U.S. patents granted per million persons per year, followed by the U.S., Japan, South Korea and Germany. China, because of its large population, is in last place among the economies under study, with a little more than 5 U.S. patents granted per million persons per year in 2014.

Chart 13: U.S. Patents Granted Annually Per Million Persons: G-7 Countries, 4 EANIEs and China



While using the number of patents actually granted in a specific country or region such as the United States as an indicator of innovation has the advantage of maintaining the same objective quality standard in the comparison of the output of R&D capital across the different countries and regions, it is also subject to possible changes in the procedures and standards of the granting country or region over time. Thus, neither the number of U.S. patent applications nor the number of U.S. patent grants by themselves can be a perfect measure of the R&D output of the different economies. It is interesting to examine the data on the success rates of the U.S. patent applications of each economy over time. Since the number of patents granted must lag behind the number of applications, the success rate may be computed by dividing the number of patents granted in the current year by the number of patent applications in the previous year. In Chart 14, the success rates of patent applications filed in the United States each year by the citizens of different countries and regions, including the U.S. itself, over time, are presented. In recent years, Japan has had the highest success rate, at 63%, and China had the lowest success rate, at 48%, with the U.S. at an intermediate 50%.[11] These success rates of almost all countries and regions show strongly synchronous fluctuations over time, with the possible exceptions of some outliers in the early years, which indicate possible changes in the procedure or standard in the approval process by the USPTO in specific years. These changes will have to be taken into account in the empirical analysis to be conducted in Part II of this study.

Chart 14: U.S. Patent Application Success Rates: G-7 Countries, 4 EANIEs and China

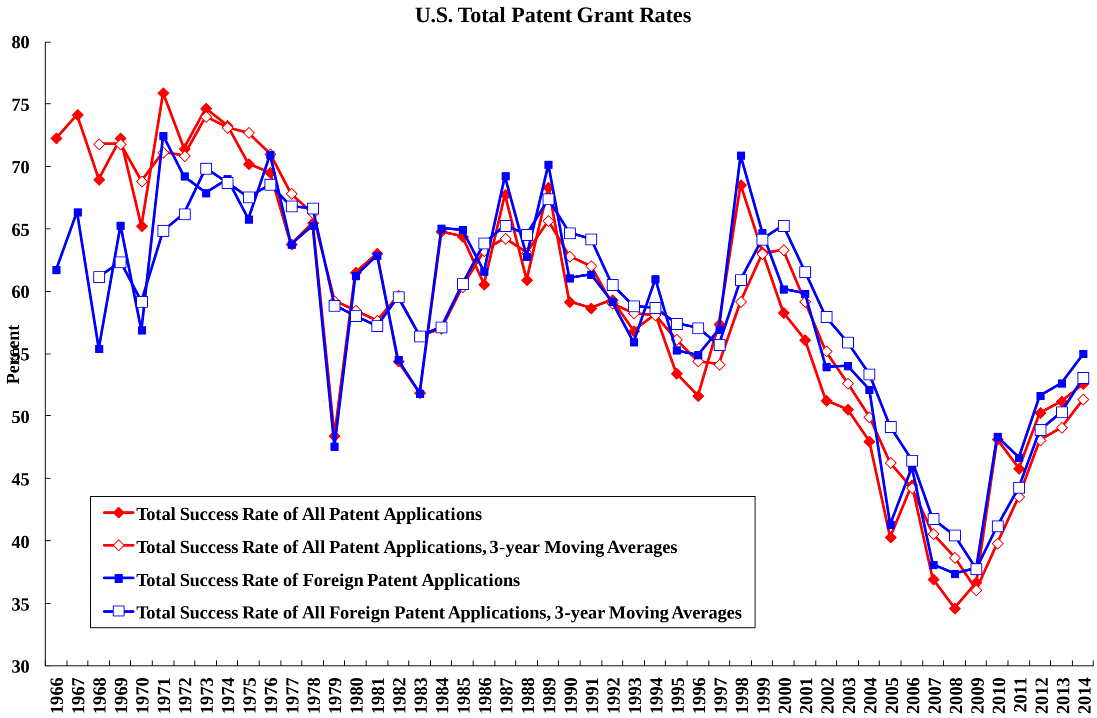


There are two possible measures of the degree of stringency of the standards applied by the USPTO. The first measure is its own total success rate of patent applications, defined as the total number of patents granted to all countries and regions, including the U.S. itself, divided by the total number of patent applications received from all countries and regions in the previous year. The second measure is

[11] This may be taken as evidence that there is no obvious home bias in the U.S. patent grants.

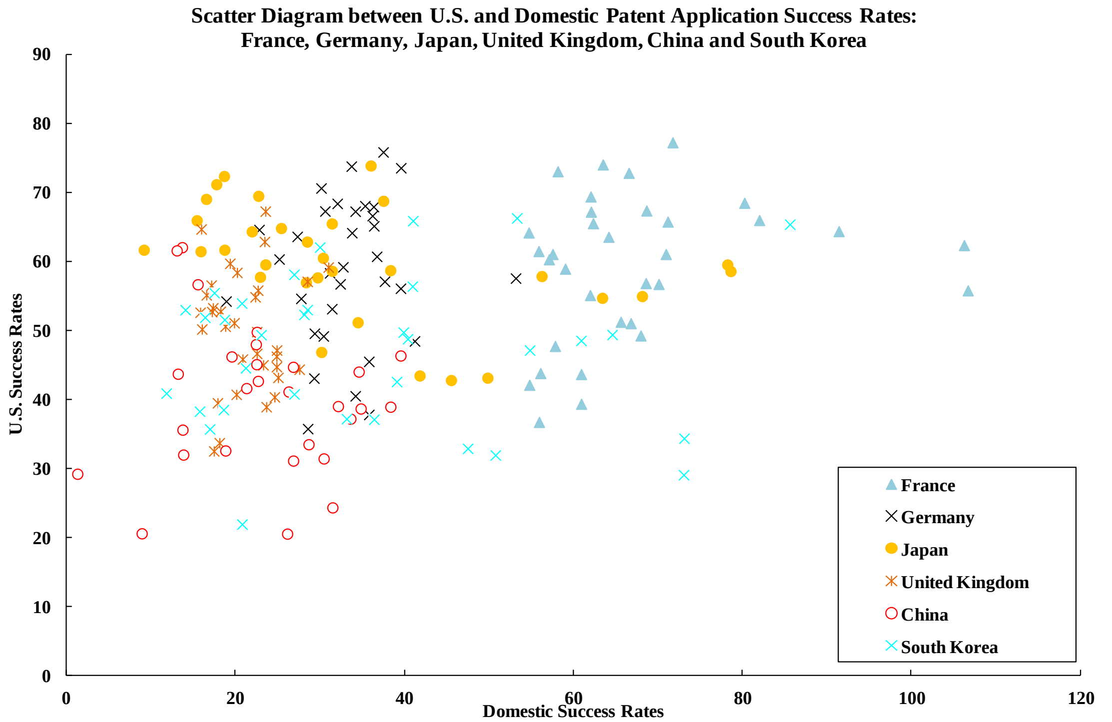
its total success rate of patent applications submitted by non-U.S. applicants, defined as the total number of patents granted to all countries and regions except the U.S., divided by the total number of patent applications received from all countries and regions except the U.S. in the previous year. In Chart 15, these two alternative U.S. patent grant rates and their three-year moving averages are presented. While the U.S. total patent grant rates show significant year-to-year variations over time, they track closely with the individual-economy-specific U.S. patent application success rates in Chart 14. Moreover, there is also a distinct and unmistakable overall downward trend. What this means is that for any economy, even if the quantity and quality of its U.S. patent applications are held constant, the number of U.S. patents granted may still fluctuate because of the changing U.S. operating procedures and/or standards over time. The variations in the U.S. patent grant rates will have to be taken into account in the econometric analysis in Part II. Chart 15 shows that the U.S. total patent grant rates, whether they include the U.S. patent grant applications by U.S. citizens and permanent residents, have been practically the same in every year since 1977. If anything, they show that foreign patent applicants have a slightly higher patent grant rates than U.S. applicants and therefore confirm that there is really no "home court" advantage for U.S. patent applicants.

Chart 15: U.S. Total Patent Grant Rates



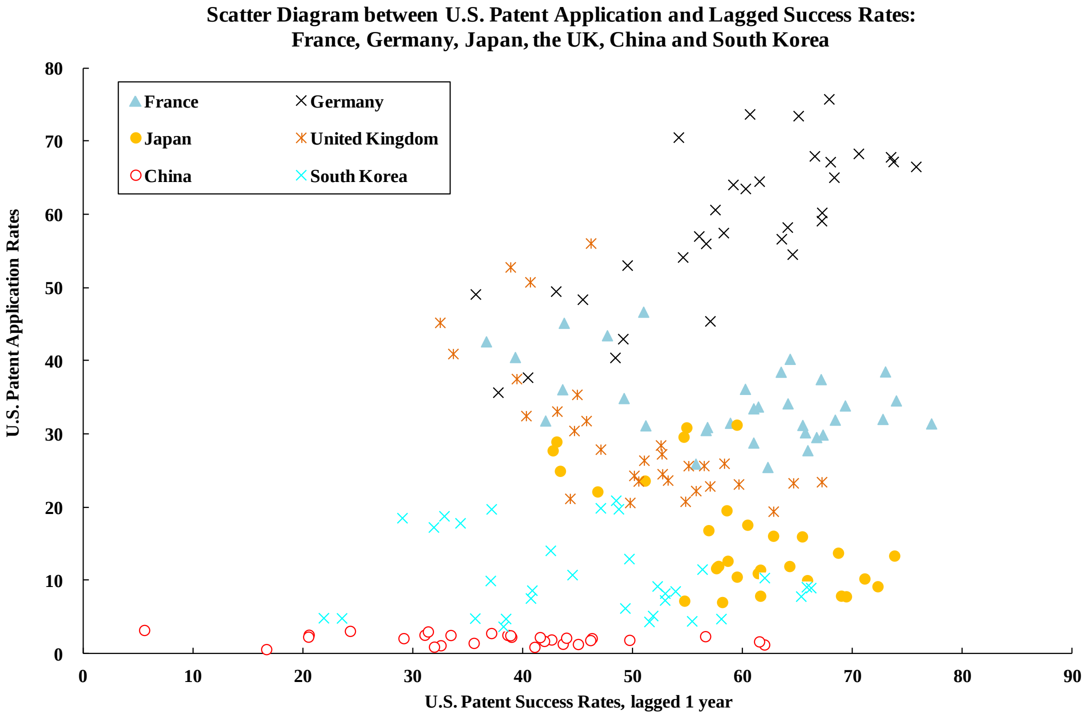
It is also interesting to examine the relationship between the domestic patent application success rate and the U.S. patent application success rate of each economy. This can provide some indirect evidence on the quality of the domestic patents granted compared to the U.S. patents granted and its evolution over time. In Chart 16, the U.S. patent application success rate is plotted against the domestic patent application success rate of each economy each year, where we have omitted the data of economies with an U.S. patent application rate of over 100 percent in any one year. While there appears to be a generally positive correlation between the U.S. patent success rate and the domestic patent success rate for some economies, the correlation is not strong.

Chart 16: Scatter Diagram between U.S. and Domestic Patent Application Success Rates: France, Germany, Japan, United Kingdom, China and South Korea



An interesting question is whether the U.S. patent application rate of an economy is influenced by its past U.S. patent application success rates. In Chart 17, a scatter diagram between the U.S. patent application rate of an economy and its lagged U.S. patent success rate is presented. Again, we have omitted the data of economies with an U.S. patent application rate of over 100 percent in any one year. However, for most of the economies, there is no obvious discernible pattern; except for Germany where there appears to be a slight positive correlation between its patent application rate and its lagged success rate, and for Japan and the United Kingdom, where there appear to be slight negative correlations.

Chart 17: Scatter Diagram between U.S. Patent Application and Lagged U.S. Success Rates: France, Germany, Japan, United Kingdom, China and South Korea



The real R&D capital stock can be shown to have a direct causal relationship to the number of patents granted. In Chart 18, the number of domestic patents granted to the citizens of a country or region is plotted against its real R&D capital stock at the beginning of that year. In Chart 19[12], the number of U.S. patents granted to the citizens of a country or region is plotted against its real R&D capital stock at the beginning of that year. Both charts show clearly that the higher the level of the real R&D capital stock of an economy, the higher is the number of domestic and U.S. patents granted to it. On an economy-by-economy basis, the positive correlation may not be so obvious (see, for example, France, West Germany and the U.K. as well as the early phases of South Korea and Singapore and even the U.S.). However,

[12] Data for real R&D capital stocks are not available for an unified Germany before 1990. Data for U.S. patents granted are not available separately for West Germany. Thus, only data for an united Germany are included in Chart 19.

taken as a whole, with data pooled across all of the economies, the overall positive correlation is most apparent. In the empirical analysis in Part II of this study, a more systematic econometric approach will be used to estimate this positive causal relationship between patent applications and grants on the one hand and the real R&D capital stocks on the other.

Chart 18: Domestic Patents Granted and R&D Capital Stocks: G-7 Countries, 4 EANIEs and China

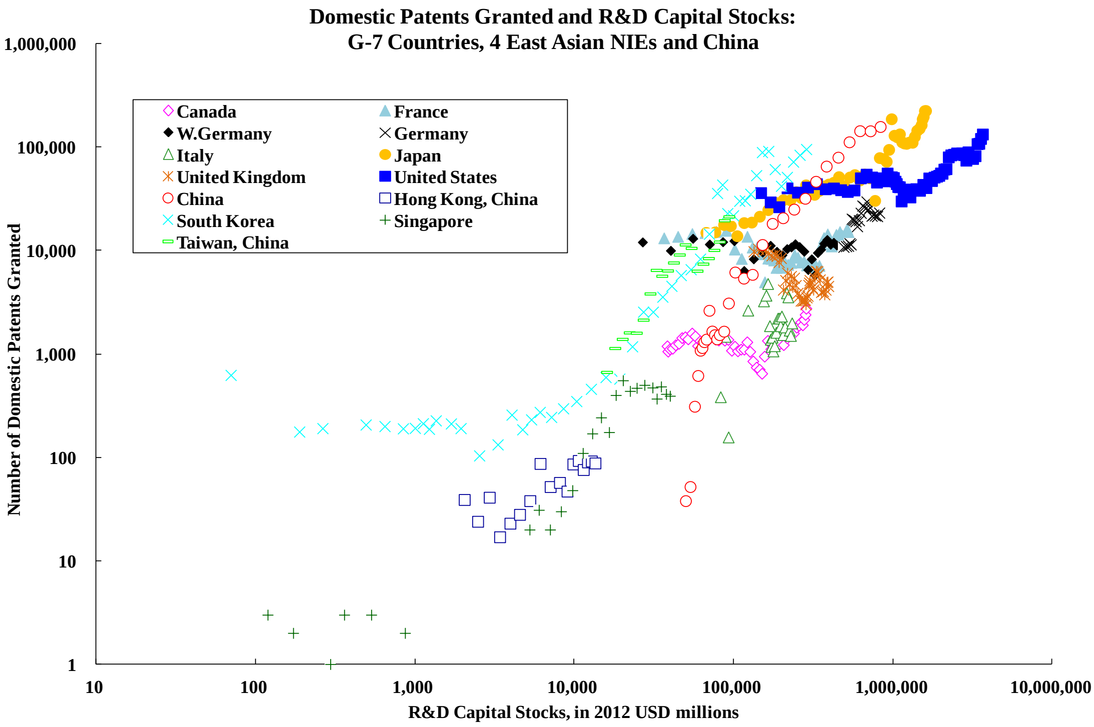
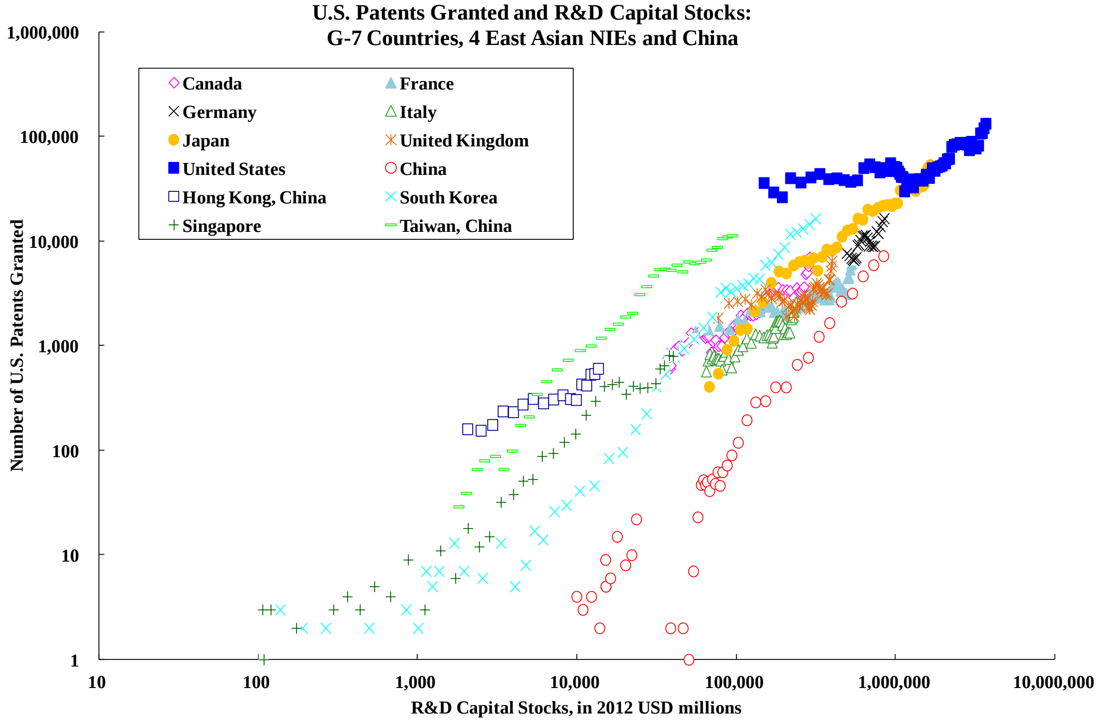


Chart 19: U.S. Patents Granted and R&D Capital Stocks: G-7 Countries, 4 EANIEs and China

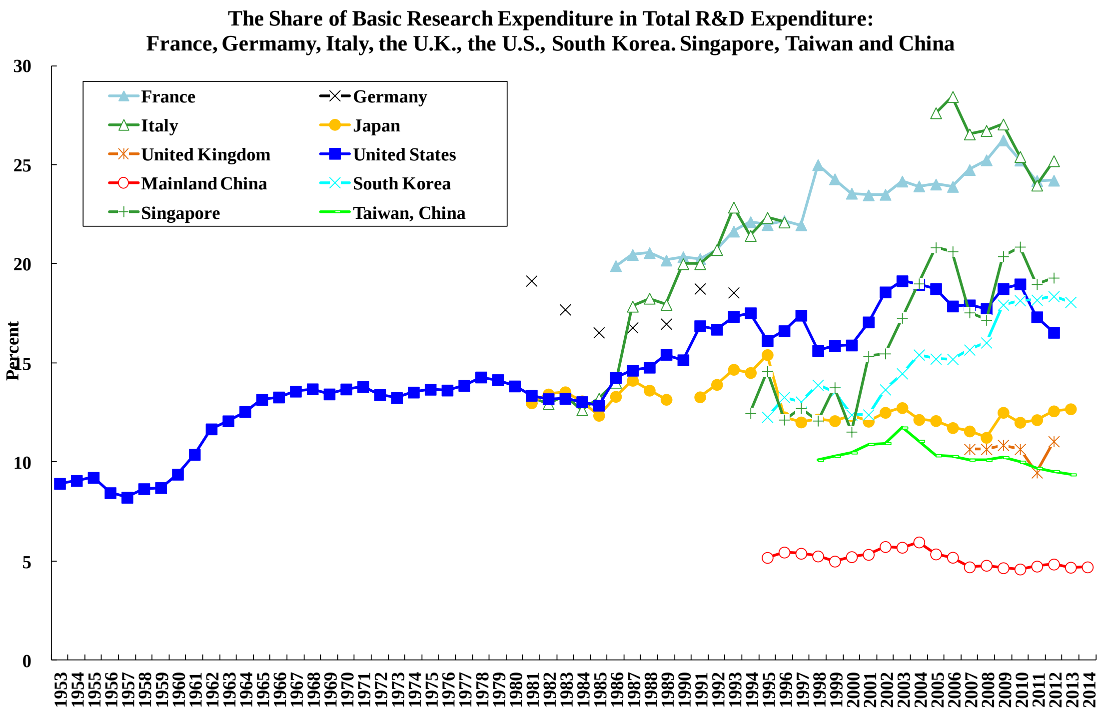


The positive correlation between the number of patents granted and the real R&D capital stock is stronger for U.S. patents granted than domestic patents granted. We believe this may possibly be due to self-selection on the part of the foreign applicants who would choose to submit applications only for patents perceived to be of higher quality and more uniform standards on patent grants on the part of the USPTO.

We may also note that there exist significant systematic differences in the efficiency in the generation of domestic and U.S. patent grants across economies, in the sense that for a given level of real R&D capital stock, the number of domestic or U.S. patents granted can be quite different across economies. For domestic patent grants, South Korea, China and Japan appear to have the highest efficiencies, and Italy, Canada, the U.K., Germany and the U.S. appear to have the lowest efficiencies. For U.S. patent grants, China appears to have the lowest efficiencies and the U.S. and Taiwan seem to have the highest efficiencies. We believe that the relative efficiencies in the generation of U.S. patent grants are probably more reliable because all economies face the same uniform standards of the USPTO as opposed to the possibly differing standards maintained by the respective domestic patent offices.

Finally, among R&D expenditures, different categories may be distinguished: basic research, applied research and development. It is well known that "break-through" discoveries and innovations can only consistently occur in an economy with a strong foundation of basic research. Thus, in the long run, leadership in innovation can only come about with significant investments in basic research. In Chart 20, the ratios of R&D expenditure devoted to the support of basic research in each of the economies under study are presented. Unfortunately, data on basic research expenditures are not complete for all of the economies included in the study. Based on the available data, Italy and France led the group of economies under study with a basic research ratio of around 25%. The United States ratio has averaged almost 20% over the past ten years, whereas Japan and the U.K. had ratios in the low teens. The Taiwan ratio was around 10%. China had the lowest ratio at around 5%.

Chart 20: The Share of Basic Research Expenditure in Total R&D Expenditure: G-7 Countries, 4 EANIEs and China



Appendix I: Construction of Time-Series of Real R&D Capital Stocks

1. Generating Real R&D Expenditure in U.S. Dollars for Each Economy

The first step in the construction of real capital stocks for the economies included in our study is to generate time series of annual real R&D expenditures in U.S. Dollars, 2012 prices, for each of the economies. The procedure is as follows:

A. Data are collected on annual nominal R&D expenditures in national currency and in current prices. The data sources are:

1. Group-of-Seven (G-7) countries

a. The U.S.: from National Science Foundation http://www.nsf.gov/statistics/nsf14304/content.cfm?pub_id=4326&id=2

b. Others:

1. 1981-2013: from Organisation for Economic Cooperation and Development (OECD), Main Science and Technology Indicators (MSTI) (online database)
2. 1969-1982: from OECD Science and Technology Indictors Unit (OECD/STIU) Data Bank, February 1985 (hard copy), Paris: OECD
3. 1963-1968: from OCED Directorate For Science, Technology and Industry (OECD/DSTII), Science and Technology Indicators: Basic Statistical Series - Volume B: Gross National Expenditure on R&D, 1963-1979 (hard copy), Paris: OECD
4. 1981-1999: from various MSTI hard copies
5. For Canada, Japan and the U.K., there are slight differences in the R&D expenditure data from 1981 to 1993 between the hard copies and the more updated online database. Thus, data before

1981 are adjusted so that they are consistent with the most updated data in the online databases.

2. East Asian Newly Industrialized Economies (EANIEs) and China

a. China, 1953-2014: from Chinese official statistical publications--Statistics of Chinese Technology; Fifty Years of New China

b. Hong Kong, China, 1998-2013: from Census and Statistics Department

http://www.censtatd.gov.hk/hkstat/sub/sp120.jsp?tableID=207&ID=0&productType=8

c. South Korea

1. 1963-1990: from Korean Statistical Yearbook
2. 1991-2013: from OECD Main Science and Technology Indicators

d. Singapore

1. 1975-1993: from Singapore Yearbook of Statistics
2. 1994-2012: from OECD Main Science and Technology Indicators

e. Taiwan, China

1. 1978-1980: from Statistical Yearbook of the Republic of China
2. 1981-1994: from Ministry of Science and Technology, Taiwan http://statistics.most.gov.tw/was2/
3. 1995-2013: from OECD Main Science and Technology Indicators

B. The nominal R&D expenditures are converted into real R&D expenditures in national currencies in 2012 prices using the GDP deflators of the respective economies. Annual GDP deflators are calculated from the differences between the annual nominal and real rates of growth of GDP, collected from International Financial Statistics (IFS) database and domestic official statistical sources.

C. The real R&D expenditures in national currencies are converted to U.S. Dollars, using the 2012 year-end exchange rates collected from the IFS database and from national statistical sources.

2. The Estimation of the Initial Real R&D Capital Stocks

In order to construct time-series of real R&D capital stocks from time-series data on real R&D expenditure of each economy, we need first of all to estimate the initial real R&D capital stocks K_{i0}'s for each economy. Once an estimate of the initial real R&D capital stock is available, a time-series of real R&D capital stock can be readily constructed using the perpetual inventory method and assuming a rate of depreciation of R&D capital of 10 percent per annum.

To estimate the initial capital stock, we assume that the annual number of domestic patent applications of an economy is a function of its augmented real R&D capital stock:

$$YA_{iDt} = A_{AiD} \exp(c_{Di}\,\mathrm{t})\mathrm{F}(K_{it}^{*}), \tag{A1}$$

where YA_{iDt} is the number of domestic patent applications of economy *i* in year *t*, K_{it}^{*} is the quantity of efficiency-equivalent (or augmented) real R&D capital stock of economy i in year *t*, and *t* is the time trend, valued from 1 to t. It is further assumed that K_{it}^{*} is related to K_{it}, the quantity of measured real R&D capital stock, by an economy-specific and time-varying multiplicative augmentation factor:

$$K_{it}^{*} = A_{KiD} \exp(c_{Ki}\,\mathrm{t}) K_{it}. \tag{A2}$$

Moreover, it is assumed that the function F(.) in equation (A1) takes the transcendental logarithmic form, so that:

$$\ln YA_{iDt} = \ln A_{AiD} + c_{Di}\,\mathrm{t} + \ln A_{0i} + \alpha_{Ki} \ln K_{it}^{*} + \frac{1}{2}\mathrm{B}_{KKi}\left(\ln K_{it}^{*}\right)^{2} . \tag{A3}$$

By substituting equation (A2) into equation (A3), we obtain:

$$\begin{aligned} \ln YA_{iDt} &= \ln A_{AiD} + c_{Di}\,\mathrm{t} + \ln A_{0i} + \alpha_{Ki}(\ln A_{KiD} + c_{Ki}\,\mathrm{t} + \ln K_{it}) + \frac{1}{2}\mathrm{B}_{KKi}(\ln A_{KiD} + c_{Ki}\,\mathrm{t} \\ &\quad + \ln K_{it})^{2} \\ &= (\ln A_{AiD} + \ln A_{0i} + \alpha_{Ki} \ln A_{KiD} + \frac{1}{2}\mathrm{B}_{KKi}(\ln A_{KiD})^{2}) + (\alpha_{Ki} + \mathrm{B}_{KKi} \ln A_{KiD}) \ln \\ &\quad K_{it} + (c_{Di} + \alpha_{Ki}\, c_{Ki} + \mathrm{B}_{KKi}\, c_{Ki} \ln A_{KiD})\ \mathrm{t} + \mathrm{B}_{KKi}\, c_{Ki} \ln K_{it}\ \mathrm{t} + \frac{1}{2}\mathrm{B}_{KKi}(\ln \\ &\quad K_{it})^{2} + \frac{1}{2}\mathrm{B}_{KKi}\, c_{Ki}^{2}\,\mathrm{t}. \end{aligned} \tag{A4}$$

Equation (A4) may be simplified into:

$$\ln YA_{iDt} = A_{AiD}^{*} + c_{Di}^{*} t + \alpha_{Ki}^{*} \ln K_{it} + \mathrm{B}_{KKi}\, c_{Ki} \ln K_{it}\,\mathrm{t} + \frac{1}{2}\mathrm{B}_{KKi}(\ln K_{it})^{2} + \frac{1}{2}\mathrm{B}_{KKi}\, c_{Ki}^{2}\,\mathrm{t}^{2} , \tag{A5}$$

where

$A_{AiD}^{*} = (\ln A_{AiD} + \ln A_{0i} + \alpha_{Ki} \ln A_{KiD} + \frac{1}{2}\mathrm{B}_{KKi}(\ln A_{KiD})^{2});$

$\alpha_{Ki}^{*} = (\alpha_{Ki} + \mathrm{B}_{KKi} \ln A_{KiD});$

$c_{Di}^{*} = (c_{Di} + \alpha_{Ki}\, c_{Ki} + \mathrm{B}_{KKi}\, c_{Ki} \ln A_{KiD}).$

Similarly, we can derive an equation for YA_{iUSt}, the number of U.S. patent applications of economy *i* submitted in the U.S. in year *t*, follows:

$$\ln YA_{iUSt} = A^{*}_{AiUS} + c^{*}_{USi}t + \alpha^{*}_{Ki}\ln K_{it} + \mathrm{B}_{KKi}\ c_{Ki}\ln K_{it}\ \mathrm{t} + \frac{1}{2}\mathrm{B}_{KKi}(\ln K_{it})^{2} + \frac{1}{2}\mathrm{B}_{KKi}\ c^{2}_{Ki}\ \mathrm{t}^{2}\ . \tag{A6}$$

K_{it}, the stock of real R&D capital, may be defined as

$$\begin{aligned} K_{it} &= 0.9K_{i(t-1)} + I_{i(t-1)} \\ &= 0.9^{t}K_{i0} + \sum_{j=1}^{t}0.9^{j-1}I_{i(t-j)} \end{aligned} \tag{A7}$$

where K_{i0} is the initial R&D capital stock of economy *i*; $I_{i(t-j)}$ is the real R&D expenditure of economy *i* in year *t-j*. Substituting equation (A7) into equations (A5) and (A6), we obtain equations A(8) and A(9), respectively.

$$\begin{aligned} \ln YA_{iDt} = {} & A^{*}_{AiD} + c^{*}_{Di}t + \alpha^{*}_{Ki}\ln(0.9^{t}K_{i,0} + \sum_{j=1}^{t}0.9^{j-1}I_{i(t-j)}) \\ & + \frac{1}{2}\mathrm{B}_{KKi}\left(\ln(0.9^{t}K_{i,0} + \sum_{j=1}^{t}0.9^{j-1}I_{i(t-j)})\right)^{2} \\ & + \mathrm{B}_{KKi}c_{Ki}\ln(0.9^{t}K_{i,0} + \sum_{j=1}^{t}0.9^{j-1}I_{i(t-j)})t \\ & + \frac{1}{2}\mathrm{B}_{KKi}c^{2}_{Ki}t^{2} \end{aligned} \tag{A8}$$

$$\ln YA_{iUSt} = A^*_{AiUS} + c^*_{USi}t + \alpha^*_{Ki}\ln(0.9^t K_{i,0} + \sum_{j=1}^{t} 0.9^{j-1} I_{i(t-j)}) \qquad \text{(A9)}$$

$$+ \frac{1}{2}\mathrm{B}_{KKi}\left(\ln(0.9^t K_{i,0} + \sum_{j=1}^{t} 0.9^{j-1} I_{i(t-j)})\right)^2$$

$$+ \mathrm{B}_{KKi} c_{Ki} \ln(0.9^t K_{i,0} + \sum_{j=1}^{t} 0.9^{j-1} I_{i(t-j)})t$$

$$+ \frac{1}{2}\mathrm{B}_{KKi} c^2_{Ki} t^2$$

Equation (A8) is estimated for France, Germany, Japan, the U.K., China (Mainland) and South Korea, as their numbers of domestic patent applications have consistently exceeded their numbers of U.S. patent applications. Equation (A9) is estimated for Canada, Italy, the U.S., Hong Kong, Singapore and Taiwan as their U.S. patent applications have been greater than or equal to their domestic patent applications[13]. Parameters such as B_{KKi} and c_{Ki} are over-identified in equations (A8) and (A9). Thus, nonlinear methods are used to estimate the two equations, imposing the over-identifying restrictions, to obtain the nonlinear estimates of parameters including the initial R&D capital stock K_{i0}.

3. The Estimation of the Time-Series of Real R&D Capital Stocks

Given the time-series of real R&D expenditures and the initial real capital stocks estimated above, the real R&D capital stocks for each economy can be estimated using equation (A7):

$$K_{it} = 0.9K_{i(t-1)} + I_{i(t-1)} \qquad \text{(A7)}$$

$$= 0.9^t K_{i0} + \sum_{j=1}^{t} 0.9^{j-1} I_{i(t-j)}$$

where K_{i0} is the initial real R&D capital stock of economy *i* and $I_{i(t-j)}$ is the real R&D expenditure of economy *i* in year *t-j*.

[13] Of course, for the U.S. the number of domestic patent applications is the same as the number of U.S. patent applications.

4. Estimated Real R&D Capital Stocks of Selected Economies

Table 1: Real R&D Capital Stocks of Group-of-Seven (G-7) Countries

	R&D Capital Stocks, in 2012 USD billions							
	Canada	**France**	**West Germany**	**Unified Germany**	**Italy**	**Japan**	**U.K.**	**U.S.**
1953								148.305
1954								170.288
1955								192.961
1956								217.327
1957								252.719
1958								291.884
1959								332.122
1960								377.427
1961								424.695
1962								471.509
1963	38.330	36.574				67.218		518.921
1964	38.770	44.742	26.858			76.559	76.478	571.865
1965	39.783	54.956	40.297			86.849	89.226	627.261
1966	41.370	66.444	55.534			95.822	101.249	681.751
1967	43.215	77.944	70.700			105.209	112.756	737.799
1968	45.339	90.068	85.615			116.205	123.694	791.502
1969	47.435	101.525	100.830			129.774	133.980	841.549
1970	49.654	112.226	116.294		64.433	145.635	143.259	887.146
1971	51.802	121.762	133.535		66.050	164.604	151.392	922.988
1972	54.846	131.281	152.015		67.909	183.929	158.753	952.389
1973	57.444	140.451	170.375		69.902	204.868	165.569	981.555
1974	59.634	148.664	186.690		71.855	226.913	173.672	1010.330
1975	61.630	156.958	201.761		73.328	246.856	181.545	1034.712
1976	63.530	164.587	216.383		75.466	265.525	187.015	1053.774
1977	65.212	171.975	230.152		77.223	284.031	192.517	1076.503
1978	67.075	179.106	243.615		79.260	302.422	198.375	1101.206
1979	69.213	185.306	258.838		80.866	321.603	205.059	1130.113
1980	71.372	192.187	276.944		82.854	343.582	211.925	1163.001
1981	73.863	199.488	293.349		85.081	367.529	217.633	1199.351
1982	76.910	208.826	308.777		88.934	394.948	224.257	1239.005
1983	80.542	219.343	323.172		92.828	424.532	229.645	1283.106
1984	83.883	229.856	337.120		97.171	457.422	234.500	1334.824

Table 1: Real R&D Capital Stocks of Group-of-Seven (G-7) Countries (continued)

	R&D Capital Stocks, in 2012 USD billions							
	Canada	France	West Germany	Unified Germany	Italy	Japan	U.K.	U.S.
1985	87.906	241.273	352.603		102.324	493.439	239.998	1398.569
1986	92.505	253.031	369.559		109.096	535.712	245.814	1473.409
1987	97.303	264.350	386.407		115.767	575.326	252.195	1546.339
1988	101.732	276.035	405.633		123.193	617.540	258.424	1616.641
1989	106.166	288.163	424.631		131.086	663.670	264.889	1685.392
1990	111.237	301.610	443.685		139.135	714.912	271.397	1752.167
1991	116.503	316.733		490.933	147.679	770.962	277.326	1819.652
1992	121.562	330.998		509.598	154.592	824.705	280.990	1885.777
1993	126.768	344.693		524.656	160.221	871.907	283.878	1946.283
1994	132.485	357.385		535.709	164.105	911.121	287.711	1995.914
1995	139.148	368.613		544.623	166.673	943.386	291.966	2040.558
1996	145.307	379.175		553.834	168.580	979.606	295.821	2096.141
1997	150.632	388.841		562.904	170.655	1020.070	298.697	2160.352
1998	156.357	396.889		573.206	172.461	1061.680	301.209	2233.577
1999	163.680	404.330		584.875	174.977	1102.800	304.727	2315.537
2000	171.924	411.988		597.239	177.271	1139.944	310.689	2409.938
2001	182.275	420.518		613.924	180.691	1177.679	316.859	2518.665
2002	194.660	430.254		630.037	184.946	1215.841	323.190	2622.542
2003	205.896	440.504		645.515	189.686	1252.593	329.814	2709.953
2004	216.523	448.795		660.208	193.518	1289.045	336.276	2798.181
2005	227.621	456.971		673.196	197.083	1324.772	341.652	2881.440
2006	238.311	464.120		685.499	200.425	1368.561	348.110	2970.826
2007	248.356	471.940		700.664	204.814	1416.369	355.636	3067.828
2008	257.062	479.548		716.706	210.130	1466.294	364.410	3173.470
2009	264.564	487.466		737.432	215.336	1509.486	372.172	3288.216
2010	271.311	496.986		755.133	219.803	1532.205	378.671	3385.770
2011	276.973	505.740		774.360	224.291	1555.286	383.993	3471.041
2012	282.103	515.265		798.034	228.231	1582.302	389.517	3559.762
2013	285.349	525.149		822.609	232.459	1607.591	393.180	3656.341
2014	287.292	534.221		843.986	235.447	1640.546	397.025	

Appendix II: The Detailed Definitions of Patents in This Study

The detailed definitions of the patents in each of our data sources are listed below.

1. World Intellectual Property Organization (WIPO):

A patent is an exclusive right granted for an invention, which is a product or a process that provides, in general, a new way of doing something, or offers a new technical solution to a problem. To obtain a patent, the technical information about the invention must be disclosed to the public in a patent application.

(Source: http://www.wipo.int/patents/en/).

2. United States Patent and Trademark Office (USPTO):

A patent for an invention is the grant of a property right to the inventor, issued by the United States Patent and Trademark Office. Generally, the term of a new patent is 20 years from the date on which the application for the patent was filed in the United States or, in special cases, from the date an earlier related application was filed, subject to the payment of maintenance fees. U.S. patent grants are effective only within the United States, U.S. territories, and U.S. possessions. Under certain circumstances, patent term extensions or adjustments may be available.

The right conferred by the patent grant is, in the language of the statute and of the grant itself, “the right to exclude others from making, using, offering for sale, or selling” the invention in the United States or “importing” the invention into the United States. What is granted is not the right to make, use, offer for sale, sell or import, but the right to exclude others from making, using, offering for sale, selling or importing the invention. Once a patent is issued, the patentee must enforce the patent without aid of the USPTO.

There are three types of patents:

1) Utility patents may be granted to anyone who invents or discovers any new and useful process, machine, article of manufacture, or composition of matter, or any new and useful improvement thereof;
2) Design patents may be granted to anyone who invents a new, original, and ornamental design for an article of manufacture; and
3) Plant patents may be granted to anyone who invents or discovers and asexually reproduces any distinct and new variety of plant.

(Source: http://www.uspto.gov/patents-getting-started/general-information-concerning-patents#heading-2).

3. The State Intellectual Property Office (SIPO) of the People’s Republic of China:

There are three kinds of intellectual property rights in China, including patent, trademark and copyright. Patents include "patents for invention", "patents for utility model" and "patents for design". Invention means any new technical solution relating to a product, a process or improvement.

(Source: http://english.sipo.gov.cn/FAQ/200904/t20090408_449727.html; http://english.sipo.gov.cn/FAQ/200904/t20090408_449709.html).

4. Intellectual Property Office, Ministry of Economic Affairs, R.O.C. (Taiwan, China):

A patent is an intellectual property right which is examined and granted by the competent authority (e.g., Patent Office) to an inventor, a utility model creator, or a designer “to exclude others from exploiting the creation without the patentee’s consent” for a limited time period in exchange for public disclosure of the creation when the patent is granted.

(Source: http://www.tipo.gov.tw/ct.asp?xItem=522178&ctNode=6818&mp=2)/