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JEL classification: O3

Keywords: Patent breadth; Cumulative innovation; Citations

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June 12, 2006

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The economic theory of the optimal patent design argues that patent protection only from imitations is not sufficient to stimulate cumulative innovation. This paper explores the effects of broadening patent breadth on cumulative innovation based on a natural experiment in 1986-87, in which Texas Instruments' lawsuits succeeded in broadening the protection of its basic patents of Dynamic Random Access Memory by out-of-court settlements. I examine changes in the quantity and quality of patents of firms involved in the lawsuits by using patent citations as a measure of the quality of patents. Both high and low quality patents increased after the lawsuits, but the increase in low quality patents was much more intense than the increase in high quality patents. Broad patent protection for basic or earlier innovation may stimulate firms' research efforts, but it may also produce a large amount of low quality inventions as by-products, which could reduce social welfare.

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1 Introduction

The main policy instruments of patent systems are length and breadth (or scope) of patents. However, since the length is fixed unless the patent law is changed, in practice, breadth is the only available patent policy tool. The Japanese government is currently pursuing “pro-patent” policies, while the U.S. government, which had been strengthening patent protection since the early 1980s, is revising its current patent system. These policy reforms affect technological areas that infringe relevant patents, i.e. the breadth of patents. Thus, exploring the relationship between patent breadth and innovation has important policy implications.

Theoretical studies suggest that breadth of patents is a key stimulus for innovation. For example, Denicolò (1996) shows that in the case of a single invention, narrowing patent breadth results in reducing the incentive to innovate. When the innovation process is a long sequence of improvements (cumulative innovation), O’Donoghue, Scotchmer, and Thisse (1998) shows that firms underinvest in R&D without "leading breadth", which protects a patented invention from improved products (protection from imitations or inferior products is called "lagging breadth").[1]

Empirical studies, however, have been inconclusive on the above theoretical results. Lerner (1994) examined biotechnology firms and showed that firms whose patents have more International Patent classes (IPCs) are valued more highly by venture capitalists, which can increase profits and innovation incentives. On the other hand, Merges and Nelson (1990) examined the historical development of electrical lighting, automobiles, airplanes and radio in the U.S., and argued that strong patent rights by early inventors inhibited the broad development of the technologies. Sakakibara and Branstetter (2001) examined the effects of the 1988 Japanese patent reform that extended patent breadth.

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[1] A patent with large leading breadth can be issued by validating broad claims. An example is a patent granted to the Harvard Medical School oncomouse (Harvard mouse) in 1984 (US Patent 4736866), whose seven claims are for a transgenic non-human mammal. Thus, applying the oncomouse technology to non-human mammals other than mouse can infringe that patent. Small leading breadth can be validated under the “doctrine of equivalence.”

Formerly, Japanese patent law allowed only one claim on a patent. In 1988, the law was changed, allowing multiple and independently valid claims on a patent.[2] They conducted an econometric analysis of 307 Japanese manufacturing firms, and found that those Japanese firms' R&D expenditures and patenting were unresponsive to the change in patent breadth.

This paper presents new empirical evidence of the relationship between patent breadth and innovation using Texas Instruments' successful lawsuits against eight Japanese electronics firms in 1986-87 as a natural experiment. Texas Instruments (TI) sued eight Japanese (and one Korean) firms alleging that they were infringing its patents of basic technologies of Dynamic Random Access Memory (DRAM). The suits covered not only current but also future generations of DRAM, and thus it can be interpreted that TI was claiming broader leading breadth. TI and the Japanese firms reached out-of-court settlements in favor of TI, and thus the leading breadth of TI's DRAM patents was virtually broadened. After this event, other large patent holders such as IBM and Motorola also began asserting patent rights to increase revenue from patent licenses (Hall and Ziedonis (2001)).

As O'Donoghue, Scotchmer, and Thisse (1998) and other theoretical studies of two-stage innovation such as Green and Scotchmer (1995) suggest, it is not lagging but leading breadth that stimulates cumulative innovation. Therefore, to examine the relationship between patent breadth and innovation, the types of breadth (lagging or leading) and the types of innovation (single or cumulative) should be matched. Sakakibara and Branstetter (2001) conjecture that, based on a number of interviews, the gap between theoretical and their empirical results can be due to poor communication between the intellectual property department and the R&D department. Yet another explanation could be a mismatch between the types of breadth and innovation to be studied. The Japanese patent reform in 1988 was not necessarily intended to broaden patent

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[2] A 1976 amendment to the Japnese patent law allowed multiple *dependent* claims, but the amendment did not substantially change the single claim system. See Sakakibara and Branstetter (2001).

protection beyond imitations. Since cumulative innovation industries such as electronics have been the highest R&D intensity industries in Japan, Japanese firms' unresponsiveness to the 1988 reform might be interpreted as being not a paradoxical but rather a natural result.

An advantage of this paper's empirical approach is that the combination of the types of breadth and innovation is appropriate. The effects of TI's lawsuits on innovation are examined by comparing the quantity and quality of electronics-related patents of the eight Japanese firms sued by TI and three major U.S. electronics firms (TI, IBM, and Motorola) before and after the lawsuits. The quality of a patent is measured by using citations to that patent. Examining changes not only in the quantity of patents but also in the quality of patent is especially important because patents are quite heterogenous in their quality and thus the number of patents does not necessarily represent the amount of innovation. However, there are several problems in using citations to a patent as a patent quality measure, primarily due to truncation. These problems can be mitigated by using the "quasi-structural" approach proposed by Hall, Jaffe, and Trajtenberg (2002).

The results of empirical analysis show that the average quality per patent for the eight Japanese firms has decreased after the TI lawsuits. However, the decrease in the average quality was due to a large increase in low quality patents. An increase in high quality patents is also observed, although the increase was much smaller compared to the low quality patents. Thus, the empirical results do not contradict theoretical results of the effects of broad patent protection when innovation is cumulative. At the same time, however, it is shown that broad patent protection may have also stimulated low quality inventions as byproducts, which could reduce social welfare.

The paper is organized as follows. Section 2 describes the natural experiment of TI's suits in 1986-87. Section 3 explains the framework of the empirical analysis, data, and results. To supplement the empirical analysis, I also interviewed intellectual property managers of two Japanese firms sued by TI in 1986, whose results are summarized in Section 4. Finally, Section 5 discusses the policy implications of the empirical analysis and interview results. The details of measuring patent quality using the quasi-structural approach are described in Appendix.

2 The TI lawsuits in the mid 1980s

On January 24, 1986, Texas Instruments (TI) filed patent infringement lawsuits in Federal District Court in Dallas against eight Japanese electronics firms (and one Korean firm, Samsung) that were producing and selling DRAMs in the United States. The lawsuits by TI were brought after the patent policy changes in the early 1980s, and TI's confidence in filing the suits was boosted by "pro-inventor" rulings by the Court of Appeal for the Federal Circuit, which was established in 1982.[3] The suits covered not only current but also future generations of DRAM chips that would be used in all types of computer systems to store data.[4] The Japanese firms were sued not necessarily for imitating existing technologies but rather for producing and selling improved technologies. In fact, Japanese firms had developed proprietary technology of their own and some of them responded by countersuing TI for infringing their patents.[5] TI also filed a complaint with the International Trade Commission (ITC) regarding the importation into the U.S. of DRAMs as infringing TI's patents, and ITC initiated an investigation on March 11, 1986. TI reached settlement agreements with the eight Japanese firms in 1987 and received significant royalty payments from them.

The patents that TI defended were basic technologies to produce DRAM, and the Japanese firms had developed improved DRAMs using TI's technologies. Thus, TI was claiming larger leading breadth in the suits. Although TI's victory was brought by out-of-court settlements rather than court decisions, it implies

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[3] Financial Times, January 28, 1986, "TI reconsiders policy on patents."

[4] Ibid.

[5] Business Week, April 28, 1986, "TI's battle plan against the Japanese."

that larger leading patent breadth became virtually effective. In fact, after the TI lawsuits, coupled with Polaroid's success in an infringement suit against Kodak in 1986, other large patent holders such as IBM and Motorola began asserting their patent rights more aggressively, and the patenting strategies of many high-tech firms have changed since then (Hall and Ziedonis(2002)). Thus, the lawsuits in 1986-87 could be interpreted as a natural experiment where leading breadth of patents was virtually broadened. In theory, innovation in semiconductor and other cumulative high technologies such as computers and communications equipment could have been stimulated after the suits.

On the other hand, there is also a theory that broad patent protection can deter innovation if an invention consists of complementary components. Shapiro (2001) argues that strong patent protection for multiple complementary technologies can create a "patent thicket," an overlapping set of patent rights requiring licenses from multiple patentees, and can have the perverse effects of stifling innovation since each patentee has strong monopoly power. Semiconductor and other electronics products are not only cumulative but also complementary innovations comprised of many components. The complementary nature of semiconductors is well shown in the fact that cross-licenses among major semiconductor manufacturers were necessary even before the TI lawsuits.[6] Thus, broader leading breadth of patents can have two opposite effects on innovation.

3 Empirical analysis

3.1 Framework

To answer the question whether or not broader patent breadth after the TI lawsuits stimulated innovation, I examine changes in the quantity and quality of patents of the eight Japanese firms sued by TI and three major U.S. electronics firms: IBM, Motorola, and TI. The quality of patents is measured using the

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[6] Ibid.

number of citations that a patent receives from other patents (forward citations).

Using forward citations as a proxy of the quality of patents can be validated by empirical findings that the quality of patented inventions is closely related to the number of citations that the patents receive from other patents. Albert et al. (1991) examined 77 patents granted to Eastman Kodak in 1982-83 and found that ratings of the technological impact of patents evaluated by researchers at Eastman Kodak are highly correlated with the counts of citations that those patents received. In economic literature, Trajtenberg (1990) studied the correlation between the change in social welfare due to innovation and the number of patent citations for Computed Tomography (CT). Using two measures of the change in social surplus due to innovation of CT, he showed that correlations between those welfare measures and the counts of CT manufacturing firms' patents weighted by forward citations were around 0.7 and statistically significant. On the other hand, there were no statistically significant correlations between the welfare measures and simple patent counts. Moreover, Hall, Jaffe, and Trajtenberg (2005) found that firms' stock of patents weighted by forward citations is correlated with firms' market value.

However, several problems exist in using forward citations as a measure of the quality of patents. One problem is truncation in observed citations: we can observe citations only by the last date in the data set. This truncation makes it difficult to compare citations to patents applied for in different years because it takes a long time to measure the citations that a patent receives. For example, it took over 10 years for patents that were granted in 1975 to receive 50% of forward citations by 1999 (Hall, Jaffe, and Tranjtenberg (2002)). Thus, patents that were applied for in the later period in the sample would receive fewer citations regardless of their quality when compared with patents that were applied for in the earlier period.

In addition to the truncation problem, differences in the Patent Office's practices across time make it difficult to compare citations in different years. Since whether citations should be made to a patent or not is determined by patent examiners in the Patent Office, the number of skilled examiners or computerization of the patent files might have affected the number of citations to a patent. Even for patents applied for in the same year, comparing citations would be complicated if different technologies have different tendencies to be cited and/or the Patent Office has different practices across technological fields.

Finally, there may have been “inflation” of citations after the patent policy shift in the 1980s, which means that later citations are less significant than earlier citations. Hall and Ziedonis (2001) argue that, based on an econometric analysis on the U.S. semiconductor industry, many large manufacturing firms engaged in “patent portfolio races” after the mid 1980s, which means that firms apply for as many patents as possible in order to avoid getting involved in patent suits. If firms increased disclosure of many low quality inventions through patents for strategic reasons to avoid costly lawsuits, then citations made by those strategic patents might have increased accordingly, which is the inflation of citations.

To solve these problems in using citations as a measure of patent quality, I use the “quasi-structural” approach suggested by Hall, Jaffe, and Tranjtenberg (2002). In this approach, the average number of forward citations is decomposed into the following three parts: (i) year effects, (ii) lag distribution independent of years, and (iii) stochastic term. The year effects are further decomposed into (i) the year effects for patents cited by other patents (cited year effects, hereafter) and (ii) the year effects for patents citing other patents (citing year effects, hereafter). The cited year effects can be interpreted as changes in the quality of innovation. On the other hand, the citing year effects can be interpreted as nominal changes or noises in the number of citations.

The number of citations to a patent in which the above problems are controlled is calculated in the following way. First, noise factors in observed citations are removed using the estimated citing year effects. Then, fixing the length of lags to 24 years for all patents, unobserved citations is added to observed citations for each patent by using the estimated lag distribution. To adjust for the difference between the average citations and citations to each patent during the unobserved years, average citations are multiplied by the ratio of each patent's citations to average citations during the observed years. See Appendix for details.

3.2 Data

The eight Japanese electronics firms that were sued by TI are Fujitsu, Hitachi, Matsushita Electronics (a subsidiary of Matsushita Electric Industrial), Mitsubishi Electric, NEC, Oki Electric Industry, Toshiba, and Sharp.[7] For these eight Japanese and three U.S. firms (IBM, Motorola, and TI), I examine U.S. patents in electronics as research outputs of cumulative innovation. The data on the U.S. patents is taken from the NBER Patent-Citation Data File, which includes all the utility patents granted from 1963 to 1999 and all citations made by patents granted from 1975 to 1999. In the following analysis, application years are used as years of creation of patents because there are lags between application and grant years due to examination processes at the Patent Office. Moreover, because of application and grant lags, many patents applied for in the later years in the data file had not yet been granted at the time that the data file was completed, which is implied by the data showing that the number of patent applications suddenly drops a few years before the end year of the data file. Thus, I use patents applied for between 1975 and 1996.

The technological classification system used in the NBER data file aggregates 400 main (3-digit) patent classes of the U.S. Patent and Trademark Office into 6 main categories (Chemicals, Computers & Communications, Drugs & Medical, Electrical & Electronic, Mechanical, Others) and 36 sub-categories. As electronics patents, I use all the subcategories in the Computers & Communications (Communications, Computer Hardware & Software, Computer Peripherals, and Information Storage), and Semiconductor Devices from the Electrical

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[7] In the following analysis, patents of Matsushita Electronics are coupled with the patents of its parent company, Matsushita Electric Industrial.

& Electronic.

3.3 Results

Figure 1 is the average number of electronics patents per firm for the eight Japanese and three U.S. firms. Both the Japanese and U.S. firms' averages increased, and the increases for the U.S. firms seem to have accelerated in the late 1980s.

Figure 2 shows the average quality of patents measured by citations, which is hereafter called "real citations" because noise factors are removed and unobserved citations due to truncation are added. Contrary to the increase in patents, the real citations decreased on average for both the Japanese and US firms.

To test whether the decrease in the real citations after the mid 1980s is statistically significant, I divide the sample into the periods before and after the TI suits, 1975-85 and 1986-96, and test the differences in the means of the two samples using the Mann-Whitney test, a non-parametric rank test.[8] The results of the tests are shown in Table 1. The null hypothesis that the means of the two samples are equal is rejected at significance level 5% for both the Japanese and US firms, and thus the decreases in the real citations are statistically significant.

The decrease in the average real citations, however, does not necessarily mean that the level of innovative activities of those firms decreased and only strategic patents increased. Figures 3 and 4 are histograms of the number of patents in different levels of real citations for the eight Japanese and three U.S. firms respectively. The histograms reveal that the decrease in the average real citations is due to a large increase in low quality patents. The number of patents with real citations of less than 10 increased by about 5 times for the Japanese firms and by about 4 times for the U.S. firms. At the same time, however, the number of patents also increased for all other levels of citations. The number of patents with real citations of more than 50, the highest quality patents,

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[8] See Conover (1999) Chapter 5 for details.

increased by about 10 times for the Japanese firms and by about 3 times for the U.S. firms. Thus, broader leading patent breadth after the TI suits could have had effects on stimulating innovations. The increase in low quality patents, on the other hand, is a possible side effect of broadening patent protection, and it supports the patent portfolio race hypothesis raised by Hall and Ziedonis (2001).

4 Field Interview

To supplement the above empirical analysis and explore policy implications of broad patent protection, I conducted interviews with intellectual property managers (IP managers, hereafter) of two of the above eight Japanese electronics firms.[9] To both IP managers, I asked the following two questions:

(1) What were the effects of TI's 1986-87 lawsuits on your company's R&D?

(2) Should the government broaden patent protection to stimulate innovation?

For the first question, both IP managers admitted the same effect as the U.S. firms that is suggested by Hall and Ziedonis (2001): aggressive patent applications to avoid litigation and to exploit license revenue. However, one IP manager also noted that the incentive to develop basic invention with broad patent claims increased after the TI suits. The other IP manager pointed out that the TI suits had different effects on different types of technologies. For highly complimentary technologies, the company tried to invent high quality technologies within the existing system to gain bargaining power in license negotiation. On the other hand, for relatively independent technologies that do not require many components, the company tried to "invent around" those technologies. These are consistent with the results of the empirical analysis in the previous section.

For the second question, both IP managers agreed that broad patent protection is important for innovation. There are at least two ways to broaden

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[9] Both interviews were conducted in July 2005. One was in person and the other was by telephone.

patent protection: issuing patents with broad claims, and extending claims of issued patents using the "doctrine of equivalents." One IP manager suggested that the Japanese government should increase issuing patents with broad claims for basic inventions.

The other IP manager noted that obtaining patents with broad claims for basic inventions is possible under the current Japanese patent system and is only a matter of "claim drafting." However, he suggested that the Japanese government should give broader patent protection not only to basic inventions but also to applied inventions. The Japan Patent Office tends to narrow the scope of patent claims of applied inventions. Although applied inventions can induce further applied or improved products, those original applied inventions have not been adequately protected because their patent claims are too narrow. This story fits the infinite sequential innovation model, showing that broad patent protection to each stage's invention could enhance firms' R&D incentive.

Both IP managers strongly objected to extending the use of the "doctrine of equivalents." The Supreme Court of Japan has shown five conditions under which two inventions are interpreted to be legally equivalent. One IP manager noted that allowing arbitrary judgment by courts to broaden the range of "equivalents" beyond the five conditions would increase the uncertainty about infringement and thus hurt firms' R&D incentive. This point is exactly the same as the amicus curiae brief of IBM, Kodak, and Ford in supporting the defendant in the *Festo v. Shoketsu* case in the Supreme Court of the United States.[10]

5 Discussion

This study empirically examined the effects of broadening leading breadth on cumulative innovation based on a natural experiment in 1986-87, namely TI's successful lawsuits claiming broad patent protections including from future prod-

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[10] Brief of International Business Machines Corporation, Eastman Kodak Company, and Ford Motor Company as Amici Curiae in support of respondents, United States Supreme Court, May 9, 2001, No. 00-1543.

ucts. The results show that the average quality of patents of eight Japanese and three U.S. electronics firms, which is measured by citations, had decreased after the TI suits. The decrease of average quality, however, was caused not by a decrease in firms' innovative activities but rather by the explosion of low quality patents. High quality patents also increased after the TI suits, although the amount of high quality patents is much smaller compared with that of low quality patents. The empirical results imply that firms increased R&D efforts and as a result, both low and high quality inventions were produced. The interviews with IP managers of two Japanese firms, both of which were among the eight Japanese firms sued by TI, support the implication of the empirical results. The interviewees noted that their firms increased research efforts both in developing basic technologies and in "inventing around" after the 1985 TI suits.

The empirical and interview results are consistent with theoretical results that leading breadth stimulates cumulative innovation. However, the results also suggest that leading breadth may also stimulate the production of low quality patents. The increase in low quality patents can be socially wasteful in the following two ways: first, if they are substitutes to other inventions, there is the inefficiency due to overlapping investment in developing the same technology; second, if they are complements to other inventions, the "patent thicket" problem, which is the inefficiency due to an overlapping set of rights, will increase.

The first inefficiency would decrease as the breadth of patents increases because "inventing around" would be more difficult if the protected area of an invention becomes larger. For the second inefficiency, however, further policy tuning would be required. When inventions are complements, broad patent claims cannot prevent an increase in low quality patents because complementary inventions do not fall in each other's infringement area. Thus, broad patents may intensify the patent thicket problem. To alleviate the problem, broadening patent claims should be packaged with patent pools, an agreement among patent owners to license a set of their patents to one another or to third parties.[11] Otherwise, high transaction costs in licensing contracts could hurt firms' research incentive and raise product prices, resulting in reduced consumer surplus.

Appendix: Constructing the citation-based measure of patent quality

This appendix explains in detail the procedure for estimating the quality of patents using citation data. As explained in the text, observed citations could contain noises due to differences in technological characteristics, changes in the practices of the Patent Office, or an increase in the pool of patents that possibly cite other patents. Hall, Jaffe, and Trajtenberg (2002) (hereafter, HJT) propose two approaches to remove those noises: the fixed-effects approach and the quasi-structural approach. The fixed-effects approach removes the noises by removing all of the time differences, even if they include real technological changes. On the other hand, the quasi-structural approach assumes some time differences are real and removes only noise factors. This paper applies the latter approach since a comparison of the patent quality between two different periods is the main objective of this paper. The model in the following is a slight modification of the one suggested by HJT.

To implement the quasi-structural approach, some structure should be imposed on the movement of citations to distinguish noises and real changes. The quasi-structural approach developed by HJT imposes the following two assumptions: proportionality and stationarity. Proportionality assumes that the shape of the lag distribution over time, which is the fraction of the lifetime citations in different lags from the time when a patent is applied for, is independent of the total number of citations received. Stationarity assumes that the lag distri-

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[11] See Shapiro (2001) and Lerner and Tirole (2004) for how patent pools can improve social welfare. Yet another way to deal with low quality patent is suggested by Hopenhayn and Mitchell (2001). They suggest providing "menus" of patents, that is, different combinations of length and breadth.

bution does not change over time. See Hall, Jaffe, and Trajtenberg (2002) for a discussion of the validity of these two assumptions.

Let P_s^k be the number of the technological field k patents applied for in year s, and C_{st}^k be the number of citations to the technological field k patents applied for in year s made by all patents applied for in year t, where $t > s$. C_{st}^k/P_s^k, the average number of citations that the field k patents in year s receive from all patents in year t, can be decomposed into the following three factors:

$$\frac{C_{st}^k}{P_s^k} = \alpha_k\left(s,t\right) f_k\left(l\right) \exp\left(\epsilon_{st}^k\right), \tag{1}$$

where $\alpha_k\left(s,t\right)$ is the effects of application years, $f_k\left(l\right)$ is the lag distribution of the average citations that only depends on the lag $l = t-s$, and ϵ_{st}^k is a stochastic term. Each component is specific to the technological field k. The specification with different year effects for different technological fields is a modification of HJT's model, which specifies that they are equal among all the technological fields.

Using the econometric specification in HJT, (1) is further specified as following:

$$\frac{C_{st}^k}{P_s^k} = \alpha_0^k \beta_s^k \gamma_t^k \exp\left(-\delta^k l\right)\left(1-\exp\left(-\phi^k l\right)\right)\exp\left(\epsilon_{st}^k\right), \tag{2}$$

where $\alpha_0^k, \beta_s^k, \gamma_t^k$ are the field k patents' parameters for constant term, the year effect of cited patents, and the year effect of citing patents, respectively. In the specification (2), $\alpha_k\left(s,t\right)$ is modeled as the product of the constant, cited year effects, and citing year effects, and $f_k\left(l\right)$ is modeled as the product of two exponential functions. The parameters δ^k and ϕ^k in the lag distribution function can be interpreted as the speed of obsolescence and diffusion of patented inventions, respectively.

The parameters of (2) can be estimated by the nonlinear least square method, taking the log of (2) and regressing the log of the average citations on lags and year dummies for cited and citing effects. Following the estimation strategy of HJT, citing-year effects are estimated for each year, while cited-year effects are estimated for five-year intervals based on the premise that cited-year effects are real changes in innovation and thus change slowly. The patent data in the following two technological fields in the NBER patent data file is used: Computers & Communications, and Electrical & Electronics (for Semiconductor Devices). The data file includes all the utility patents granted in 1963-99, and its citation file includes all citations made by patents granted in 1975-99. Thus, application years of cited patents are 1963-98, and application years of citing patents are 1975-99, yielding 600 observations for each technological filed. The estimated parameters of (2) and their standard errors are shown in Table A1.[12] The estimated lag distributions are shown in Figure A1.

Citing-year effects can be interpreted as noises in the citation counts, which should be removed from the count of citations in order to evaluate the quality of patents, while cited-year effects can be interpreted as real changes in innovation. Thus, to calculate the citation-based measure of patent quality ("real citations," hereafter), the count of observed citations for a patent is deflated by $\hat{\gamma}_t^k$.

The duration for which a patent receives citations is fixed to be 24 years for all patents by supplementing unobserved citations.[13] For example, for the patents applied for in 1976, one year (year 2000) is supplemented, and for the patents applied for in 1977, two years (year 2000 and 2001) are supplemented. Unobserved citations can be estimated in the following way. First, the fitted lag distribution in lag l is defined as

$$D_l \equiv \exp\left(-\delta^k l\right)\left(1-\exp\left(-\phi^k l\right)\right),\ l=0,\ldots,24.$$

If a patent receives at least one citation during observed years (1975-99),

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[12] Table A1 shows results using the Newton-Raphson method. However, the estimation results using the Newton-Raphson method are quite different from the results using the Gauss-Newton method, implying that residuals in the fitted (2) are not small and thus the specification (2) might not be a good approximation of the observed average citations. See Davidson and Mackinon (1994). Finding a better specification for the average citations would be an important topic in future works.

[13] HJT used 30 years of lags. I use shorter lags because the fit of model (2) is not satisfactory enough as noted in the previous footnote. Shortening lags could mitigate the bias due to using estimated citations.

then the amount of citations that the patent will receive in year $s + L > 1999$, $C_{s,L}$, where L represents all lags in which citations are not observed, is predicted in the following way:

$$C_{s,L} = D_L \frac{\sum_{l=0}^{M} C_{s,l}}{\sum_{l=0}^{M} D_l} \tag{3}$$

where M=1999-s is the maximum lag in which citations are observed. Predicting unobserved real citations based on D_L is valid under the stationarity assumption, and adjusting the average citations in lag L (D_L) for an individual patent's unobserved citations using the ratio between individual and average observed citations is valid under the proportionality assumption.

On the other hand, there are many patents not receiving any citations during observed years, though those patents may receive some citations in unobserved years. For example, some patents that were applied for in 1975 received the first citations in 1999, 24 years after their applications. The equation (3) cannot be used if a patent did not receive any citations during observed years since $\sum_{l=0}^{M} C_{s,l} = 0$. Unobserved citations for patents that were applied for in year $s > 1975$ (all 24 lags are observed for 1975 patents) but received no citations during observed years are estimated using the conditional expected number of citations to patents applied for in 1975 given that they did not receive any citations for the first $M < 24$ years:

$$E\left[\sum_{l=0}^{24} C_{s,l} \mid \sum_{l=0}^{M} C_{s,l} = 0\right] \equiv E\left[\sum_{l=0}^{24} C_{1975,l} \frac{\beta_s}{\beta_{1975}} \mid \sum_{l=0}^{M} C_{1975,l} = 0\right].$$

For example, for patents applied for in 1976 without any citations by 1999, the expectation of real citations in 2000 (24-th lag for 1976 patents) is estimated using the average real citations to patents applied for in 1975 that received citations only in 1999 (24-th lag for 1975 patents), adjusting for different cited-year effects ($\beta_{1976}/\beta_{1975}$).

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Table 1: Test results for the differences in the means

	Eight Japanese firms		Three U.S. firms	
	1975-85	1986-96	1975-85	1986-96
Mean	6.954	5.130	9.426	6.403
Mann-Whitney test statistic	38.000		35.089	
P-value	0.000		0.000	

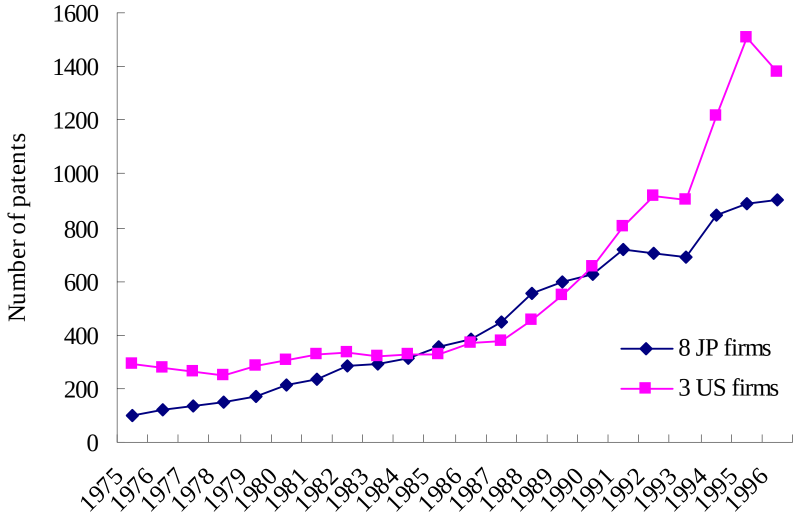

Figure 1: Average number of electronics patents per firm

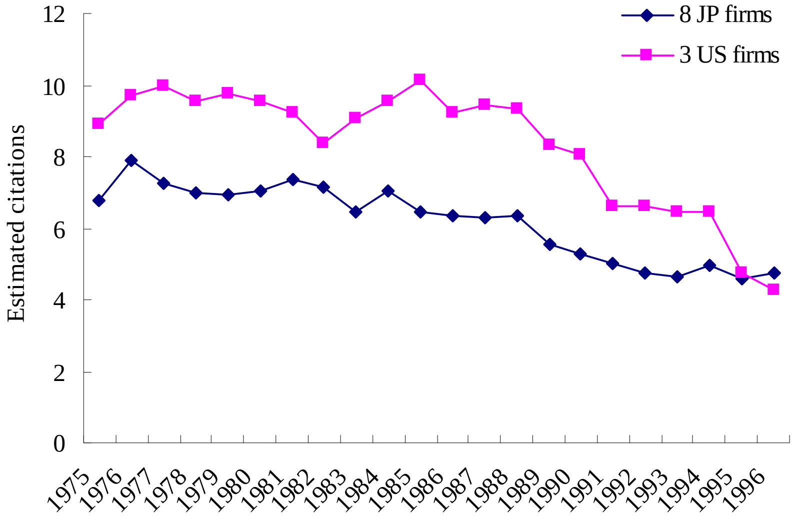

Figure 2: Average estimated (real) citations per patent

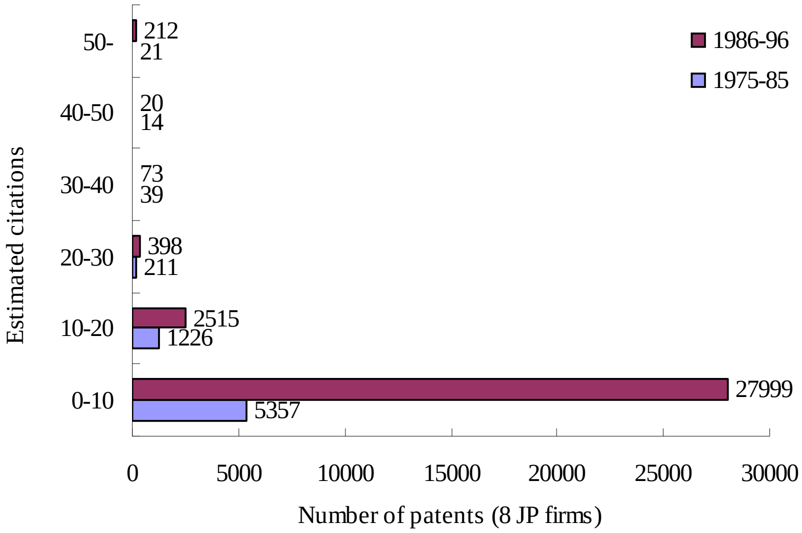

Figure 3: Histogram for the eight Japanese firms' patents

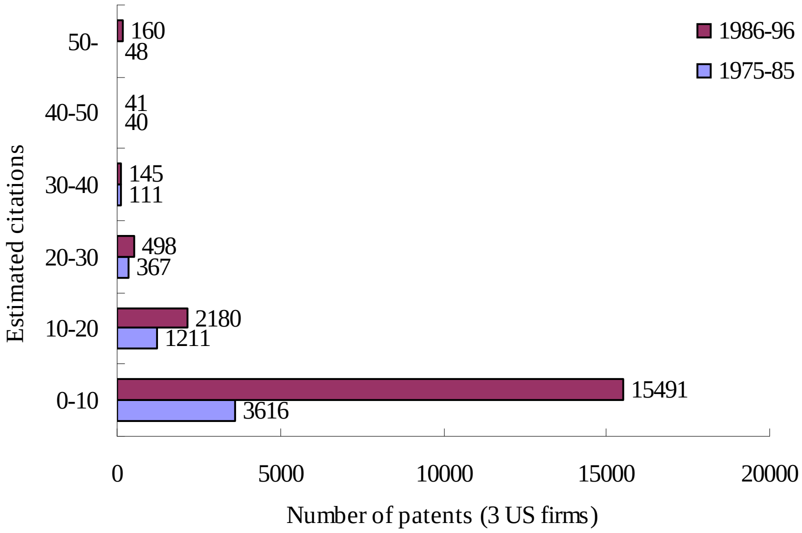

Figure 4: Histogram for the three U.S. firms' patents

Table A1: Estimated parameters

	Computers & Communications		Electrical & Electronic	
	coefficient	s.e.	coefficient	s.e.
Alpha	0.7561	0.0148	0.4836	0.0162
Beta (cited effect)				
1965-69	0.9989	0.00003	0.9911	0.0002
1970-74	1.2277	0.0124	1.1511	0.0052
1975-79	1.3302	0.0251	1.2126	0.0109
1980-84	1.2865	0.0292	1.1534	0.0101
1985-89	1.1685	0.0207	1.1574	0.0135
1990-94	0.9377	0.0081	1.1240	0.0123
1995-99	0.4635	0.0662	0.7381	0.0281
Gamma (citing effect)				
1976	0.9650	0.0018	0.9264	0.0027
1977	0.9466	0.0026	0.8981	0.0039
1978	1.0289	0.0014	1.0034	0.0001
1979	1.1038	0.0057	1.0324	0.0013
1980	1.1649	0.0084	1.0661	0.0025
1981	1.1907	0.0107	1.0578	0.0021
1982	1.2679	0.0154	1.1146	0.0046
1983	1.2063	0.0125	1.0611	0.0025
1984	1.3104	0.0214	1.1695	0.0077
1985	1.4207	0.0323	1.3085	0.0158
1986	1.5542	0.0463	1.3925	0.0221
1987	1.7003	0.0612	1.5382	0.0319
1988	1.8222	0.0781	1.6783	0.0442
1989	2.1154	0.1199	1.7674	0.0543
1990	2.0998	0.1229	1.7887	0.0572
1991	2.1872	0.1405	1.8076	0.0626
1992	2.3524	0.1751	1.9582	0.0805
1993	2.6968	0.2443	2.1001	0.1013
1994	3.4165	0.4007	2.3908	0.1411
1995	4.6023	0.6945	2.8583	0.2148
1996	3.8993	0.5486	2.6306	0.1828
1997	3.0644	0.3662	2.2720	0.1384
1998	0.5677	0.0377	0.6232	0.0238
1999	0.0226	0.0112	0.0283	0.0095
Lag Distribution				
Delta	0.1146	0.0046	0.0850	0.0032
Phi	0.5081	0.0255	0.6816	0.0282

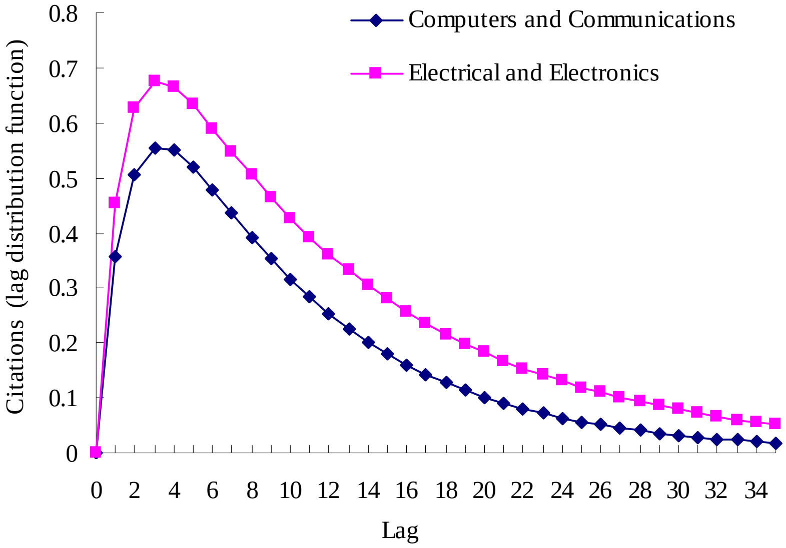

Figure A1: Estimated lag distributions