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How Do Science and Technology Intersect in Complex Products? An Analysis of LCD-Related Patents

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How do science and technology intersect in complex products?
An analysis of LCD-related patents[1]

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Abstract

In this paper we discuss liquid crystal displays as an example of "complex goods," or products composed of multiple constituent elements, in order to elucidate the linkages between science and technology. Exploratory analysis of bibliographic information from patents reveals two primary characteristics of such linkages in the field. First, although technology may not display strong linkages with scientific findings over all, some scientific knowledge is highly valuable for patented inventions. Companies in this field may be able to leverage scientific findings not used by competitors in order to produce more inventions. Second, because complex goods are based on an array of constituent elements, players in the field have the option whether or not to pursue inventions with strong links to science.

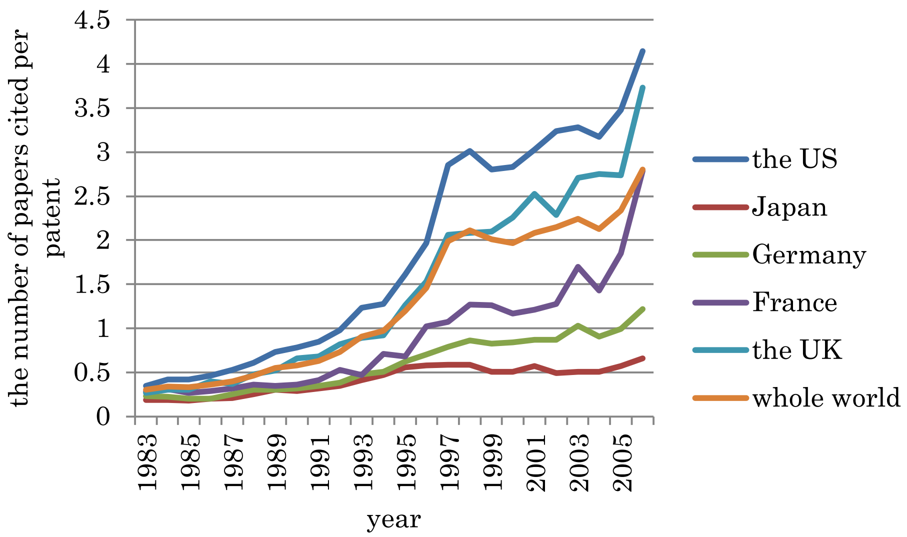
1. Motivation

Scientific knowledge has become increasingly important in various industrial sectors; industries relying on science or for which basic sciences play a crucial role are called "science-based industries." Typical examples of science-based industries are biotech and electronics (semiconductors, devices, etc.). The relationship between industrial technology and science is particularly strong in biotechnology, as may be seen in sectors such as drugs, foods, chemicals, bioinformatics and other fields utilizing large genome or protein databases, and biomechanics (Goto and Odagiri ed., 2003, pp. 3–4).

[1] This work was supported by JSPS KAKENHI Grant Number 22330123.

Science linkage is a measure of the strength of the relationship between scientific findings and industrial technologies, and is quantified by the number of scientific articles cited per patent. In the US, patent applications must include information on preceding patents and related scientific articles. Failure by a patent applicant (inventor) or their representative to disclose such information on "prior art" may be considered intentionally misleading if the applicant knew or should have known that the information was relevant (Murakami and Asami, 2004, p.63). Therefore, in the US patent application bibliographic data contains preceding patents and scientific articles highly relevant to the invention in question, and searching such references may reveal the scientific findings on which the invention is based.

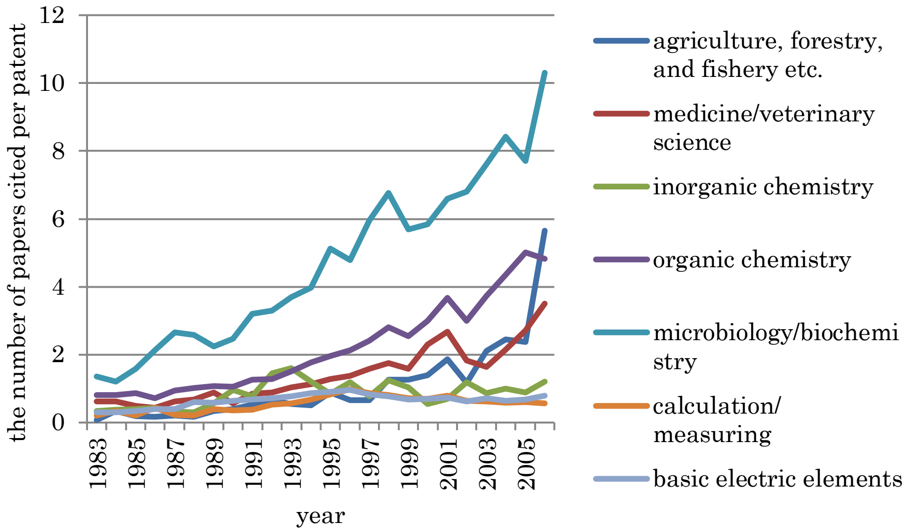
Figure 1: Science linkage in the US patents



Source: Kanda, Ebisawa, and Tomizawa (2007), p.334, Table 8-2-1. The data is based on the Patent Board, "Global patent scorecard data years 1980-2006."

According to a survey by the National Institute of Science and Technology Policy (NISTEP) (Kanda, Ebisawa, and Tomizawa, 2007), there is a trend towards increased science linkage in US patents (Figure 1). Whereas bibliometric analysis reveals worldwide science linkage values of 0.30 in 1983 and 2.80 in 2006, the increase is greater in the US at 0.35 and 4.15 respectively, followed by the UK, France, and other countries. The increase for Japan is much smaller at 0.19 in 1983 and 0.66 in 2006. In other words, in the US science linkage increased by a factor of about 11.9, while in Japan only by a factor of about 3.5. Although the worldwide pattern is one of increased science linkage, the extent of this trend varies significantly by country.

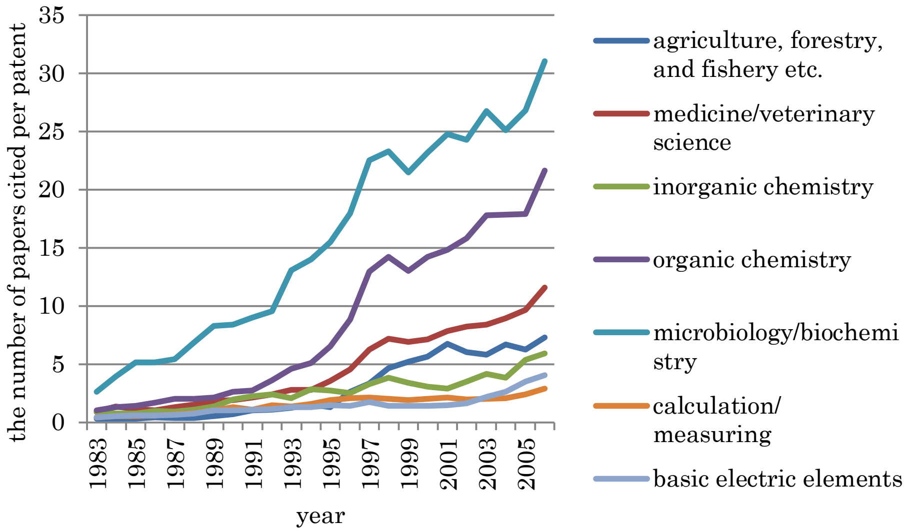
Figure 2: Science linkages in seven areas (Japan)



Source: Kanda, Ebisawa, and Tomizawa (2007), p.334, Table 8-2-1. The data is based on the Patent Board, “Global patent scorecard data years 1980-2006.”

Kanda et al. (2007) compare science linkage in patents from Japan and the US in seven areas, three with high science linkage values in international patents (microbiology/biochemistry, organic chemistry, and medicine/veterinary science) and four with high numbers of scientific citations (Figures 2 and 3). These results show that science linkage differences between Japan and the US by individual technical field mirror the significant overall differences by country. Science linkage values are consistently high for microbiology and biochemistry: 1.36 versus 2.60 for Japan and the US respectively in 1983, and 10.31 versus 31.06 in 2006. Japan increased by a factor of only about 7.6 compared to about 11.9 for the US, demonstrating not only lower absolute science linkage for Japanese patents, but also lower rates of growth compared to the US.

Figure 3: Science linkages in seven areas (US)



Source: Kanda, Ebisawa, and Tomizawa (2007), p.334, Table 8-2-1. The data is based on the Patent Board, "Global patent scorecard data years 1980-2006."

Although science linkage varies according to country and field, science linkage values as a whole have dramatically increased from 1983 to 2006, both for individual countries and fields within countries. This implies that scientific findings are increasingly important across countries and industrial fields.

Science linkage in the US far surpasses that of Japan. Branstetter and Ogawa (2005) point out that in the US, where growth in science linkage is particular predominant, patented inventions are more likely to leverage knowledge created recently by university scientists. This trend is particularly strong in bioscience-related disciplines. The rise of science linkage in the US is strongly influenced by advances in bioscience-related fields (which they term the "bio nexus") and the contributions to technology for which these advances are responsible.

Advances in bioscience-related fields account for a large portion of the increase in scientific citations in US patents. This makes drug-related industries and technological fields a natural subject for investigating linkages between industry and science. Indeed, there has been abundant research in this area (for example, Kato and Odagiri, 2012; Breschi and Catalini, 2010; Odagiri, 2006; Pisano, 2006; Gittelman and Kogut, 2003; Murray, 2002; Zucker, Darby, and Brewer, 1998; Henderson and Cockburn, 1994; and Noyons, van Raan, and Schmoch, 1994). Mansfield (1995) points out that scientific findings are leveraged in inventions in different ways according to technological domain. He states that 27% of pharmaceutical products would have been significantly delayed without recent academic research, but this figure is only 6% for electronics products. There has been research on linkages between electronics and science (for example, Shirakawa, Furukawa, Nomura, and Okuwada, 2011; Shirakawa, Nomura, and Okuwada, 2010, 2009; Breschi and Catalini, 2010), but biosciences remain the predominant subject for research into linkages between science and industry.

There is one crucial distinction in technological characteristics between some electronics fields and bioscience- or pharmaceutical-related disciplines. Levin, Klevorick, Nelson, and Winter (1987) studied the primary means by which innovators in a variety of industries extract exclusive profit from their innovations. Of the 18 industry types which yielded the greatest number of survey responses, only chemical-related industries (pharmaceuticals, plastics, inorganic chemistry, and organic chemistry) and the petroleum refining industry scored patents as an effective source of profits at 4 or higher on a Likert scale of 1 to 7. Only the pharmaceutical industry considered patents the greatest alternative source of profits (product patents). Levin et al. (1987) provide two explanations for why patents are highly effective only in the chemical and pharmaceutical fields in appropriating innovation. First, it easier to demonstrate the novelty of specific molecular structures than it is to demonstrate the novelty of an electronic or mechanical part. Second, whereas molecular structures can clearly be demonstrated as identical in order to prove patent infringement, the burden of proof is more onerous for large-scale complex goods assembled from multiple components. One further reason patents do not necessarily lead directly to appropriation of innovation in large-scale complex goods such as semiconductors is the trend towards cross-licensing among multiple companies involving multiple patents (von Hippel, 1982).

The efficacy of patents in appropriating the fruits of innovation clearly provides a first-mover advantage for corporations. It is often much more difficult for other companies to invent something else fulfilling the same function. Fleming and Sorenson (2004) state that science serves as a map of systematized knowledge, enabling inventors to more efficiently "combine highly coupled components" in their combinatorial search for innovation. Discovering new scientific combinations is crucial in technological areas which reward making and patenting inventions before the competition.

In contrast, many areas of electronics demonstrate low levels of appropriating innovation through patents. First, competitors may either avoid infringing on existing patents by simply inventing alternate mechanisms which fulfill the same role, or they may develop other key technologies used in the same complex goods to use in cross-licensing agreements. Therefore, although companies will strive to outpace their competitors in terms of inventions and patents, there are various other creative ways of gaining advantage as well. This means that science linkage will play a different role in electronics than in biosciences or pharmaceuticals, which are more often considered typical science-based industries. Corporate strategy should reflect these differences as well[2].

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1. Teece (1986) points out that complementary assets such as production facilities and sales networks become key factors in securing profits when there is low appropriability of innovation. In other words, greater appropriability of innovation through patents tends to advantage venture companies, which do not have the same access to complementary assets as larger companies. While it is inherently difficult for venture companies to enter areas such a biotech and pharmaceuticals because of the high-level R&D required, interaction between such industrial technologies and universities enable venture companies to leverage university research, which effectively lowers barriers to entry. These fields have high appropriability of innovation through patents. These two combinations spur university scientists to make patent applications, and the dramatic rise of scientific paper citations in bio-related patents may be because these scientists are highly knowledgeable about the scientific literature. (It may also be true that university-affiliated scientists and corporation-affiliated scientists exhibit different tendencies with regard to maximizing or minimizing the scientific literature references they include in patent applications.) This means that interaction between industrial technology and university research may not result in university-based ventures or more patent applications from university scientists in areas with low appropriability of innovation. This suggests that scientific literature citations in patents in these fields may not raise to the same level as for bio- and pharmaceutical-related patents.

Case studies on two different products performed by the authors are particularly illuminating regarding this point.

Panasonic's purchase of Plasmaco: Japanese electronics manufacturer Panasonic developed direct current (DC) plasma TV technology in the 1990's, but rival Fujitsu developed alternating current (AC) versions which became the standard technology in the market. Most US companies had ceased plasma TV development, leaving only a single venture company in the field, Plasmaco. Cashflow problems were forcing Plasmaco to the brink of bankruptcy, and the company placed its entire future on the line in developing new AC plasma technology. The company displayed the new technology at an academic conference in the hope that it would help secure funding to allow the company to survive. It was here that someone from Panasonic saw the new technology on display, which lead to Panasonic's purchase of Plasmaco after studying their technology in depth. Plasmaco's patents ended up serving an important role in subsequent patent negotiations between Panasonic and Fujitsu; the successful cross-licensing agreement enabled Panasonic to make rapid advances in the AC plasma TV market (Sakakibara, Tsujimoto, and Matsumoto, 2011, pp. 59–79).

Kaneka's bringing solar cells to market: Kaneka is a Japanese chemical manufacturer, one of whose main divisions is solar cells. This sets the company apart in Japan, where most solar cell manufacturers are electronics companies. Kaneka sent research staff to Osaka University in 1980 to investigate possibilities of entering the solar cell market, but at this point the company was already a late entrant in the industry. The company had made a startling success in inventing amorphous silicon solar cells, but this innovative technology alone hardly compensated for its latecomer status in entering the marketplace. The company made presentations at many academic society meetings in order to increase its name recognition and appeal to potential customers. This resulted in Casio becoming interested in the company, and Casio approached Kaneka about jointly developing ultrathin solar cells for its new credit card-type calculators. By responding rapidly and developing solar cells suited to Casio's needs, Kaneka was able to successfully enter the solar cell market (Sakakibara et al., 2011, pp.92-109; Matsumoto, 2011).

These are only two examples, but they amply demonstrate the significance for companies of contact with the world of academic science. To summarize, academic societies play an important role in helping companies acquire new technologies or search for new directions in developing their own technologies. In other words, academic societies function as a locus of knowledge aggregation. Taken one step further, our theory shows that there is no single correct answer in combining the multiple technological elements that comprise complex goods, and academic societies serve as a medium allowing one candidate solution of many to emerge. These solutions do not emerge naturally, but as the result of efforts by those concerned (in this case employees of Plasmaco and Kaneka) who are aware of the merits of academic societies. As a result companies which had suffered from delayed starts gained momentum, and we see that crucial technological elements for Panasonic and Casio were actually developed by Plasmaco and Kaneka.

It is difficult to use indicators such as science linkage to quantify the function of academic societies and corporate activities striving to utilize these. The reason for this difficulty is that, according to cases we have studied, the knowledge exchanged at such societies is not necessarily in concrete forms such as papers or articles. Indeed, even inventors of a given technology may be unaware of business implications that are clear to someone hearing about their invention. Therefore, although detailed case-based research does have a significant role to play, some form of comparative methods or indicators are required if the goal is elucidating differences according to nation, technology or industry in the linkages between science and industry. This raises the question of whether or not the type of technological differences we are interested in will be reflected in public materials allowing for comparisons according to nation, technology, and industry. Given these issues, we decided to use liquid crystal displays (LCDs) as a case study of complex goods and evaluate patent data in a multidirectional framework.

This study uses LCD patents and their bibliographic data on scientific literature to study science linkage and time lag until citation. Science linkage is defined as the number of scientific references cited per patent, and is a representative indicator of the strength of connection between science and industry. Closer relationships between scientific results/findings and industrial technologies in science-based industries should be reflected in shorter time lags between scientific publishing and those results being utilized in patents. It may also be the case that inventors may apply for patents before publishing scientific results in order to secure rights. Either way, closer relationships between science and industry should result in shorter time lags between scientific publishing and patent applications. Our goal is to elucidate characteristics of scientific literature citations in patents by comparing them with characteristics of preceding patent citations. Finally, we wish not to propose a new indicator for measuring linkages between science and industry, but to use the existing well-known indicator from a different perspective in order to investigate the new analytical possibilities.

Below we first provide background behind LCDs as an example of complex goods, and describe the datasets used in this study. Next, provide in-depth analyses of science linkage followed by time lag until citations. Finally, we discuss the implications of these findings for the intersection of science and industry in the context of complex goods, and touch upon future developments.

2. Scope of analysis and summary of data

The subject of our research on complex goods consisting of multiple constituent elements is liquid crystal displays (LCDs). While liquid crystals were discovered in Europe, the fundamental technology for using them in displays was developed in the US, while Japanese companies industrialized the process (Numagami, 1999). In the 2000s LCDs gained popularity in use for large-screen TVs, but it was Korean and Taiwanese manufacturers which took the lead in this market. This demonstrates the idea that LCDs have low appropriability of innovation; companies first to develop technologies do not necessarily reap the greatest profits from those innovations. LCDs consist of many elements: liquid crystal materials, glass substrate and thin film transistor (TFT) elements, color filters, polarizing plates, backlights, driver ICs, and more. Manufacture requires knowledge of a diverse array of fields, including mechanics, chemistry, physics, and electronics (Suzuki, 1998; SEMI color TFT LCDs Revision Committee, 2005). All of these characteristics make LCDs an appropriate subject of our study.

Our dataset was patents registered with the US Patent and Trademark Office (USPTO) as provided by Thomson Innovation, a Thomson Reuters service. Thomson Innovation also allows access to patents from the EU, Japan, and other countries, but we limited our analysis to patents from the largest market (the US) alone in order to eliminate potential confounding discrepancies according to national patent systems. We identified LCD-related technologies with Derwent Manual Codes, a proprietary method of classifying patents in the chemical and electronic fields manually input by Thomson Scientific specialists according to consistent criteria. We searched for code category names including "liquid crystal" or "LC," then narrowed our search to display-related categories in order to select patents for analysis. Specifically, we included patents assigned any of the following codes: L03-G05A (liquid crystal display devices), T04-H03C2 (LCD), U14-K01 (liquid crystal displays), and W03-A08B (liquid crystal display). In 2001 the US instituted an early publication system for patents, but we restricted our analysis to patents which were actually granted. Our final data set consisted of 8767 patents identified according to the above methodology on July 13, 2011.

Figure 4 shows LCD-related patent applications over time. Available data begins in 1979, during which 5 LCD-related patent applications were made. This number increased to a temporary peak of 90 in 1985, at which point they experienced a decline. Applications began increasing again, however, numbering 125 in 1991 and 455 in 1995, which was another peak year. Applications stagnated again in the late 1990s, but then began a dramatic increase in the 2000s, reaching an all-time high of 815 in 2001. Applications appear to stall gain from the mid-2000s, but the time lag from application to granting makes it difficult to determine the meaning of the drop-off of applications after 2006. There remains a strong trend of increases of LCD-related patents during the period in question, with three noticeable peaks in 1985, 1995, and 2001. These peaks likely coincide with increased development efforts during periods in which LCDs were adopted for use in calculators and watches, notebook computers, and TVs.

Figure 4: The number of LCD-related patents

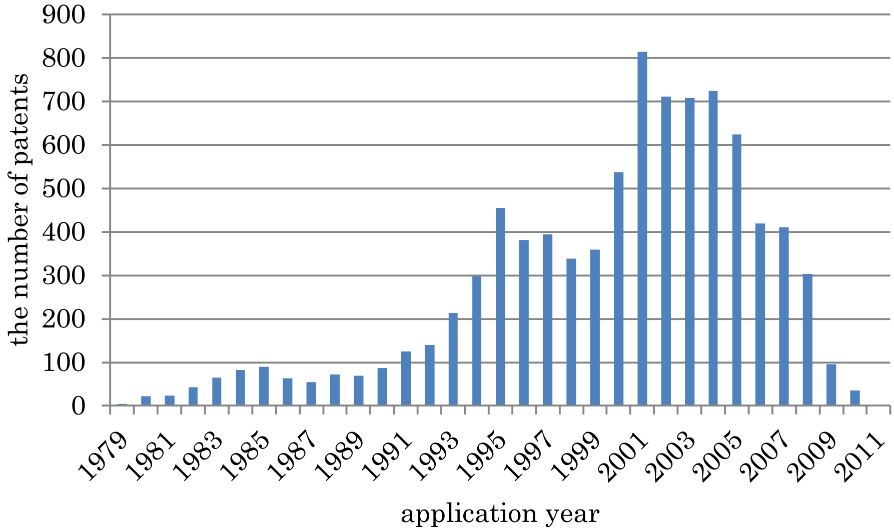


Figure 5 shows the ratio of total patents according to region (Japan, US, EU, Asia excluding Japan, and other regions). Japanese patents account for 80% of the total in 1979, but only 5 related patents were granted this year, so this number is not very significant. Japan's share of patents increased in the 10 years from 1980 to 1989. After declining in 1990 and 1991, Japanese share again increased to 60% in 1992, after which they decline gradually to 40% in 2006. US share declined dramatically in the 1980s, then maintained a steady range of 20–40%. Share of Asian countries excluding Japan ("Asia") began increasing from the mid-1990s, and have exceeded 30% in the 2000s. Meanwhile, the EU had share of more than 10% in the 1980s, but this decreased dramatically from the 1990s forward. LCD-related patents granted by the USPTO originate almost exclusively from these four countries and regions.

Figure 5: Regional shares of the numbers of patents

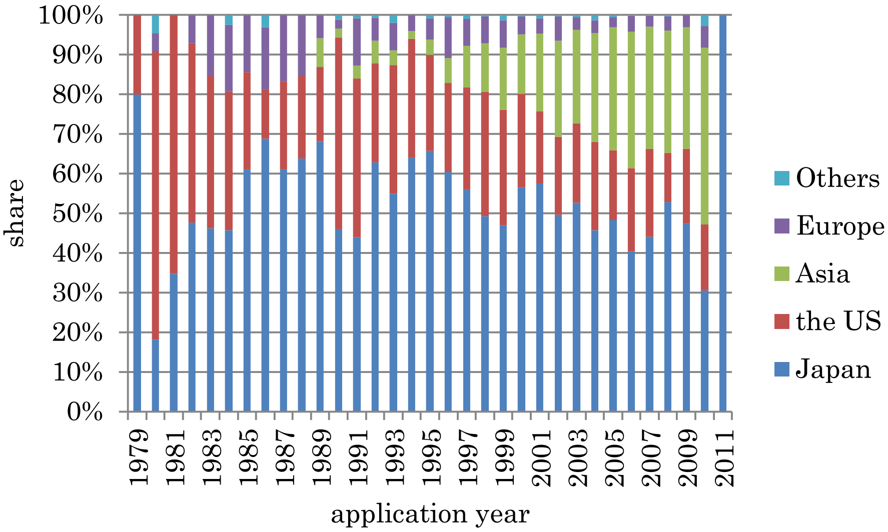


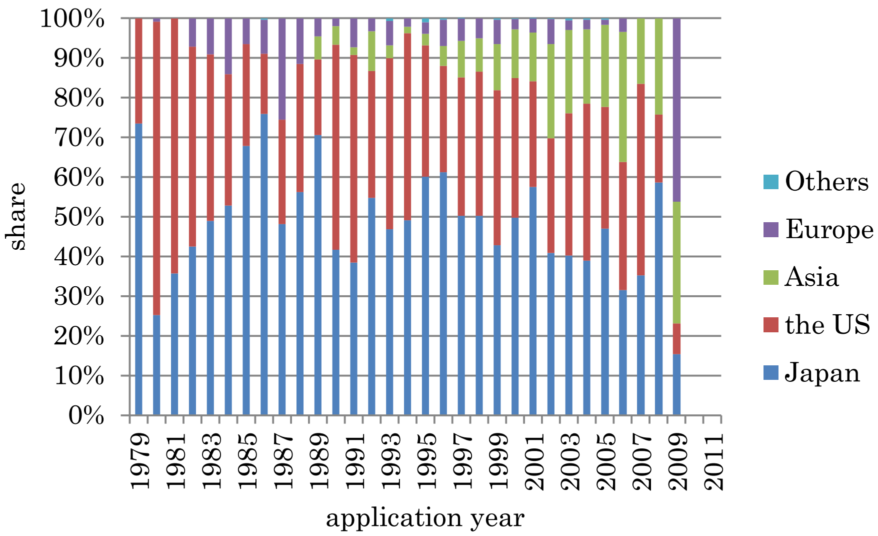
Figure 6 shows regional shares of citations in patents, or how many times a given patent is cited in subsequent patents. As explained above, US patent law mandates inclusion of relevant prior art in patent applications. Greater citations in subsequent patents is an indicator of influence on subsequent technological development, which is a proxy for higher value. Therefore, Figure 6 may also be considered to illustrate the value of patents produced by various regions. The figure reflects all citations in patents granted at the time of database search.

First we see a strong surge in citations of Japanese patents beginning in the 1980s. Japan's ratio of patent citations begins the decade with about 20% in 1980, but climbs to near 80% by 1986. Japanese patents accounted for about 70% of all related patents in 1986, so the value generated by these patents somewhat exceeded their absolute number. Citations of Japanese patents fell to the 40–60% range in the 1990s, during which time the share of Japanese patents granted also stagnated. However, from 1992 to 2006 Japan's share of patents fell to 40% only in 2006, while the country's share of citations fell to 40% five times during the same period (1999, 2002–2004, and 2006).

In contrast, the US's share of patent citations fell dramatically in the 1980s together with its share of patents awarded, while from the 1990s forward its share of citations (20–50%) have been slightly higher than its share of patents. Further, although the share of patent citations belonging to Asia begins to rise from the mid-1990s, this share is lower than patent share in more years than not.

In these figures IBM patents are counted toward US totals because the company, listed as either patent applicant or assignee, is a US corporation. However, many inventors of IBM patents residents of Japan. For this reason we analyzed the figures including IBM patents in Japan's share, but this did not alter the fact that US patens had a higher citation rate than absolute share.

Figure 6: Regional shares of citations in patents



Now we shall summarize the two types of patent share described above for Japan, the US, and Asia. First, in the 1980s Japan rapidly expanded its share of patents awarded, while also increasing the value of those patents as seen through citations. Japan's share of patents stagnated overall in the 1990s and beyond, while its share of citations shrunk even further relative to the absolute numbers of patents. Even though Japan made great strides in the 1990s, the quality of its patents suffered in the 1990s forward. Second, in the 1980s the US suffered a severe decline of both patents awarded and share of citations. Thereafter the number of US patents stabilized, although at a low share, while its share of citations has been larger in proportion than the number of patents awarded. In other words, the US has been successful in producing high-value patents despite the absence of LCD manufacturers in the country. Third, although the number of patents applications awarded to Asia has increased through the 1990s and 2000s, citation share has remained relatively low for these countries, showing that quality has not kept pace with quantity of patent applications.

Next we analyze science linkage and time lag to citations.

3. Measuring Science Linkage

Measuring science linkage requires analyzing the scientific literature in the "Other References" section of patents. This section lists all references other than patents, and includes a wide variety of materials from scientific papers to books and corporate technical reports or manuals. Therefore, we must find a way to narrow references in this section to include only scientific literature that serves as a valid measure of science linkage. Narin et al., who have researched issues related to science linkage in depth, use a method which involves comparing items listed in Other References to the Science Citation Index (SCI), and extracting only those references which also exist in the SCI (McMillan, Narin, and Deeds, 2000; Narin, Hamilton, and Olivastro, 1997). We used the same methodology to identify scientific literature cited in LCD-related patents. Specifically, we used five databases in Thomson Reuters's Web of Science: Science Citation Index Expanded (SCI-EXPANDED), a database of natural science literature; Conference Proceedings Citation Index–Science (CPCI-S); Social Sciences Citation Index (SSCI), a database of social science literature; Arts & Humanities Citation Index (A&HCI); and Conference Proceedings Citation Index–Social Science & Humanities (CPCI-SSH). We manually identified relevant references according to journal name, paper title, author, and page listed. This process was performed by three research assistants, and was checked by one of the authors.

This process resulted in 3279 scientific papers referenced by 8767 patents for a science linkage value of about 0.37 for the period in question. There were 16903 citations in Other References in our sample, about 19% of which were identified as scientific papers. Figure 7 shows science linkage by year of patent application, a figure which fluctuates significantly across time. Science linkage is only 0.2 for patent applications made in 1979 (one scientific literature citation across five patents), while the figure climbs to about 0.63 in 1986. It falls again to about 0.28 in 1991, then fluctuates wildly between about 0.3 and 0.5 until 2003, after which it climbs rapidly to about 0.59 in 2007. As observed above, the time lag from patent application to granting means that our data set does not contain patent applications made in recent years. This makes us hesitant to draw any significant conclusions about the significant decline from 2007 onward, but we can state that 1) science linkage varies across time even within the field of LCD-related patents, and 2) there are no consistent trends to be observed with regard to either increases or decreases.

Figure 7: Trend of the science linkage of LCD-related patents

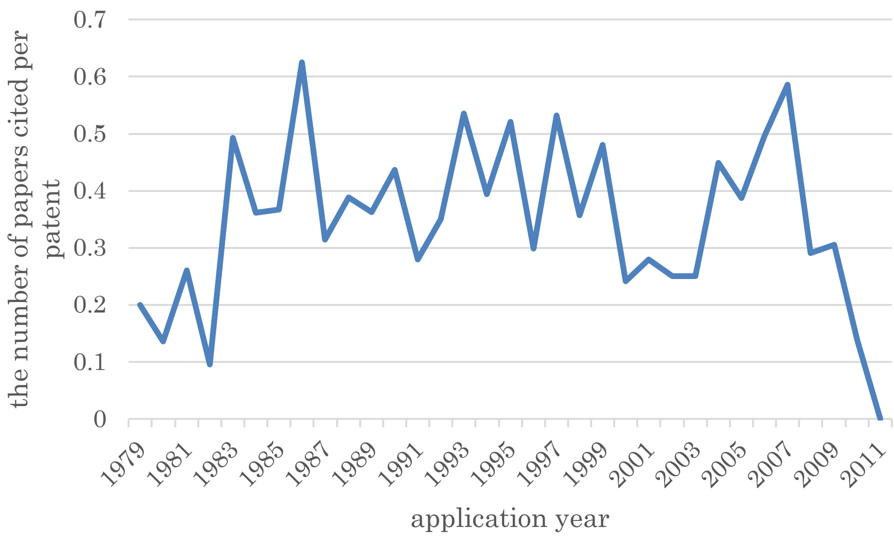
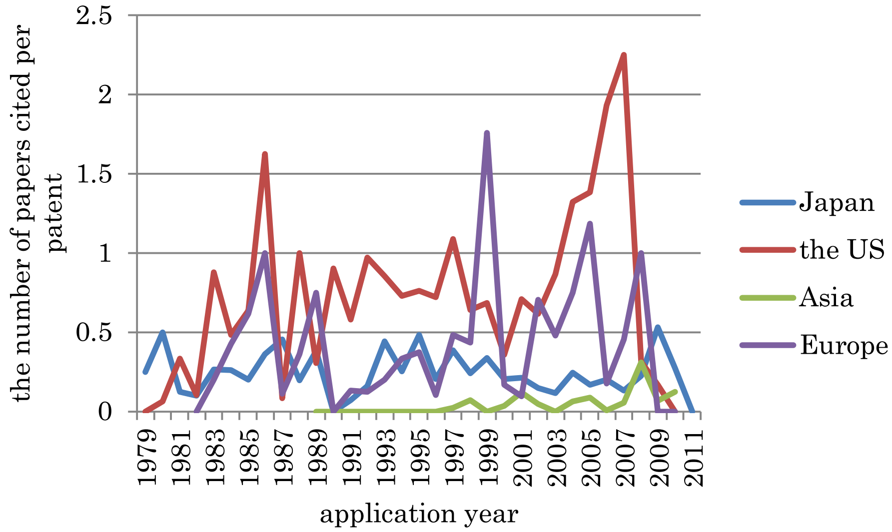


Figure 8 shows science linkage across time for Japan, the US, Asia, and the EU. Japan's highest year is about 0.5, while most years vary within the 0.1–0.3 range. US patents have higher science linkage than Japan's in almost all years; in particular US patent science linkage spikes once in 1985 and then rises again after 2000. Asian countries have lower science linkage than Japan. EU countries have low absolute numbers of patent applications in the field, making it difficult to interpret fluctuations in science linkage. However, we can observe multiple dramatic rises. It is instructive to observe the differences between Japan and the US, the two countries with the greatest number of related patents. Scientific linkage of Japanese patents is consistent but at a low level, while US patents fluctuate much more wildly, but at a higher level overall.

Figure 8: Science linkage across time for Japan, the US, Asia, and the Europe



Before examining the distribution of scientific papers cited, we first examine the distribution of patents cited. In Figure 9 the vertical axis shows number of patents, while the horizontal axis shows the number of patents cited. A total of 569 patents cited 6 existing US patents, while more than 500 patents cited 4, 7, or 8 patents each. The shape of the distribution may be described as a distorted single peak.

Figure 10 shows the distribution of patents citing scientific papers. It shows that the overwhelming majority of patents do not cite scientific literature at all. A total of 7692 patents cite no scientific papers, or 88% of the total. Meanwhile, 483 patents cite one paper, followed by 233 patents citing two papers. In contrast to the distorted single peak distribution of patent citations above, this graph tapers off gradually, demonstrating that distributions of patents cited by other patents differ qualitatively from the distribution of scientific papers cited by patents. Finally, the greatest number of scientific papers cited was 51.

Figure 9: The distribution of the number of patents cited

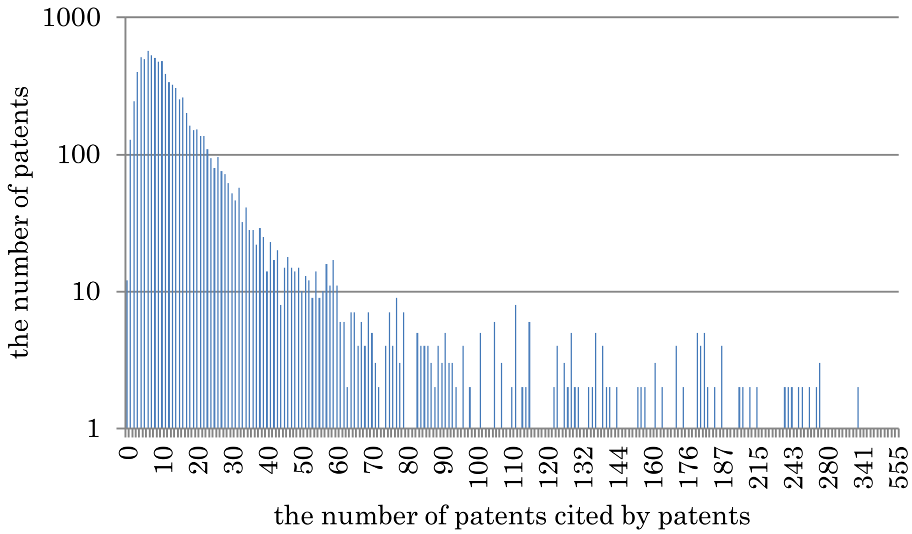
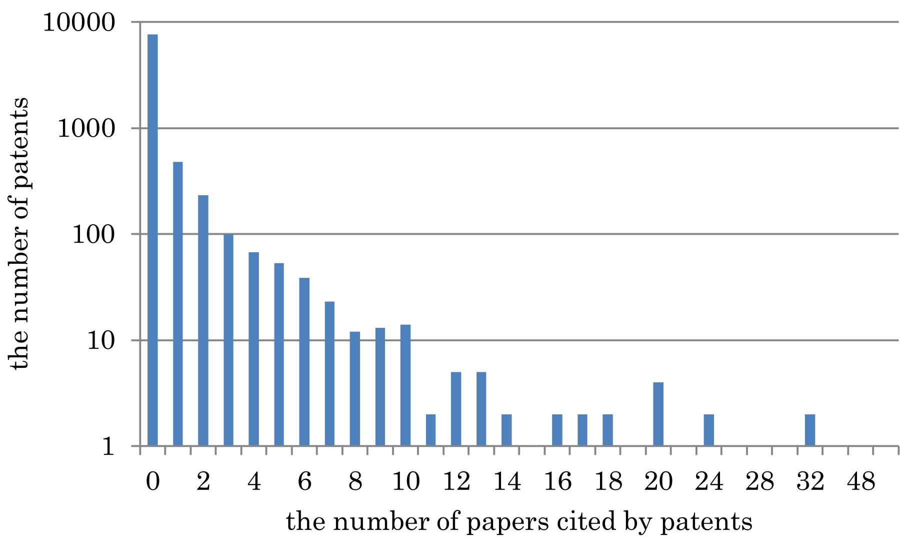


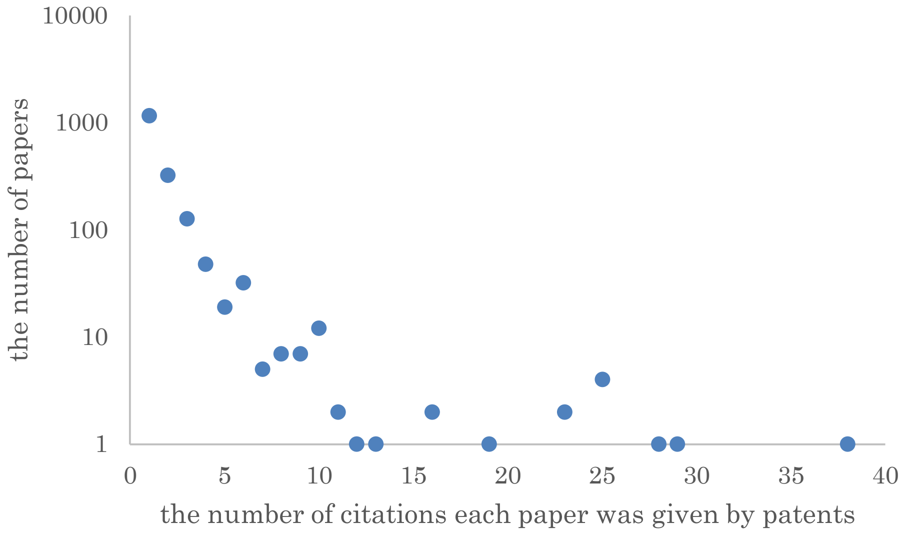
Figure 10: The distribution of the number of papers cited



Next we change our viewpoint to the cited scientific literature itself. Figure 11 shows how many times each paper is cited by patents. The vertical axis shows number of papers and the horizontal axis the number of citations each paper was given by the patents in our sample. Of the

3279 scientific papers in this sample, only 13 were cited 13 or more times, while 1160 (35%) were only cited once. This graph shows the same gradual decline in Figure 10 above. It would be instructive to repeat the analysis for other technical areas to determine whether or not the 35% of scientific papers cited only once is relatively low or high.

Figure 11: The distribution of the times each paper cited

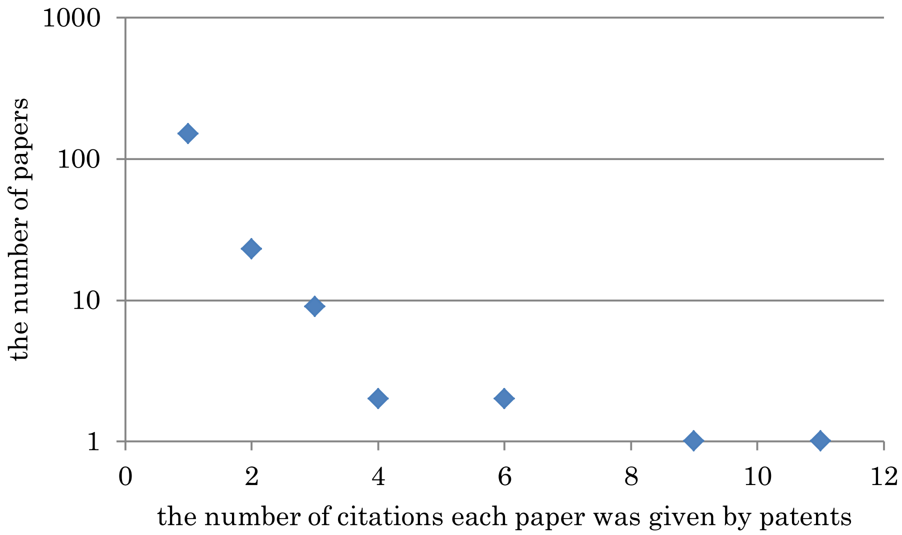


Our study does not evaluate the overall diversity of scientific literature cited by LCD-related patents, but we may narrow our focus to study the issue. Specifically, we analyzed the distribution of scientific literature citations in patents of companies either currently or previously engaged in the LCD market. One possibility is that similar research goals may lead such patents converge on similar scientific findings more than our data set as a whole. Conversely, competing organizations may seek to gain an edge by pursuing development along divergent scientific and technical lines.

We analyzed patents from the following ten companies: Fujitsu, Hitachi, IBM, LG Display, Mitsubishi Electric, NEC, Panasonic, Samsung Electric, Sharp, and Toshiba. We limited our search up to 2002 in order to eliminate confounding effects due to the time lag from patent application to granting. There were 1423 patents from these companies during the period in question, all of which cited 189 scientific papers a total of 264 times. This results in a low science linkage value of about 0.13.

Do similar aims in R&D and patent acquisition of these LCD manufacturers result in more or less overlap in scientific papers cited? Figure 12 shows the distribution of scientific literature cited by the patents in question. We see that 151 papers were cited only once, which at 57% is a greater ratio than the data set as a whole. This indicates a greater diversity of scientific literature citations among the subset of patents belonging to LCD manufacturers alone.

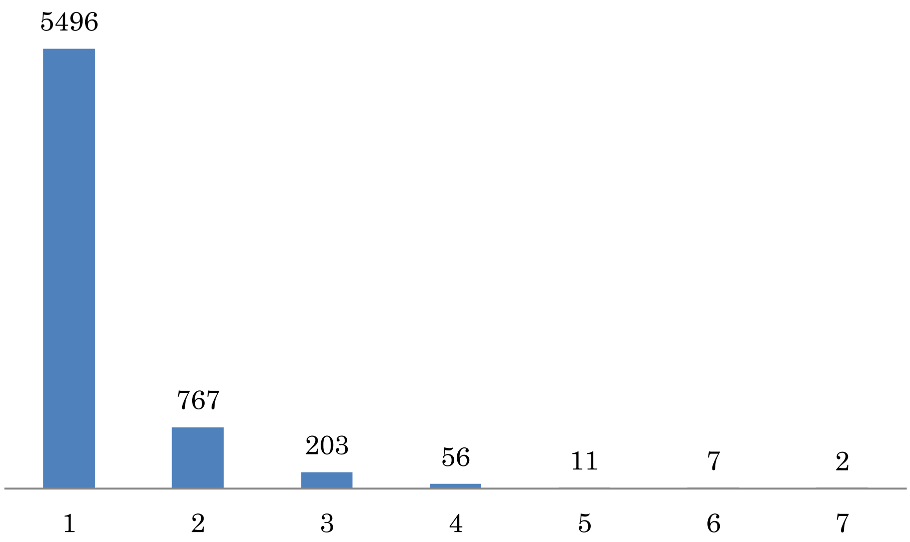
Figure 12: The distribution of the times each paper cited by major LCD companies



However, Figure 12 also includes instances in which multiple patents from the same company cite the same scientific paper multiple times. This makes it impossible to judge whether or not this subset of patents truly demonstrates diversity of scientific references. Therefore, we eliminated overlapping references from the same company and analyzed the data again to see if different companies still tended to cite the same scientific papers. First, for comparison, Figure 13 shows overlap between companies in terms of patents cited by patents belonging to major LCD manufacturers. Eliminating multiple citations by the same company, we see that 6542 patents were cited by patents in question. Of these, 5496 (84%) were cited by only one company, while 767

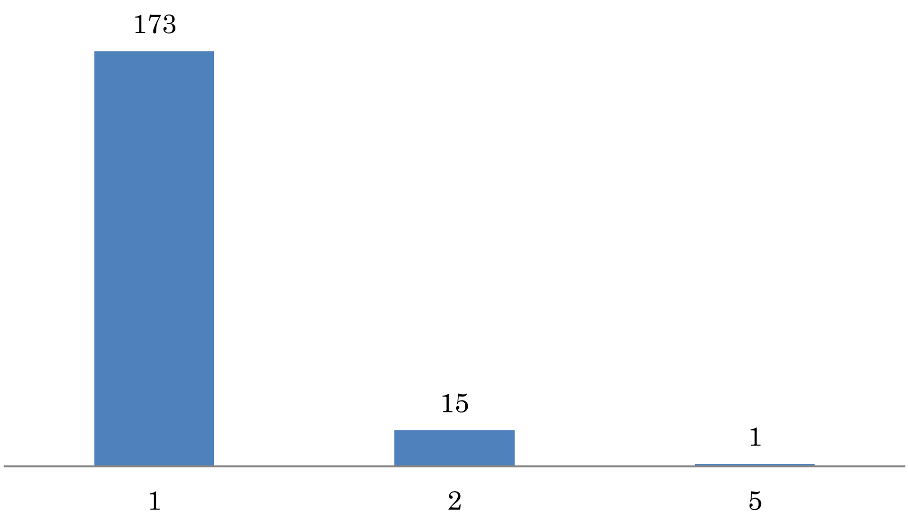
(12%) were cited by two companies. The two patents cited by the most companies were cited by 10 and 7 respectively.

Figure 13: The overlap between companies in terms of patents cited



Note: Actual numbers above bars mean the variety of patents cited, those under bars mean the number of companies

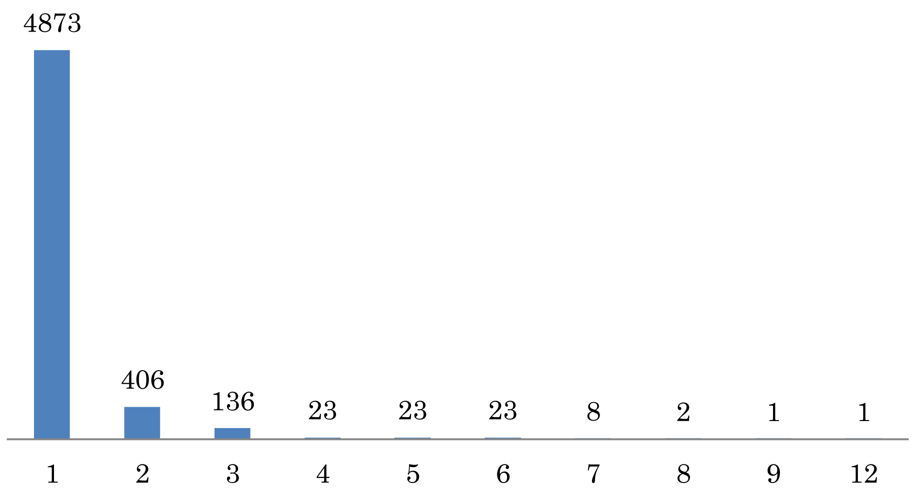
Figure 14: The overlap between companies in terms of papers cited



Note: Actual numbers above bars mean the variety of papers cited, those under bars mean the number of companies

Figure 14 shows the same analysis with regard to scientific literature. After eliminating multiple citations by the same company, we see that 189 papers were cited overall. Of these, 173 (about 92%) were cited by a single company alone, 15 were cited by two companies (8%), and one was cited by five companies. Thus, there is more diversity and less overlap in scientific literature cited in patents by multiple companies. Whereas 84% of patents were cited by a single company alone, 92% of scientific papers were cited by patents of a single company.

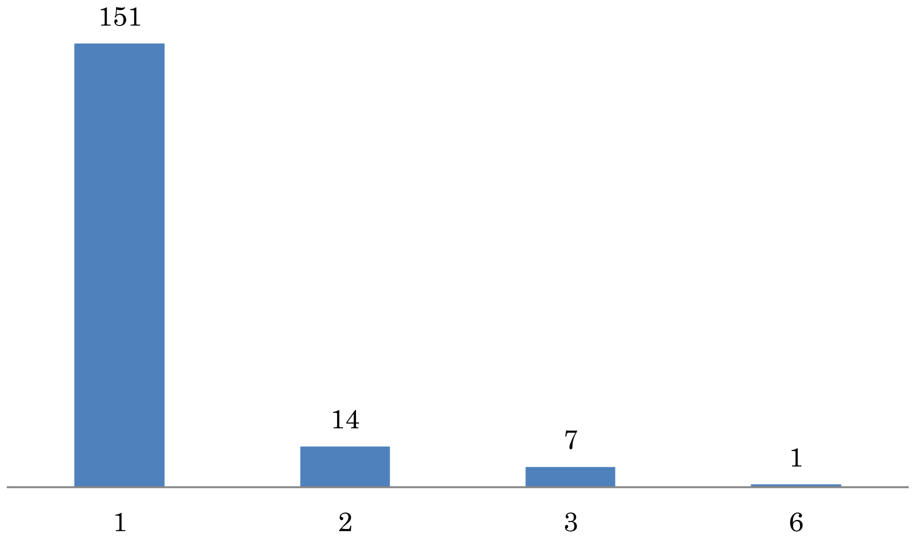
Figure 15: The times of citations made of each patent which were cited by one company



Note: Actual numbers above bars mean the number of patents cited, those under bars mean the times patents cited.

Overlap among cited scientific literature was extremely low even among LCD manufacturers. A scientific paper cited by only one company has low value for other companies; in other words, it is valuable only to the company whose patent actually cites it. We examined citation trends to elucidate influence of scientific papers cited only once on the companies making the citations. First, Figure 15 shows the number of citations made of each patent from Figure 13 above which were only cited by a single company. These patents, which were deemed valuable as sources of information only by one company, were used for this this purpose by those companies only once in the overwhelming majority of cases. These patents were cited only once in 4873 instances (89%), twice in 406 instances (7%), and three times in 136 instances (2%).

Figure 16: The times of citations made of each paper which were cited by one company



Note: Actual numbers above bars mean the number of papers cited, those under bars mean the times papers cited.

Next, Figure 16 shows the same analysis with respect to scientific literature citations instead of patents. Scientific papers were cited only once in 151 instances (87%), twice in 14 instances (8%), and three times in 7 instances (4%). As with patents above, the great majority of scientific papers cited by a single company alone were cited only once.

These results point to a subtle but interesting trend. First, there is more diversity in scientific literature cited by LCD manufacturers than in patents cited: 92% of scientific papers were cited by a single company compared with 84% of patents. However, there is less overlap in scientific papers cited than in patents. If we consider sources of information cited only a single company to be valuable sources of information specific to that company's needs, then scientific literature fulfills this function more often than patents. Further, most patents (89%) or scientific papers (87%) cited by a single company were only cited once, although there is less overlap among patents. In other words, of patents and scientific papers serving as valuable sources of information specific to only certain companies, the latter are more likely to be cited by multiple patents. From these findings, we speculate that: first, scientific literature may be a better source of information specific to their needs for companies than patents; and second, of patents and scientific papers serving as sources of information specific only to certain companies, papers are slightly more likely to impact multiple future patents.

To summarize our results thus far, LCD-related science linkage has varied in the range of 0.3 to 0.5, although it has risen to about 0.6 several times. Although rising trends are visible for some subsets such as specific countries or patent types, there is no general rise overall. Japan and the US are the two leading patent assignees, but the two countries exhibit differing characteristics: science linkage in Japan has remained consistently low, while it has been much higher in the US and rising rapidly in recently years.

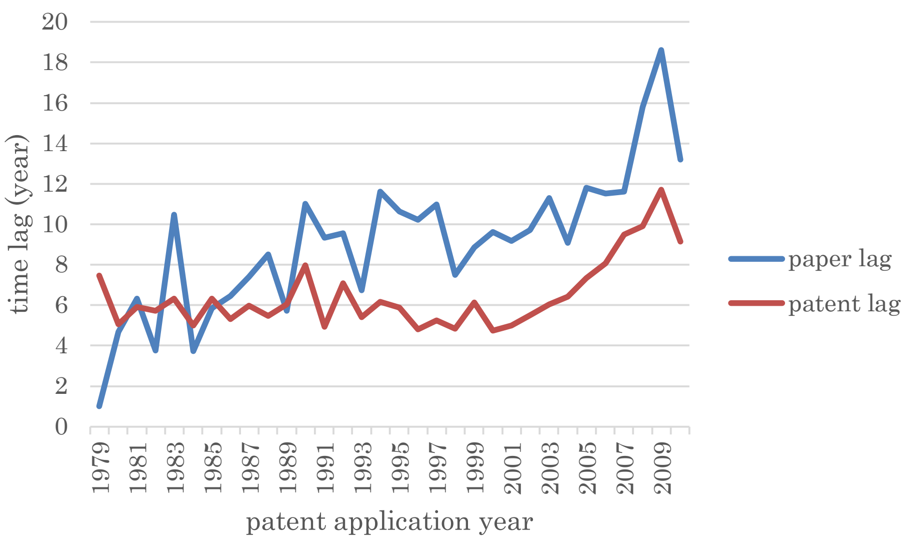
Analysis of citations of scientific literature shows a diversity of papers cited rather than a few major papers being cited by many patents. Further, the ratio of scientific papers cited only once is higher for the LCD-related field than for our dataset as a whole, indicating that competing companies base their inventions on a diverse array of literature. Narrowing the dataset to LCD manufacturers, scientific papers cited only by a single company are more common than patents cited only by a single company. However, of scientific papers or patents cited by a single company alone, single citations are more common for patents than scientific papers. In other words, scientific papers or patents not cited by competing companies are cited only once in the majority of cases, and there is a slightly higher ratio of the former leading to more inventions.

4. Measuring the Citation Time Lag

In this section we will discuss the time lag between the publication of cited scientific papers or patents, and citations of these made in patent applications. There is a significant difference between January and December of any given year, but difficulties in obtaining scientific literature data force us to calculate time lag in terms of years. We refer to time lag to cited scientific literature as "paper lag" and to cited patents as "patent lag."

Figure 17 shows time lag data for our entire dataset. Paper lag for the first year available, 1979, is only one year, but as stated above this year had a very small sample size and so is not meaningful. The sample size is much larger for 1983, a year in which mean paper lag jumped to more than 10 years before declining to four years in 1984. Lag increases dramatically again from 1989 to 1990 and from 1993 to 1994, while falling dramatically from 1997 to 1998. Approximate 5-year means from 1985 onward are as follows: 1985–1989, 6.8 years; 1990–1994, 9.7 years; 1995–1999, 9.6 years; 2000–2004, 9.8 years. The mean rises to 13.9 years in 2005–2009, but the fact that data before patents are awarded is not included could be warping the data. In contrast, the patent lag is relatively stable at about six years. It increases to eight years in 1990, but then declines gradually to about 4.7 years in 2000. In 2000 patent lag begins to increase significantly, mirroring paper lag, until it hits about 11.7 years in 2009. Patent lag is shorter than paper lag in all years since 1985 with the exception of 1985 and 1989.

Figure 17: The trend of time lag



Next we evaluate the distribution of time lag. Figure 18 shows patent lag distribution. The existence of negative time lags is due to the long periods until patents are granted. We were able to identify year of publication for 97143 patents cited in LCD-related patents. Patent lag was highest at two years (8823 patents), followed by one year (8611 patents), three years (8143), and zero years (7851). The longest patent lag was 141 years (2 patents). This figure also shows a single peak distribution distorted to the left.

Figure 18: The distribution of patent lag

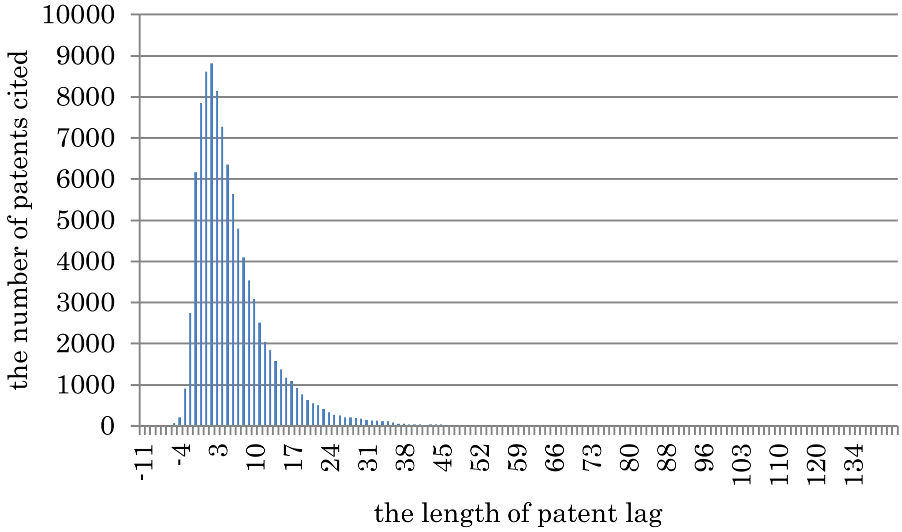


Figure 19: The distribution of paper lag

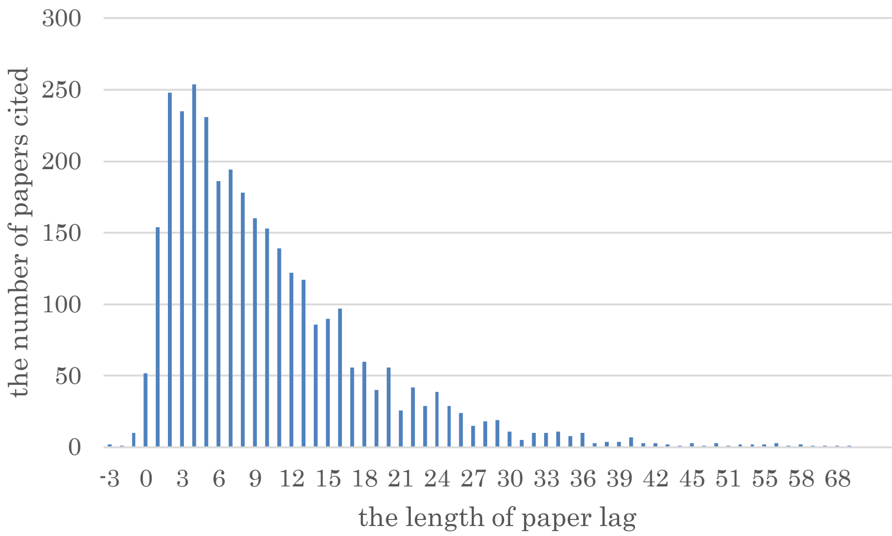
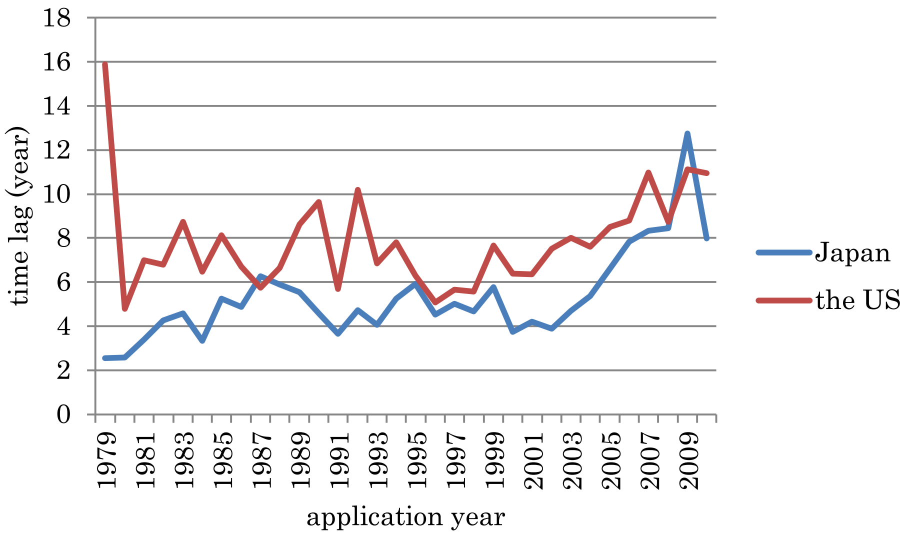


Figure 19 shows the paper lag distribution. As with patents above, the existence of negative time lags is due to long periods required for receiving patents; or, in the case of scientific literature, papers may have been published after obtaining patents. Of the 3279 scientific papers in this data set, time lag was four years for 254, followed by two years for 248, three years for 235, and five years for 231. The longest time lag was 69 years for one paper. As with the patent citation time lag above, this shows a single peak distribution distorted to the left. Although patents and scientific literature exhibited different science linkage distribution profiles, there was no such difference for time lag.

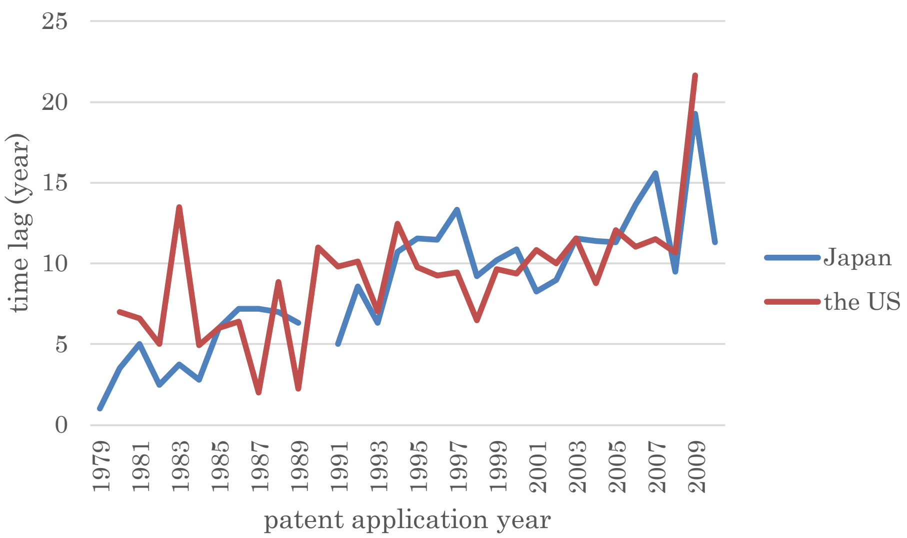
Figure 20: Patent lag in Japan and the US



Next we examine paper lag of the two prime patent-producing countries, Japan and the US. Figure 20 shows the patent lag, which we examine as a comparison to paper lag. Patent lag varies within the time period in question. Lag rises in the US around 1983 and from the late 1980s to the early 1990, then trends upward gradually beginning in the 2000s. In Japan patent lag rises in the late 1980s and from the early 1990s to 1995, then trends upward gradually in the 2000s in a pattern similar to the US. Of particular interest is the fact that the US had a shorter patent lag than Japan only once in the 20 year period from 1985 (when the sample size increased) to 2004. This suggests that Japanese patent applications are based on more recently-granted patents than US patent applications are.

Figure 21 shows the same analysis with regard to paper lag. The overall trend for both Japan and the US is increasing lag from the 1980s to the first half of the 1990s, followed by stabilization from the mid-1990s for the next decade or so. Paper lag for the two countries remains relatively close from 1985 to 2004, with shorter paper lag in the US than Japan in 10 out of 19 years (there is Japanese data for 1990). However, paper lag is shorter in the US for 7 out of the final 10 years (1995 to 2004).

Figure 21: Paper lag in Japan and the US



Comparing patent lag and paper lag in the period from 1985 to 2004 shows that while patent lag varies in the 4–8 year range, paper lag varies in the 6–10 year range. This demonstrates that in general patents are used more rapidly than the scientific literature as a source of information for further inventions. Further, Japan has shorter patent lag than the US. This fact may be due to the technological excellence of Japanese manufacturers, which were the driving force behind large-scale industrialization of LCDs. There is no clear pattern in comparative durations of paper lag between the US and Japan. In contrast, in the second half of this period the US was more proactive in leveraging new scientific findings in its patents, indicating that US inventions in the field are more strongly tied to the latest science. This mirrors overall recent trends in science linkage, which has been rising dramatically in the US remaining stable at a low level in Japan.

Our analysis thus far has focused on the time lag from publication of a patent or scientific paper to citation in a patent. Next we turn our attention to the duration for which patents or scientific papers continue to be cited after the first citation. In other words, what is the lifespan of utility of patents or scientific papers for new inventions? We can imagine two possible patterns: one in which scientific results rapidly lead to new inventions before becoming irrelevant; or, scientific findings may build cumulatively, with older sources maintaining their relevance and being continually referenced. The first pattern would result in higher science linkages associated with shorter time lags, while the second pattern should result in the reverse.

To study the issue, we first identified the set of patents or scientific papers which were cited at least once from 1985 to 2004, but not cited from 1979 to 1984 (earliest period for which data is available) or from 2005 (the year patent applications began declining) forward. We then calculated the number of years from first to last citation, which we consider the "lifespan of utility" of these patents, and plotted the mean lifespan of utility against year of publication.

Figure 22 shows mean lifespan of utility for patents and scientific papers published from 1980 to 1999. The mean lifespan of utility for patents in 1980 was about 1.0 years, although this lengthened during the 1980s until reaching about 2.1 years in 1988. Thereafter the utility lifespan of patents declines consistently, with the exception of a rise in 1992. In contrast, lifespan of utility for scientific literature was about 1.8 years in 1980, a figure which then declines rapidly until reaching about 1.5 years in 1985 and then rising again to about 1.4 years in 1989. Utility lifespan for scientific literature then begins a long consistent decline in 1990 forward, falling about 0.2 years in 1998 onward. Comparing the two, lifespan of utility is longer for patents than for scientific literature in all years after 1985.

Figure 22: The trends of mean lifespan of utility for patents and scientific papers

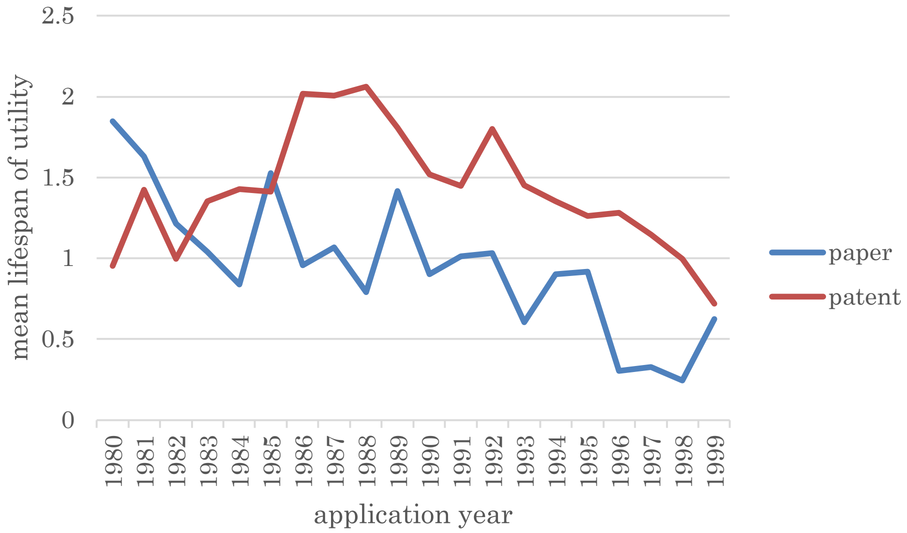
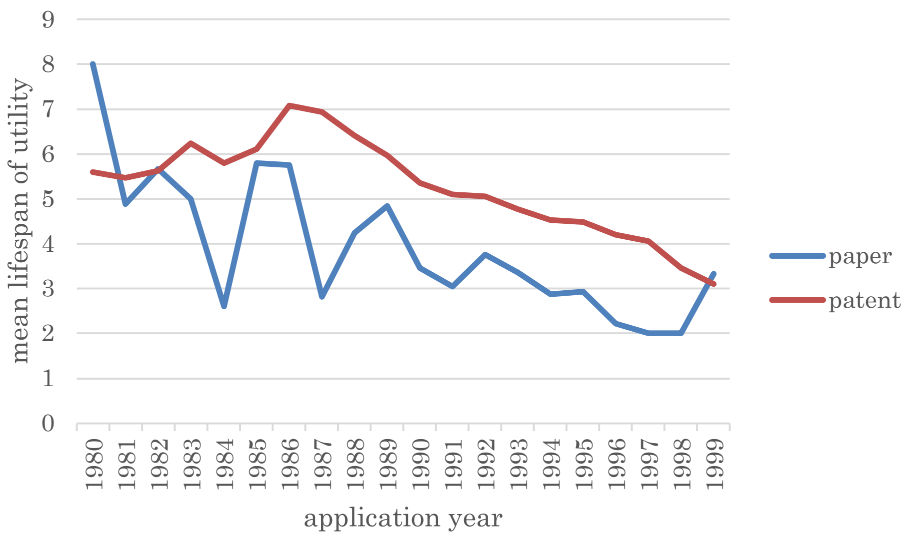


Figure 23: The trends of mean lifespans of utility for patents and scientific papers excluding those cited only once



The great majority of cited patents and scientific papers are cited only once, resulting in a lifespan of utility of 0 years. Taking simple means of the data therefore distorts our perspective, so Figure 23 shows the same data excluding patents and scientific papers cited only once. Excluding these data points does result in larger mean values, but overall trends and relationships between patents and scientific literature remain consistent. However, this figure does show a more pronounced tendency for decreased utility lifespans for patents when compared with scientific papers.

To summarize, scientific paper lag is as follows: 1985–1989, about 6.8 years; 1990–1994, about 9.7 years; 1995–1999, about 9.6 years; 2000–2004, about 9.8 years; and 2005–2009, about 13.9 years. In contrast, patent lag was relatively stable at about 8 years from the 1980s to 2000, after which it increased dramatically. The wide variation in paper lag up until 1985 makes it difficult to determine whether patent lag or paper lag was longer during this period, but after 1985 patent lag was consistently shorter. Comparisons of Japan and the US show that whereas patent lag is shorter in Japan most years, paper lag is largely equivalent between the two countries. However, paper lag was shorter in the US for seven years in the period from 1995 to 2004, showing that recently the US has been more successful than Japan in leveraging new scientific findings in inventions.

Further, analysis of lifespan of utility for patents and scientific literature, or the number of years from first to last citation, shows that utility gradually lengthened for both until around 1990, after which it began shrinking. However, eliminating patents or scientific papers cited only a single time results in changes in observable patterns. Specifically, the trend of gradual lengthening until around 1990 becomes clearly observable only for patents, while for scientific literature only the trend of shrinking from around 1989 remains. We consider it highly interesting that the lifespan of utility has been shrinking in recent years (from around 1990, that is), even if this trend does emerge from data from which patents and scientific literature cited over the long term have been excluded. Also of interest is the fact that scientific literature published in nearly all years has a shorter lifespan of utility than patents published in the same year. Combined with the time lag data above, it becomes apparent that there is a longer time lag for scientific literature from publishing to actual use in inventions, and that the duration of said use is shorter as well compared to patents.

5. Discussion

In this paper we have evaluated science linkage through the lens of LCD-related patent information. We specifically selected this industry as an example of complex goods, a category which has not received significant treatment in such discussion to date.

Traditionally, bioscience-related disciplines have been the focus of research studying linkages between science and industrial technology, as these fields are clearly heavily dependent on science. At the same time, these fields exhibit high appropriability of innovation through patents. In contrast, appropriability of innovation through patents is lower for electronics, a field which has not played as major a role in study of science linkage. Large-scale, complex products have been noted for their tendency towards low appropriability of innovation. Because they consist of multiple constituent elements, there is no single technological element playing a pivotal role within the system. This makes it easier to avoid conflicts with existing patents and is a reason for the prevalence of cross-licensing. This results in a state of affairs in which successfully creating and patenting a complex goods-related invention does not necessarily lead to significant income from that innovation. We focused on patents related to complex electric goods in the hopes of elucidating some latent characteristics in the relationship between these system-based products and science linkage, not merely out of a desire to measure the closeness of their relationship with science. We arrived at three major conclusions through our analysis of US patent data.

First, overall science linkage trends vary according to time period even among the field of LCD-related patents, and there is no obvious pattern of rise or decline. Further, Japan and the US, which are the two major countries in terms of patent applicants and assignees, display differing characteristics: Japan is stable at a low levels, while the US fluctuates more but at a higher level. In particular, science linkage in the US has increased dramatically from around 2000 forward.

Second, analysis of distribution of scientific literature citations in patents shows that the overwhelming majority of patents cite no scientific papers. Whereas the most common number of patents cited in other patents is six, the most common number of scientific papers is zero, with 87% of patents citing no scientific literature. Of all the scientific papers in our dataset, 1160, or 35% of the total, were only cited once. This figure rises to about 57% if we restrict the set to patents held by major LCD manufacturers. In other words, overlapping of cited scientific literature decreases among competing companies. A total of 84% of patents cited in patents of major LCD manufacturers are cited by only a single company, while this figure is 92% for scientific papers. Of references cited by only one company, 89% of patents were cited only once compared to 87% of scientific papers. In other words, this means that of all patents or scientific papers cited by one out of the ten major LCD manufacturers examined here, slightly more scientific papers contributed to multiple patented inventions. These reveal that scientific papers are more likely to function as source of knowledge specific to certain companies, and that this company-specific knowledge is somewhat more likely to lead to multiple inventions for scientific literature than for patents.

Third, our analysis of time lag shows a general trend of longer periods for scientific literature than patents from publication to being referenced in patents. This time lag until use in inventions is longer for scientific literature than for patents in every year since 1985 with the exception of 1985 and 1989. The difference in lag time widened in particular in the late 1990s. Japanese patent lag is consistently shorter than the US; comparisons show that patent lag was shorter for US than Japanese patents in only one year from 1985 to 2004. In contrast, the US shows shorter paper lag for 10 years out of the same 20 year period, seven years of which occurred in the last ten years. In other words, while Japanese tend to more rapidly utilize findings from industry in generating new innovation, the US tends to more rapidly utilize findings from the world of science, a trend which is particularly pronounced from 1995 forward. The fact that Japanese are more adept at using latest technologies to generate new innovation may be due to the fact that Japanese companies actively engaged in the marketplace may be better positioned to leverage existing technologies in inventing new ones. In contrast, the US’s success in leveraging the latest scientific findings may reflect a preference for utilizing science for inventing LCD-related technologies, an interpretation consistent with our findings related to science linkage. Another interesting finding was that the length of time both patents and scientific papers were referenced in later inventions began falling overall from around

1990. Although it must be remembered that patents and scientific papers referenced for extremely long durations were excluded from the data set, and it is difficult to make certain statements within the context of this research, our observations suggest that the useful lifespans of both patents and scientific literature are shortening.

What do these facts mean for the linkage between LCD-related technologies and science? The first obvious implication is that the linkage in the field between science and industry is not particularly strong. Most patents refer to no scientific papers at all, and science linkage in patents from Japan, the country which lead expansion in the area, has remained stable at a low level. Comparison of time lag also shows that new knowledge arising from the sciences is slower to be adopted than new knowledge from technical sources, and it is used for a shorter period of time. The above observations allow us to draw two tentative conclusions about the intersection of science and industry in the context of complex goods.

First, as may be surmised by points one and two above, companies seem to have pursued scientific findings not leveraged by competitors in order to secure their own company-specific sources of knowledge. Narrowing the focus to major LCD manufacturers shows that scientific papers are more likely than patents to be cited by specific companies alone. In this way, science serves as a better tool for companies to differentiate their sources of knowledge. We also see that scientific papers not used by other companies are slightly more likely to be leveraged in multiple patents than patents not cited by other companies. In other words, although the LCD-related technology field as a whole seems to maintain distance from the latest scientific findings, companies have been successful in utilizing science by identifying papers they alone leverage. However, the 88% of related patents not citing any scientific papers speaks to the fact that, in most cases, scientific findings are hardly crucial for invention in the field. These factors contribute to a state in which LCD manufacturers must find the rare pieces of scientific knowledge suited to their own particular developmental needs, even if science as a whole does not fulfill a crucial function for them. Because complex goods consist of multiple constituent elements, there is no single technological element playing a pivotal role within the system. Therefore it is reasonable to assume that utilizing scientific literature for company-specific sources of information in order to differentiate their products in the market place is a valid corporate strategy. This also implies that the best-known scientific findings may not help companies differentiate their inventions from their competitors. In the domain of complex goods, inventions based on widely-known scientific findings may have inherently compromised value.

Second, as stated in 1 and 3 above, companies appear to have a choice when selecting sources of information in order to obtain competitive advantage. While Japanese companies successfully contributed to large-scale industrialization of LCDs, their patents have consistently demonstrated a low level of science linkage. At the same time, they have shorter patent lag times, using existing patents more readily to spur new innovation. In contrast, the US boasts fewer patents than Japan in terms of absolute number, but the frequency with which US patents are cited speaks to their high level of overall quality. Science linkage of US patents has not only been high overall, but it has been increasing dramatically in recent years. US patents also demonstrated shorter time lag than Japanese patents from publication of scientific literature to citations in seven out of the ten years between 1995 and 2004. These facts indicate that while the US is no longer active as a manufacturer of LCDs, US companies have increasingly turned to science as a source of knowledge for innovation. Complex goods consist of an array of constituent elements, each of which has its own technological and scientific background. Japanese companies have largely selected a path for innovation of utilizing the latest technologies, while US companies have chosen a path of utilizing the latest science. Different options exist even within the same field for sources of knowledge to form the basis for inventions.

Our analysis of LCDs as an example of complex good using patent data has demonstrated two main patterns with regard to the linkage between science and industry in the context of complex goods. First, although the linkage between science and the field is not particularly strong, companies may strive to differentiate themselves from competition by identifying scientific findings unused by the rest of their competitors and leverage these through multiple inventions. At the same time, in the context of complex goods it is likely much more difficult to identify such useful scientific findings compared to fields with closer relationships between science and industry. At the same time, there is a choice within this environment whether or not to pursue inventions strongly based on the latest science. This leads to coexistence of products within the same category based on, or not based on, the latest scientific findings. There may be no simplistic answer as to which approach is more likely to lead to higher-quality products, at least for this type of industry. Indeed, sources of competitive strength may differ qualitatively according to whether a given company pursues innovation based on the latest technology or science.

These conclusions are based on the exploratory research performed in this study. We have examined a particular form of complex goods here, but further research is necessary to draw comparisons with other forms of complex goods as well as non-complex goods.

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