RIETI Discussion Paper Series 04-E-021

The Restructuring of Japanese Research and Development: The increasing impact of science on Japanese R&D

Lee BRANSTETTER
RIETI

KWON Hyeog Ug
Hitotsubashi University

RIETI
Research Institute of Economy, Trade & Industry, IAA
The Research Institute of Economy, Trade and Industry
http://www.rieti.go.jp/en/

RIETI Discussion Paper Series 04-E-021

THE RESTRUCTURING OF JAPANESE RESEARCH AND DEVELOPMENT: THE INCREASING IMPACT OF SCIENCE ON JAPANESE R&D[*]

Lee Branstetter
Daniel Stanton Associate Professor of Business
Columbia Business School
Visiting Fellow, Research Institute of Economy, Trade, and Industry
Visiting Scholar, Hitotsubashi University, Institute of Economic Research

Kwon Hyeog Ug
Special Researcher, Hitotsubashi University
Research Assistant, Research Institute of Economy, Trade, and Industry

lgb2001@columbia.edu
This Version: April 30, 2004

ABSTRACT

Concerns about the competitiveness of Japan's high-technology industries has prompted a number of recent reforms seeking to strengthen the ability of Japanese firms to utilize scientific discoveries, often originating in universities, in their R&D activities. Using an original panel data set comprised of over 300 leading Japanese R&D-performing firms, we seek to measure changes in the connection between science and Japanese industrial technology by using data on the citations to scientific articles appearing in the U.S. patents of these firms. Econometric analysis suggests that this connection is substantial, that it has grown over time, and that it contributes significantly to the research productivity of Japanese firms. Our data suggest that scientific research originating outside Japan, particularly in the United States, generates a particularly important component of these knowledge spillovers, and that measured knowledge flows are systematically related to firms' efforts to forge research alliances with American firms and universities. We integrate our econometric findings with data on the scientific publications of Japanese firms as well as a series of semi-structured interviews with Japanese R&D managers, academic scientists, and other experts. These various sources reveal that the interaction between Japanese firms and universities, domestic and foreign, is complex and takes a number of forms, only some of which are well captured by our data. The implications of this for public policy and for future research on this topic are discussed at length.

---

[*] We wish to acknowledge the financial support and hospitality of the Research Institute of Economy, Trade, and Industry (RIETI). We are grateful to Professor Masahiko Aoki, Dr. Kazuyuki Motohashi, Dr. Yoshiaki Nakamura, and Dr. Schumpeter Tamada for their advice, encouragement, and support. We benefited from the comments and suggestions of Reiko Aoki, Kyoji Fukao, Akira Goto, Robert Kneller, Fumio Kodama, Sadao Nagaoka, Richard Nelson, Hiroyuki Odagiri, Yosuke Okada, Ryuhei Wakasugi, and John Walsh. We also wish to thank a number of Japanese R&D managers for describing to us their "sangaku renkei" activities in detail. By prior agreement, these individuals will remain anonymous. Some of the data used in this study were obtained through a grant from the U.S. National Science Foundation, and we thank Tony Breitzman of CHI Research for his assistance in providing the data on patent citations to science. Esther Kim, Grace Lin, and Yoshiaki Ogura provided excellent research assistance. We assume full responsibility for any errors. The ideas and opinions expressed herein are those of the authors and do not necessarily reflect the views of RIETI, the Ministry of Economy, Trade, and Industry, or the U.S. National Science Foundation.

I. Introduction

During the 1980s, a major source of Japanese growth – and a major source of concern for Japan's trading partners – was the widely admired innovative capacity of Japanese firms. Over the course of this decade, Japanese firms entered and successfully competed in high-technology industries that had formerly been the preserve of U.S. and European multinationals. Japanese firms' expanding innovative capacity was clearly reflected in aggregate statistics on R&D expenses, patenting, and productivity, all of which showed a steady increase in R&D input and output.[1] Technological leadership in a broad range of critical technologies seemed to be inexorably passing from American to Japanese firms.[2]

This situation changed quite dramatically over the course of the 1990s. R&D spending by the private sector in Japan has grown much more slowly during the course of the *Heisei* recession. Some measures of R&D output in Japan have declined relative to the United States and relative to recent Japanese historical trends. There was also a widespread sense by the mid-1990s among Japanese R&D managers, industry observers, and government officials that the Japanese approach to technological innovation was no longer working effectively, and fundamental reform of the national innovation system had to take place.[3]

The implications of this apparent slowdown in the growth of Japanese innovative capacity are potentially quite serious for Japan's long-run economic prospects. The *Heisei* recession has *not* been driven primarily by technological factors. Rather, the

---

[1] See Saxonhouse and Okimoto (1987), Arison et. al. (1992), and Mansfield (1988). See also the book length treatment of Goto (1993).

[2] A study by the respected National Academy of Engineering (1987) concluded that Japan was superior to the United States in twenty-five out of thirty-four "critical" technologies.

[3] See Goto (2000) and Branstetter and Nakamura (2003).

collapse of asset prices, the resulting crisis in the banking system, and the inappropriate macroeconomic policy responses of the Japanese government over the last ten years have arguably been the primary cause.[4] However, when sustained economic growth resumes in Japan, the maximum rate at which that growth can be maintained in the long run will be closely tied to the ability of Japanese firms to develop and deploy new technology.

In striking contrast to developments in Japan, recent research points to an evident surge in innovative activity in the United States over the past fifteen years.[5] This is suggested by, among other things, a sharp rise in patent applications and patent grants that started in the late 1980s and has persisted through the end of the 1990s – a rise that has outpaced, by a considerable margin, increases in public and private R&D spending. While a large fraction of U.S. patent grants are awarded to foreign inventors, the fraction obtained by domestic inventors has risen – and this fraction has risen particularly rapidly in fields where patenting has grown most sharply. The recent patent surge could potentially be explained by an increase in the propensity of Americans to patent inventions, rather than an increase in the productivity of American research and development, but the recent research of Kortum and Lerner (1998, 2000, 2003) strongly suggests that recent trends in patenting and related data are more consistent with the latter interpretation. If this conclusion is correct, then it could help explain the widely observed increase in U.S. TFP growth in recent years.[6]

---

[4] For recent research which supports this view see Posen (1998).

[5] See Jaffe and Lerner (forthcoming), Kortum and Lerner (1998), Kortum and Lerner (2000), and Kortum and Lerner (2003).

[6] See Gordon (2000) and DeLong (2001).

But if American R&D productivity has increased, then that raises the question of what factors are driving the increase.[7] Popular discussion of this question has increasingly focused on one potential contributing factor – increased knowledge spillovers from U.S.-based academic science. Belief in the potential importance of this factor is linked to the phenomenon graphed out in Figure 1. This figure shows that citations made by patents granted in the United States to articles in the scientific literature increased very rapidly from the mid 1980s through the late 1990s.[8] Over this period, the number of patents granted by the U.S. Patent and Trademark Office to U.S. residents more than doubled, real R&D expenditures in the United States rose by almost 40%, and global output of scientific articles increased by about 13%, but patent citations to science *increased more than 13 times*.[9] Many at the National Science Foundation and other U.S. science policy agencies find this graph extremely interesting, because it seems to suggest – at least in some broad sense – that academic science and industrial technology are "closer" than they used to be. This could mean that publicly funded science is generating more spillovers to industrial innovation than in the past.[10] This, in turn, may have contributed in important ways to the apparent surge of innovative activity in the United States in the 1990s.

---

[7] The work of Kortum and Lerner (2000) has stressed the potential role of venture capital-linked firms in improving U.S. R&D output.

[8] This graph does not break down growth in citations by the nationality of the inventor, but data from the 2002 *National Science and Engineering Indicators* shows that the majority of these citations are made by domestic patent applicants, and U.S.-based academic science is disproportionately likely to be cited. The fraction of citations to science made to U.S. authors has increased over this period. See also Narin et. al. (1997) and Hicks et. al. (2001).

[9] These data come from the 2002 edition of the *National Science and Engineering Indicators*. The data on scientific article output may understate the growth in articles, but even a substantial correction of the official statistics would leave the basic message of Figure 1 essentially unchanged.

[10] This interpretation has been stressed in recent editions of the *National Science and Engineering Indicators* and in the recent work of Narin et. al. (1997).

This positive interpretation of recent trends in the data is influenced by the theoretical contributions of Evenson and Kislev (1976) and the more recent analysis their work inspired, such as Adams (1990) and Kortum (1997). In this general class of models, applied research is a search process that eventually exhausts the technological opportunities within a particular field. However, basic science can open up new "search distributions" for applied researchers, raising the productivity and the level of applied research effort – at least temporarily. Viewed through this theoretical lens, the concurrence of rapid growth in U.S. private R&D expenditures, even more rapid growth in patenting, mounting evidence of an acceleration in TFP growth, and still more rapid growth in the intensity with which U.S. patents cite academic science would all seem to suggest a response to new technological opportunities created by academic research.[11] Not surprisingly, other advanced industrial nations are deliberately trying to foster closer connections between university-based scientific research and industrial R&D in conscious imitation of the "U.S. model."

Perhaps no other country is more passionately pursuing the strengthening of academic-industrial research linkages more than Japan.[12] A wide-ranging consensus now seems to exist within Japan that a strengthening of the country's R&D system requires a strengthening of these connections. Building on previous work by Lee Branstetter and Yoshiaki Nakamura (2003), this paper *examines the changing degree of connection*

---

[11] The language used here may seem to imply endorsement of the much-maligned "linear model" of the impact of science on technology. Clearly, the interaction between science and technology is complex and the borders between them are difficult to draw. Private firms contribute to open science and universities now create inventions. We acknowledge this, but we believe that an increasingly close interaction between frontier science and technological development has developed in some fields over the course of the 1980s and 1990s, raising the research productivity of actors in both science and technology.

[12] For a useful review of policy initiatives in this area, see Kobayashi (2003). An extensive discussion is provided in English in Walsh and Cohen (2004).

between Japanese corporate R&D and science conducted in Japan and elsewhere.[13] This study will use previously unexploited data on industrial patents and academic publications to empirically measure this changing relationship. Econometric analyses of these new data will be coupled with in-depth interviews with leading Japanese academic scientists and corporate researchers to ensure that the econometric results are interpreted in an appropriate way.

II. University-Industry Interactions: A Taxonomy

Popular discussion of “sangaku renkei” in the Japanese popular press is often hampered by the fact that the term is rather indisciminantly applied to all kinds of university-industry interactions. The simple fact is that university scientists and industrial engineers interact in a number of very different ways. These different categories of interaction involve different kinds of relationships and they generate different kinds of outcomes. We want to identify four different categories of interaction, and make it clear from the beginning of this presentation which category this paper will focus on.

First, basic scientific discoveries can open up new areas of applied research and development. For instance, the way that new drugs are created in the pharmaceutical industry has been completely transformed by a series of revolutionary scientific discoveries made in the life sciences. For at least the past 15 years, there has been an increasingly direct and strong connection between university research at the scientific

---

[13] However, we hasten to add that our focus is not on formal collaboration between universities and firms, *per se*. Rather, our focus will be on quantifying the extent to which Japanese invention is influenced by science, much, but not all, of which is conducted in universities. While this may be facilitated by formal contracts and extensive contact, such direct connection may not be required in all cases. To put this another way, we seek to focus not on the mechanism of university-industry interaction, but rather on one set of outcomes these various mechanisms presumably generate – useful learning from science.

frontier and efforts to develop new drugs and medical devices.[14] We might refer to this kind of fundamental change as industrial researchers "using science" – typically, science that is recent in origin and constitutes an important breakthrough – directly in their R&D. Our main interest is in this kind of impact, and it is this that we will seek to measure in our research. Broadly speaking, this is the kind of interaction at the heart of the Evenson-Kislev model: a basic scientific discovery opens up a new "search distribution" for applied researchers. We emphasize that this kind of impact need not imply or require direct collaboration or formal contracts between the pioneer scientists and the firms that seek to apply these discoveries, although such direct collaboration may exist in some cases. To the extent that we believe that innovative productivity has actually increased in the United States in the 1990s, it may be that some kind of development along these lines has occurred.

However, this is only one kind of interaction. Even in fields where "frontier" science has little direct impact on industrial technology, firms can often find it useful to obtain guidance from university professors. For instance, consider the case of a small manufacturer of packaging machinery. It is seeking to make minor modifications to its machine to improve performance. These minor modifications do not require any basic scientific breakthrough. They require only the intelligent application of basic engineering principles and well-known "old science."[15] However, even in this case, the small firm may benefit from the expertise of a local professor of mechanical engineering, who can assist the firm in making the adjustments. Many engineering professors in the U.S. and

---

[14] This transformation has been documented by Kenney (1986), Cockburn and Henderson (1998, 2000), Cockburn, Henderson, and Stern (1999), Faulkner and Senker (1995), and Murray and Kaplan (2001).

[15] This distinction between frontier science and "old science" goes back at least to Sherwin and Isenson (1967). See also the useful study by Lieberman (1978).

Japan engage in this kind of consulting. We may refer to this, not as "using science," but as "using scientists." It is increasingly recognized in the academic literature that much of the interaction between universities and firms is of this form.[16] Evidence suggests that there is a long tradition of such consulting in both Japan and the United States.[17]

In between the two extremes of using revolutionary new science and using scientists to help the firm apply well-known engineering principles, there is an intermediate kind of university-industry interaction which we might call "collaborative implementation." Being influenced by a revolutionary scientific breakthrough produced at one university, firm engineers may seek to collaborate with scientists at another university to apply the new science to development of a particular product. Because the science is new to the firm, the firm seeks to engage the services of academic scientists, who may understand it better.[18] However, these academic scientists may not be the same ones that made the revolutionary basic discoveries. Often, they are not.

Finally, there are cases in which university scientists actually produce an invention – not just new science, but a product or prototype that uses that science – and they patent the invention, then seek to license the technology to a company. Sometimes the company is a venture firm founded by university scientists. In this case, the function of the company is to develop the product to the point where it can be mass-produced and market it successfully. But this is quite different from "collaborative implementation." In collaborative implementation, both university scientists and firms contribute to the

---

[16] On this point, see the studies by Rosenberg and Nelson (1994), Mansfield and Lee (1996) and Adams (2001).

[17] See Kobayashi (2003) and Walsh and Cohen (2004).

[18] See Kneller (2003) for an investigation into the role of this kind of collaboration in the Japanese pharmaceutical industry.

research stage. In this final example, the university side does the research, while the firm focuses chiefly on development, marketing, and production.

Given that these kinds of interactions are fundamentally quite different, it stands to reason that different methodologies will be required to measure these different kinds of interaction. Indeed, social scientists have used a number of different methodologies, all of which have their strengths and weaknesses.

III. Alternative Methodologies for Tracking the Impact of University Science on Industrial Research

Much recent research has focused on analysis of university patents and the licensing of university technology. This is particularly true of research in the United States. University patents are relatively easy to identify in America because, under U.S. law since the passage of the Bayh-Dole Act in 1980, most inventions generated by university professors must be assigned to the university. Pioneering research of this kind was undertaken by Henderson et al. (1998), but other researchers have used these data.[19] One key result of the Henderson et al. (1998), later confirmed by the work of Hicks et al. (2001), is that as the number of university patents has grown, the marginal quality of these patents, as measured by their impact on subsequent invention, has *declined*.

In the United States, some of these university patents have been licensed to firms, including new "venture firms" founded by university scientists. The licensing contracts and the royalties generated by these licenses have produced data that other scholars have used to statistically analyze university technology licensing. Important contributions to this stream of literature include Barnes et. al. (1998), Mowery et. al. (1998), Thursby and Thursby (2002), Shane (2000, 2001), and Lach and Schankerman (2003). As in the case

---

[19] See, among others, Barnes, Mowery, and Ziedonis (1998).

of university patents, there is evidence that as the number of licensing agreements has grown, the marginal value of licenses has declined. This stream of literature suggests that university-generated inventions are typically quite “embryonic” – bringing such inventions to market requires extensive additional investment by firms. Furthermore, the literature seems to support the notion that, at any point in time, only a small fraction of university research is “commercializable.” The incentives generated by the Bayh-Dole Act and other public policies seem to have led universities to reach progressively deeper into this pool of discoveries that might also be made into inventions, with the consequence that their marginal quality has steadily declined. These results suggests limits to the extent to which aggressive patenting and licensing of university invention can raise the productivity of the national R&D system, in the United States or any other country.

America’s booming venture capital markets of the 1990s inspired academic research concerning high-technology “venture businesses,” many of which had formal or informal ties to scientists at leading research universities. Examples of important work in this stream of literature include Zucker et. al. (1998) and Audretsch and Stephan (1996).[20] Over the long run, there is no doubt that the growth and competitiveness of high-technology industries in the United States has been enhanced by firms whose early growth was at least partially funded by venture capital. On the other hand, the magnitude of the collapse of the IT bubble in the United States in 2000-2001, the enormity of the capital losses sustained by many investors in these firms, and the ex-post realization that many firms billing themselves as “high-tech” startups had actually generated relatively little or no really no technology has caused many to have second thoughts about the role

---

[20] The financial dimension of this activity is investigated in Lerner and Gompers (1999, 2001).

of venture businesses in promoting technological advance in the U.S. at the end of the 1990s.[21] Long-run studies of the private equity market, including venture capital, typically show that the risk-adjusted returns to such investment are lower than investment in more mature enterprises.[22] Furthermore, the amount of R&D conducted by venture firms, and the total number of patents they generate, were only a small fraction of the national total in the United States, even at the height of the IT bubble.

In the case of Japan, the number of patents assigned to universities has, until very recently, been quite small. While Japanese professors may have produced a fair number of patents, the overwhelming majority of these were assigned to firms, not universities. Likewise, the number of formal licensing agreements in Japan has been quite limited. Patents and licenses are growing rapidly, but from a small base and, at the moment, the ability of these two methodologies to shed light on "sangaku renkei" in Japan is limited. For better or worse, the number of "gaku-hatsu venture" companies in Japan is also quite small, relative to what we see in the United States.[23] As a consequence, these formal measures of "sangaku renkei" are arguably unable to shed much light on the actual degree of university-industry interaction in Japan.

Of course, many researchers in the U.S. and Japan have used surveys, interviews, and case studies to study sangaku renkei. Important research in the U.S. relying on such methods includes Mansfield (1995), Cohen et. al. (1994), Faulkner and Senker (1995), Gambardella (1995), Adams (2002), and Agrawal and Henderson (2002). Recent research in Japan relying primarily on surveys or interviews includes Odagiri et. al.

---

[21] See Lerner and Gompers (2002). These authors suggest that, as the level of U.S. venture capital funding soared to unprecedented levels, the quality of the marginal "start-up" firm that received funding plummeted precipitously.

[22] See Lerner and Gompers (1999, 2001)

[23] See Motohashi (2001)

(2003), Okada et. al. (2003), Motohashi (2003), and Walsh and Cohen (2004). We believe that this kind of research is extremely valuable, and we have conducted some interviews with firm R&D managers in Japan in order to get managers opinions on sangaku renkei. For some kinds of sangaku renkei, such as “using scientists,” there is often very little quantitative data, so these kinds of interactions can only be measured through surveys and interviews. On the other hand, we would also note that surveys, case studies, and interviews also have their limitations. The response rates to surveys are often rather low. The answers firm managers give to these surveys is often subjective and the interpretation of these answers can be quite difficult. Finally, most surveys only reflect manager’s beliefs at a single point in time.

In order to quantify university-industry linkages and changes in these linkages over time, researchers have attempted to use scientific articles that are co-authored between a university professor and an industrial researcher as a way of tracking the connection between university science and industrial R&D. Research based on copublication includes the work of Cockburn and Henderson (1998, 2000) and Zucker et. al. (1998). Use of these data in a Japanese context includes work by Hicks (1993), Kobayashi (1998), and Pechter (2000, 2001). We agree that examination of the scientific publications generated by firm researchers may contain useful information on university-industry linkages, and we incorporate data on firm publications into our analysis.

However, there are good reasons for doubting the extent to which firm publications are a perfect or complete indicator of the impact of university research on the firm’s most strategic R&D activity. After all, firms seek to maximize the profits generated by their R&D efforts, and this requires that they seek to monopolize the benefits generated by their research. This places constraints on the degree to which they publish in the open scientific literature. Industrial firms, even within the same industry, vary considerably in the extent to which their researchers engage in academic publication. The breadth of the window into a firm's R&D provided by its publications thus varies widely from firm to firm. Second, firms are quite aware of the risks involved in publishing the results of their strategically significant R&D. In interviews, managers consistently stressed that publications are carefully screened in order to prevent strategic technology from leaking out, at least until the firm has secured adequate patent protection.[24]

IV. Patent Citations to Science as an Indicator of University-Industry Research Interaction

Given the problems with scientific publications and co-authorship as an indicator of university-industry research linkages, and given the fact that firm patents are likely to be more reflective of their strategic technological activity than publications, an argument can be made for the use of patent citations to scientific articles as a measure of this linkage.[25]

As indicators of knowledge spillovers from academia to the private sector, these data have a number of potential advantages. The academic promotion system creates strong incentives for academic scientists, regardless of discipline, to publish all research results of scientific merit. As a consequence, the top-ranked research universities generate thousands of academic papers each year. Similarly, inventors have an incentive

---

[24] Murray (2002) has also questioned the extent to which firm publications and corporate-university co-publications are a useful indicator of science-technology interaction.

[25] Of course, there are problems with the use and interpretation of these data as well. These problems will be discussed at length below.

to patent their useful inventions, and a legal obligation under U.S. patent law to make appropriate citations to the prior art – including academic science.

The recent research discussed in previous paragraphs indicates that, in response to the Bayh-Dole Act and other public policy measures, universities have increased the extent to which they patent the research of university-affiliated scientists. They have also increased the extent to which they license these patented technologies to private firms. Nevertheless, it is clear to observers that only a *tiny fraction* of the typical research university's commercially relevant research output is ever patented, and only a fraction of this set of patents is ever licensed.[26] To illustrate this, Figure 2 shows the trends over the 1988-1997 period in several alternative indices of university research output and knowledge spillovers for one of the university systems in my data set, the University of California, which includes nine separately managed campuses and a number of affiliated laboratories. The figure graphs university patents by issue year (patents), invention disclosures by year of disclosure filing (invention disclosures), new licenses of university technology by date of contract (licenses), the number of citations to previous university patents by issue year of the citing patent (citations to UC patents), and the number of citations to UC-generated academic papers by issue year of the citing patent (citations to UC papers). Clearly, citations to papers are far more numerous than any other indicator. This figure suggests that patent citations to academic papers may provide a much broader

---

[26] This limited role of university patenting and licensing is also emphasized strongly in the interview-based evidence presented by Agrawal and Henderson (2002).

window through which to observe knowledge spillovers from academic science to inventive activity than any available alternative.[27]

Citations to scientific articles can reflect learning on the part of industrial inventors through multiple channels. For instance, a firm may learn about a useful scientific discovery through an informal consulting relationship with an academic scientist or through the hiring of graduate students trained by that scientist rather than through a systematic and regular reading of the professional scientific literature. Even in these cases, the confluence of academic scientists' interest in rapid publication of significant discoveries combined with firms' legal obligation to cite relevant prior art means that citations to scientific articles will often show up in patent documents, providing a "paper trail" of knowledge diffusion, even when the particular means of knowledge diffusion was something other than the publication itself.[28]

What this methodological approach clearly fails to measure is the contribution of "old science" to industrial invention. A significant component of the consulting work undertaken by university faculty consists of helping private industry understand and apply well-established – or, "old" – scientific techniques and engineering principles, rather than helping firms incorporate the latest frontier science into their research agendas. Likewise, recent science and engineering graduates are often employed in functions that are quite far removed from the scientific frontier, but are nevertheless quite economically important to the financial success of their employers. This contribution will be

---

[27] Other recent studies using data on patent citations to scientific papers include work by Fleming and Sorenson (2000, 2001) and Lim (2001). Neither of these studies focuses on the large change in citations to academic science over the course of the 1990s, which is the focus here.

[28] Of course, the legal role played by patent citations means that not all patent citations to science reflect true learning. As studies by Meyer (2001) and others have indicated, there is considerable "noise" in the patent-to-article citation data. Nevertheless, Meyer's critical study acknowledges that patent-to-article citations are broadly indicative of the importance of science in a particular class of inventions. See Meyer (2001), p. 425.

completely missed by my approach. In such cases, there is no new patented invention incorporating recent science. But as the older literature on university-industry interaction has stressed, the propagation of "old" scientific and engineering knowledge to industry through training and consulting is a *long-standing feature of the university system*, in both the United States and Japan.[29] The new development stressed by the recent literature is the closer relationship between technology and relatively recent science. It is precisely this aspect of university-industry interaction that our methodological approach will most closely reflect.

Our research will rely on the citations to science found in the U.S. patent documents of Japanese firms. We thus differ in our approach from that of Tamada et. al. (2003a, 2003b), who use a recently constructed data base of Japanese patents that include citations to scientific papers found in these patents. Why use the U.S. patents of Japanese firms, when data on Japanese patent citations to science exist? This is a fair question. While we commend Dr. Tamada and his collaborators on their impressive achievement in constructing their database, and while we believe strongly that much can be learned from their database, we think that there are at least two good reasons for looking at the U.S. patents of Japanese firms and the citations contained therein.

First of all, U.S. patent law explicitly requires all patent applications to make "appropriate citations to the prior art." There are serious penalties for inventors that fail to make these citations accurately. Japanese patent law does not require inventors to make these citations, and there is no penalty for failing to include them. While many Japanese inventors include citations in their patent applications, there is no requirement

---

[29] For a historical survey that stresses this fact in a U.S. context, see Nelson and Rosenberg (1994). For Japan, see Kobayashi (2003) and Odagiri (1999).

for them to do so. This raises the possibility that Japanese citations to science are incomplete.

On the other hand, the legal function that patent citations play in the U.S. means that citations get added to patent documents by parties other than the inventor, such as patent attorneys and patent examiners. Citations added by these other parties may identify earlier work either unknown to the inventor or considered to be of peripheral importance. Thus, they do not reflect "knowledge spillovers" – rather, they constitute "noise" in the data. Some evidence suggests that inventors and their attorneys have become increasingly careful about citing prior art for legal reasons. As a consequence, we need to use U.S. patent citation data with appropriate caution and be aware of these potential biases. We are somewhat assured by the assertion made in interviews both attorneys and inventors that, while patent attorneys often know the patent literature better than the inventors, and often add citations to other patents, they are much less likely to add citations to the academic literature. This is for the simple reason that they are often much less knowledgeable of the relevant academic literature than the inventor. As a consequence, patent citations to science may be less contaminated by the "noise" described above than citations to previous patents.

A second reason for looking at the U.S. patents of Japanese firms relates to one of the fundamental problems with the use of patent data as economic indicators: most patents are, in economic terms, virtually worthless. That is, the inventions they describe are not important technical advances valued by consumers or, in the case of process technology, manufacturers. The value distribution of patents is highly skewed, with a small fraction of patents accounting for most of the economic value generated by corporate R&D.[30]

Firms often cannot perfectly forecast the economic value of their inventions when they first apply for a patent. Because it takes considerable time and money to apply for patent protection in multiple countries, firms will only do this for some of their patents. The U.S. patents of a Japanese company thus represent a subset of inventions that the company considers to have the most potential, at least at the time the patent application decision is made. Evidence on the potential usefulness of this as a screening mechanism is provided in Figure 3. This figure uses data from Japanese patents published in 1998.[31] The left axis measures the total number of patents, in units of 10,000, while the right axis indicates the percentage of Japanese patents for which patent protection is also sought in the United States and Europe. Japanese firms produce relatively few patents in fields associated with "biotechnology," including genetic engineering, drugs, and medical devices, but a relatively higher percentage of these patents are protected in the U.S. and Europe. On the other hand, while Japanese firms produce a much larger number of electronics patents, only about 16% of these patents are protected in the United States and Europe. To put this another way, out of 100 randomly drawn Japanese patents, only 16 would be judged by the inventor to be sufficiently valuable that patent protection is sought in the world's largest economies.[32]

---

[30] This point is forcibly made by a series of papers by F.M. Scherer, D. Harhoff, and K. Vopel. See, for instance, Scherer, Harhoff, and Vopel (1998).

[31] We essentially reproduce a graph provided on page 55 of the 2003 Patent Administration Annual Report.

[32] The reasons why Japanese firms produce so many "marginal" patent applications are rooted in traditional employee incentive systems and the historical evolution of the Japanese patent system. For some time, Japanese employees were rewarded for meeting a "quota" of patent applications, which encouraged an emphasis on quantity at the potential expense of quality. Likewise, prior to 1988, the Japanese patent system itself limited the scope of patented inventions. For a discussion of this and the reform that took place in the late 1980s, see Sakakibara and Branstetter (2001).

We are interested in the extent to which knowledge spillovers from academic science helps Japanese firms to create valuable new technology that can create benefits for customers and strengthen the competitiveness of Japanese industry. Given this objective, it may be appropriate to focus on the subset of inventions for which protection is sought outside of Japan.

V. Data Used in This Study

We begin by assembling complete data on the U.S. patents granted to 335 Japanese firms over the period 1983-1999. Our sample includes most of important R&D performing manufacturing firms in Japan. As is well known, both R&D expenditure and patenting in Japan are highly concentrated in the larger manufacturing firms. Thus, while the number of firms is small, the fraction of total private sector R&D activity our firms account for is reasonably high.

Our data on U.S. patents include, in principle, the universe of citations made on the front page of these patents to peer-reviewed scientific articles in the more than 4,000 journals tracked by the Science Citation Index. This definition of "scientific article" is biased toward English language journals, but provides fairly comprehensive coverage of the more internationally influential journals across a broad range of scientific fields. For the vast majority of these citations, we can identify the author, the author's institutional affiliation and geographic location, the scientific field of the article, and the publication date. When there are multiple authors, we obtain this data for each of the first five authors named in the publication.

For roughly 200 of our sample firms, we have also obtained information on the scientific publications generated by authors affiliated with these firms over the 1983-

2001 period. These data come from the Institute for Scientific Information and, again, are based on articles appearing in the journals tracked by the Science Citation Index. These data include information on all authors named in the publications, the affiliations and geographic location of the authors, the scientific field of the article, and the date of publication.

Because all of the firms in our database are publicly traded, we can include firm-level annual data on firm sales, capital stock, employment. These data come from the Corporate Finance database created by the Development Bank of Japan. The R&D data in this data base are incomplete, so we supplement it with the R&D data obtained from the annual surveys published in the Kaisha Shiki Ho and the Nikkei Kaisha Joho.[33] We also include data on firm's overseas R&D subsidiaries from the Toyo Keiza Kaigai Kigyou Shinshutsu Souran and information on overseas technology alliances from the CATI database developed by John Hagedoorn and his associates and the University of Maastricht.[34]

VI. A Review of Trends in the Data

Before reporting the results of our regression analysis, we present some tabulations of the raw data. The text below refers extensively to figures available at the end of the paper. Figure 4 presents a tabulation of the total number of Japanese patent citations to scientific articles over time. The top line sums all such citations, regardless of the institutional affiliation of the author. The bottom line sums up citations for papers generated by university-based scientists only. Immediately, we see that the "science base" upon which firms build is not exclusively provided by universities. Firms and

---

[33] Because firm responses to these surveys are voluntary, data are not available for all sample firms in all years.

[34] For a description of this data base, see Gomes-Casseres, Hagedoorn, and Jaffe (2003).

government-affiliated research institutes contribute substantially to this science base. In both lines, we observe a sharp increase over time. The years correspond to the patent grant years of the citing patents. There is an evident leveling off – even a modest decline – in the final years of our sample, but this reflects, in part, a decline in U.S. patenting by our sample firms, in response to domestic economic conditions and other factors.

Figure 5 classifies these citations on the basis of primary industry of the firm generating the citing patent. As we can see, the two most important industries are electronics and chemicals. This fits with the popular notion of these two sectors as being "science based industries."[35] Within the chemical sector, roughly three quarters of the patent citations to science come from Japan's major pharmaceutical companies.

Our data allow us to identify the geographic location and institutional affiliation of the authors of the scientific articles cited in Japanese firms' U.S. patents. As one can see from Figure 6, aggregating across firms, time, and industries, more than half of citations are made to articles generated by authors located in the United States. Japan-based authors account for less than 25% of such citations. Figure 7 provides a similar breakdown of geographic location of the author by primary industry of the citing firm. Citations to American articles are most numerous in all of the major industries in which there are relatively large numbers of patent citations to science. Even in electronics, American articles are cited more frequently than Japanese articles, although Japanese citations are especially numerous in that field.[36]

Based on the name of the institution with which the authors are affiliated, we can also assign every cited article to a category of institution: private firm, university,

---

[35] See Goto and Odagiri (2003).

[36] Obviously, we want to be alert to the potential bias toward American articles in these data. On this point, see Tamada et. al. (2003a, 2003b) and Meyer (2001). We discuss this issue further below.

research hospital, and an “other institutions” category. “Other institutions” includes government laboratories and other public sector research institutes. Needless to say, the categorization of thousands of unique institution names required data work that was time consuming and tedious. Nevertheless, we believe our categorization is reasonably accurate.

As can be seen in Figure 8, articles generated by “Public science institutions” – hospitals, universities, and “other institutions” -- account for the vast majority of citations. Furthermore, university-generated articles are the most important single category of cited article. This is interesting, as it suggests that much of the impact of science on industrial R&D traced out by the patent citations of Japanese firms to science is indeed coming from universities. This validates our approach as a measure of university-industry research interaction.

However, when we restrict ourselves to articles with Japanese authors, it turns out that articles generated by *firms* are cited more frequently than any other category. In fact, they are cited more frequently than all other categories put together. The university citations disproportionately come from foreign universities, not Japanese universities. This is evident from Figure 9.

Finally, Figure 10 presents the distribution of lags between the date of publication of the cited article and the date of application of the citing patent. As is evident from the figure, these lags tend to be quite short. The modal lag is only three years, and the distribution tends to drop off sharply after four years. In other words, Japanese patents are, on average, citing very recent scientific papers. This helps strengthen the interpretation of patent citations to science as being reflective of “using science” –

especially recently generated “frontier” science – in industrial R&D. We see a small number of negative lags. This indicates that some cited papers are published after the citing patent is applied for. Clearly, some papers are cited in patent applications while they are still in working paper form. Others may be added to a patent application while it is still in the process of being reviewed by the U.S. patent office.

VII. Econometric Analysis at the Patent Level

Of course, we want to do more than simply offer tabulations of the raw data. We want to conduct econometric analysis at two different levels of aggregation: the level of the citing *patent* and the level of the citing *firm*. To that end, we first present results at the level of the citing patent. We aggregate our raw data on patent citations to science, such that the dependent variable is the total number of citations to science made by patent *i*. We can then regress this on characteristics of the patent and characteristics of the firm that generated the patent. Because the dependent variable is a count variable, we do not use linear regression methods. Instead we use logit, Poisson, and Negative Binomial models.

In our initial regression, we take a “logit” approach, which requires that we truncate our dependent variable to a binary variable equal to 1 if there is a positive number of citations to science and 0 otherwise. As it turns out, the variable is zero for the vast majority of patents in our database. The equation estimated is:

$$Cite_i = \beta_0 + \beta_1 lrnd_i + \beta_2 lrsale_i + \beta_3 lrsub_i + \beta_4 lalliance_i + \sum_{t=1}^{T} \delta_t T_t + \sum_{j=1}^{I} \gamma_j I_j + \varepsilon_i \qquad (1)$$

The binary dependent variable is regressed on the log of real R&D expenditures (*lrnd*) of the firm that generated patent *i*, the log of real sales of that firm (*lrsale*), the log of the number of overseas R&D subsidiaries in the United States maintained by that firm (*lrsub*), and the log of number of alliances with American firms and universities maintained by that firm (*lalliance*). All of these data correspond to the firm fiscal year in which the patent was granted. However, qualitatively similar results obtain when we conduct a regression based on the application year of the patent. We also include a full set of dummy variables corresponding to the primary industry of the firm to which the patent is assigned as well as a full set of dummy variables corresponding to the patent grant years. Estimated standard errors on the "firm-year" variables will tend to be biased downward because of the large number of patents generated by the same firm in some years.

Table 1 presents results from this simple logit regression. The first set of estimated coefficients correspond to dummy variables associated with the primary industry of the firms generating these patents. It is clear that, although the electrical machinery industry generates a large number of patent citations to science, this occurs simply because the electrical machinery industry generates more patents, by far, than any other Japanese industry. Once one controls for the number of patents, the number of citations to science is not especially high. In fact, the coefficient on the dummy variable associated with the electrical machinery industry is *negative* and statistically significant.

On the other hand, even after controlling for the number of patents generated by pharmaceutical firms, the estimated tendency of these patents to cite science is particularly high. As is the case with American inventors, Japanese patent citations to science are disproportionately concentrated in the pharmaceutical industry. This does not mean that knowledge spillovers from academic science do not occur outside the pharmaceutical industry – but it suggests that the spillovers may be strongest in this sector.[37]

We also see that the number of patent citations to science is positively related to the size of the firm, even after controlling for the number of patents. In Japan, it is the larger firms that tend to draw most heavily on academic science in their research activities. This is likely related to the fact that only the larger, more financially successful firms can afford to make a major investment in the kind of "basic research" that is proximate to academic science.

Finally, given that the majority of patent citations are made to articles generated by U.S.-based scientists, it is probably not surprising that the number of technology alliances a Japanese firm has with American firms and American universities is positively and significantly correlated with the total number of citations its patents make to scientific articles. In this particular regression, we also see a separate and positive impact of the number of overseas R&D subsidiaries possessed by the citing firm on citations to science.[38]

The regression reported in Table 1 also included a full set of year dummy variables. The regression coefficients on these year dummies, along with the 95% confidence intervals, are graphed out in Figure 11. This picture shows us how the tendency to cite scientific articles has changed over time, controlling for the number of patents. This graph confirms that there has been a sharp increase since the mid-1980s in

---

[37] We have omitted the coefficient on the R&D term for space reasons. It seems to add little to the model, once we control for the number of patents granted to a particular firm.

[38] For other studies of the impact of overseas subsidiaries on international "learning" by Japanese firms, see Odagiri and Iwasa (2002) and Branstetter (2000).

terms of the measured impact of science on industrial research in Japan – a finding similar to that which can be obtained with U.S. data.[39]

Readers will note that the timing of this increase in the per-patent propensity to cite science broadly corresponds to the widely observed increase by Japanese firms in basic R&D. By the mid-1980s, Japanese firms had reached the technological frontier in a number of industries, and they were under increasing pressure from lower-cost competitors in other Asian nations.[40] The managers of these firms became increasingly convinced that they would have to innovate in order to continue to grow. The quest for generation of proprietary "breakthrough" technologies over the course of the late 1980s and early 1990s necessarily brought Japanese firms closer to frontier science, and this is traced out in Figure 11. Long before the Japanese government was promoting such activities, Japanese firms were participating in the "sangaku renkei" programs of American universities, and part of the growth in citations to science probably stems from this participation, even though we control separately for increases in formal alliances with American firms and universities.[41] By way of comparison, Figure 12 provides the timing of some key sangaku renkei promotion policies in Japan, as well as indicators that reflect largely "intranational" sangaku renkei activity.

To more fully exploit our patent-level data, we use Poisson and Negative Binomial models, which are designed to predict the number of citations to science, based on the characteristics of the patent and the firm. Results of these regressions, provided in Table 2, yield results broadly similar to those of Table 1. The equation estimated is

---

[39] See Branstetter (2003a).
[40] See Goto (2000) and Branstetter and Nakamura (2003).
[41] See Kobayashi (2003).

$$Citation_i = \beta_0 + \beta_1 lrnd_i + \beta_2 lrsale_i + \beta_3 lrsub_i + \beta_4 lalliance_i + \sum_{t=1}^{T} \delta_t P_t + \sum_{j=1}^{I} \gamma_j I_j + \varepsilon_i \quad (2)$$

where the variables remain as they were defined for equation (1), with the following exception: rather than include a separate dummy variable for every patent grant year, as in the previous regression, here we assign patent grant years to categories corresponding to the early 1980s, the late 1980s, the early 1990s, and the late 1990s. The regression results show a sharp increase in the tendency of patents to cite science, confirming our earlier finding. The inclusion of dummy variables corresponding to selected industries shows a pattern similar to that revealed in the earlier regression. Once again, we find that the patents of pharmaceutical firms are especially likely to cite science, whereas the dummy variable for patents generated by electronics firms is not statistically significant in the Negative Binomial specification preferred by the data. Finally, we find positive and significant effects associated with firm size and the number of technology alliances with American firms and universities, as in the earlier regression. On the other hand, the earlier concerns regarding standard errors apply to this specification as well.

VIII. Econometric Analysis at the Firm Level

While the earlier regressions provided us with some preliminary findings on the relationship between patent citations to science and firm characteristics, they did not tell us anything about the impact of patent citations to science on the R&D productivity of the firm. If patent citations to science really reflect knowledge spillovers – that is, if they really trace out the application of useful new science to firm R&D – then controlling for the level of R&D spending, firms that make more patent citations to science should systematically deliver a higher level of R&D output. In other words, there should be a positive relationship between the intensity of patent citations to science and a firm's inventive productivity.

Does that relationship exist in our data? We find that this relationship does exist in the data and it is statistically significant. Results of regressions attesting to this are presented in Tables 3 and 4. In these regressions, the unit of analysis is the firm-year. Unlike in previous regressions, patents are dated by their year of application rather than year of grant. This is done because we are seeking to relate Japanese firm patenting to the year in which the R&D was undertaken.

If firms learn useful lessons from recent academic science, this learning should enable them to create higher-quality inventions. How can one measure the quality of an invention? If a patent is really valuable, we might expect it to be frequently cited by subsequently granted patents. Significant past research has documented a connection between the frequency with which a patent is cited by later patents and its economic value.

Building on this idea, the first four columns use a count of patents generated by firm *i* in year *t*, where the patents are weighted by the number of citations they receive from patents granted over the next four years. This dependent variable is our quality-adjusted measure of inventive output. The equation estimated is

$$P_{it} = \beta_0 + \beta_1 lrnd_{it} + \beta_2 lrsale_{it} + \beta_3 lscience\_cite_{it-l} + \beta_4 lpatent_{it-l} + \alpha_i + \sum_{t=1}^{T} \delta_t T_t + \varepsilon_{it} \quad (3)$$

Quality-adjusted patenting by firm i in year t is regressed on the log of the firm's real R&D spending (*lrnd)* in that year as well as log of real sales (*lrsale*), to control for firm size effects. The "science citation" variable is a log of the count of all citations made by the U.S. patents of firm *i* applied for in year *t-l.* We reason that firms' learning from their "use of science" may have an impact on the quality of subsequent invention. Thus, we incorporate different lags of our citation measure, of varying length *l*, into our regression. Obviously, firms that apply for larger numbers of patents will generate more citations. To control for this, we include the log of the lagged number of patents taken out by firm *i* in the same year from which our science citation measure is drawn ($lpatent_{it-l}$) We are thus effectively regressing contemporaneous patents, adjusted for their quality, on firm-level R&D spending and sales and a lagged measure of the "science citation intensity" of previous patent cohorts. A full set of time dummies corresponding to patent application years is included in this table (the $\delta_t's$) as is a firm fixed effect (α_i). The quality-adjusted patent measure is a count variable. Hence, we use the fixed effects negative binomial estimator proposed by Hausman, Hall, and Griliches (1984).[42]

Results from Table 3 indicate that science citation has a positive effect on quality-adjusted inventive output, and this is statistically significant for all but the shortest lags. Columns 1-4 of Table 3 correspond to lags of varying length. The coefficients in columns 2-4 range from a bit over 4% to a bit under 3%. While the coefficients are not so large, they imply that the output elasticity of science citation intensity is between roughly 30% and 60% of the output elasticity of the firm's own R&D spending. This does not seem like such a small effect. Another way of illustrating the impact of science citations on inventive output is to evaluate the impact of an increase in science citations equivalent to one standard deviation from the mean. Using the coefficient in column 2 implies an *annual* increase in quality-adjusted inventive output on the order of 32%. This would seem to suggest a significant linkage between knowledge spillovers from science,

---

[42] There are some similarities between this research and recent work by Sadao Nagaoka, although Nagaoka has focused his analysis on the information technology sector. See Nagaoka (2004).

as evidenced by patent citations to articles, and inventive productivity. The strength of this linkage is even more striking given that we are using a fixed effects specification that, in principle, controls for much of the heterogeneity across firms.[43]

Of course, if this learning effect is real, it should increase not only the measured quality of the firms' patents, but also the measured total factor productivity of the firm. In columns 4-8, we estimate a simple Cobb-Douglas production function. The estimated equation is

$$Q_{it} = \beta_0 + \beta_1 lkap_{it} + \beta_2 lemp_{it} + \beta_3 lrnd_{it} + \beta_4 lscience\_cite_{it-l} + \beta_5 lpatent_{it-l} + \alpha_i + \sum_{t=1}^{T} \delta_t T_t + \varepsilon_{it} \quad (4)$$

We regress the log of real sales of firm *i* in year *t* (Q_{it}) on a measure of the log of contemporaneous real capital stock (*lkap*), the log of employment (*lemp*), the log of contemporaneous R&D spending (*lrnd*), and various lags of our science citation measure (*lscience_cite*).[44] As before, we include as a control the size of the patent cohort that produced the count of science citations in our various lags (*lpatent*). In this context, lagging the science citation measure is especially important, because we might think that it takes a while for a patented product to be developed, marketed, and sold. It is only after significant sales are generated that the invention will positively affect measured productivity. As in earlier regressions, we include firm and year fixed effects.

In this context, a linear fixed-effects approach is appropriate. Here, the coefficient on our science citation term measures the contribution of learning from science to the firm's *productivity growth*, because identification comes from the

---

[43] Concerns that lagged science citation measures might proxy for the effects of lagged R&D spending prompted the authors to re-estimate equation (3), including measures of lagged R&D spending. This did not affect the qualitative nature of our results.

[44] Ideally, an output specification should use an R&D stock measure rather than the flow measure introduced here. Efforts to construct such a measure are ongoing.

correlation between within firm changes in productivity levels and within firm changes in levels of science citation. Results from this regression analysis are presented in Table 4. Once again, we find that there is a positive and statistically significant relationship between science citations and our output measure – in this case, TFP. This relationship exists regardless of the lag we assume between science citations in the patent and the impact on sales. While the estimated coefficient is not so large, it implies that the elasticity of output with respect to changes in science citations tends to be about 30% as large as that of the firm's own R&D spending. To evaluate this another way, the coefficients imply that an increase of one standard deviation of the mean in the level of science citations generates an annual increase in productivity growth on the order of 14% per year. This suggests a fairly strong and direct impact.[45]

The magnitude of these results is all the more surprising when we consider the many reasons why our current approach may actually underestimate the full impact of learning from science on both invention quality and productivity. First, the extensive literature on "bibliometrics" notes that there is a substantial degree of "noise" in U.S. patent citation data. That is, as we have already acknowledged elsewhere in this paper, many of the citations are added by parties other than the inventor. This level of measurement error could be expected to attenuate the measured relationship between science citations and inventive output. Second, given the long and variable lags between patenting and commercialization, we might expect the statistical relationship to be hard to identify. Indeed, lags between patenting and commercialization are often considerably longer in the pharmaceutical industry – where the impact of science on invention is

---

[45] Note that the coefficients on the standard factors of production, labor and capital, imply decreasing returns to scale. This is a frequent finding in panel regressions with firm level data, and it likely stems from errors in measurement in both capital and labor.

probably the strongest – than we have allowed for in the regression results in Table 4. As a consequence, we may not be fully capturing the impact in this industry. Third, learning from science may lead firms to increase their R&D spending in order to apply the new breakthroughs to the development of new products or processes. Our current specification does not attribute any of the increase in R&D spending observed over the sample period to the increase in knowledge spillovers, and this may also underestimate the impact. [46]

Given these considerations, the findings in Tables 3 and 4 considerably strengthen our confidence in the potential usefulness of data on patent citations to science. After all, if these citations were purely the creation of patent lawyers or patent examiners, and if they were completely unrelated to the patterns of knowledge spillover between firms and universities, then we would not expect them to be systematically related to changes in invention quality or TFP – and they are. Indeed, these findings may constitute the most important scientific contribution of the current paper.

IX. Comparing Our Findings to Other Approaches

The picture of knowledge flows from science to technology generated by our data is somewhat different from that generated by some other recent studies using different approaches. It is therefore appropriate to consider these differences and their implications for the interpretation of our results. We will consider three groups of studies – those based on interview and survey evidence, those based on university-industry copublications, and those based on data on the patent citations to articles found in the Japanese patent applications of Japanese firms.

---

[46] A simultaneous equation approach that allows for the potential endogeneity of R&D is the subject of ongoing research.

One of the most provocative recent studies based on firm surveys is the recent paper by Walsh and Cohen (2004), which uses survey responses from a comprehensive survey of Japanese R&D labs conducted in 1994 to provide evidence on the strength of the impact of "public research" on industrial R&D. The authors compare the survey responses of Japanese R&D managers to a similar set of responses obtained from U.S. R&D managers at about the same time. Somewhat surprisingly, the authors find that Japanese R&D managers consider universities to be at least as important a source of "spillovers" to industrial research as do U.S. R&D managers. Furthermore, in contrast to our results, they find that, with few exceptions, this beneficial impact seems to come primarily from Japanese, not U.S. institutions. The authors argue that, even in the absence of formal mechanisms for licensing university-generated patented technology to firms, Japan's traditional "informal" set of connections between firms and universities functioned reasonably well in terms of mediating knowledge spillovers from universities to firms.

Our results also broadly support the notion that Japanese firms were increasingly benefiting from academic science over the course of the 1990s, even in advance of the implementation of a number of government policies explicitly designed to foster university-firm interaction. In that sense, our findings provide some support for the conclusion that interaction between universities and firms can take place, even without an extensive network of university-affiliated technology licensing offices and other formal institutions in Japan. However, our results suggest that American science has had a more significant impact than Japanese science, and this impact holds broadly across industries. We therefore need to consider how we might reconcile these two results.

To do so, we return again to the distinction we made at the beginning of the paper between the different kinds of university-industry interactions. We believe that much of the interaction reflected in Walsh and Cohen's survey responses may be "using scientists" rather than using science. It is clear from a number of related studies that, for the purposes of consulting on well-known engineering principles or "old science," firms prefer to interact with professors at geographically proximate universities.[47] It is obviously much cheaper to conduct this kind of interaction on a local basis. Furthermore, there is considerable anecdotal and historical evidence to suggest that this kind of interaction, much of it informal, has been important throughout postwar Japanese history.[48] We also know from other studies that this kind of interaction is important across a broad range of industries and academic disciplines, including those in which current technological trends are not closely related to recent developments in academic science. However, it is less clear that the survey evidence used by Walsh and Cohen reflects "using science."

Recent research on industry-university co-authorship patterns in Japan, and our data on scientific publications generated by firms, may help to provide a partial explanation for this discrepancy. Hicks (1993), Kobayashi (1998), and Pechter (2000, 2001) have all used publication and co-authorship data to understand the linkage between university science and industrial R&D in Japan. These authors tend to find that the patterns of co-authorship are highly concentrated in Japan. That is, industry-university co-authorships tend to take place overwhelmingly with local (that is, Japanese) universities rather than with foreign universities. At first glance, this finding, consistent

---

[47] See Mansfield and Lee (1996) and Adams (2001).

[48] See Kobayashi (2003).

across a number of studies, would seem to confirm the assertion made in Walsh and Cohen that university-industry knowledge spillovers are primarily an "intranational" phenomenon.

However, our interviews with Japanese R&D managers have raised questions about the extent to which the publications of Japanese industrial scientists and engineers can be viewed as an accurate indicator of the strategic technological activities of the firms for which they work. Firms, even in Japan, are in business to earn profits, not to contribute to the open science literature. It can be observed that there is considerable variation across firms, even within the same narrowly defined industries, concerning the degree to which their scientists publish in the open science literature. Thus, the degree to which publications reflect firms' strategic technological activity varies in important and complex ways from firm to firm. In our interviews, managers stressed that firms were quite sensitive to the possibility that premature publication of an important result would compromise their ability to patent the discovery. Therefore, the contents of publications were carefully screened, and publications were often delayed until after the patent had been granted.[49]

Managers also mentioned that research results that were not part of the firm's core technology strategy would often be deliberately published as a defensive mechanism. That is, information would be introduced into the public domain in order to make patenting by rivals in that area harder. There was also a sense in which firms had few qualms about publishing the results of more basic research that had little direct connection to product development, whereas basic research that was clearly viewed as

---

[49] Murray (2002) has also questioned the extent to which firm publication and firm-university co-publication functions as a useful indicator of university-industry interaction.

leading quickly to new products would be less likely to be published. This suggests, at the very least, an inexact correspondence between the scientific content of publications and the strategic inventions of the firm. Managers confirmed this, and strongly maintained that the technological content of their patents was much more reflective of the firm's important "core technologies" than was the scientific content of their papers.

On top of this are concerns raised by the traditional training practices of corporate researchers in Japan. Until quite recently, it was common for corporate researchers across a wide range of scientific and engineering disciplines to begin their formal employment after receiving a master's degree. It was only after several years of working for their company that they would be temporarily dispatched to a university research lab to earn a Ph.D. under the supervision of a sponsoring professor.[50] Japanese universities allowed such individuals to skip the general and specialized coursework associated with American Ph.D. programs and earn a Ph.D. simply by submitting a doctoral dissertation. During this period, the sponsoring firm would pay the salaries of their dispatched employees and provide some financial support for the professor. The mutual benefits from this arrangement were well understood by all participants. University professors in Japan received both funding and research assistance – resources that have been reasonably scarce in postwar Japan given the government's limited support of university science and the limited degree to which this government funding has been allocated on the basis of individual research productivity. Companies were able to expose their employees to the recent scientific literature and to modern laboratory techniques in a manner that would have been difficult to replicate within the firm. The dispatched

---

[50] Manager interviews suggest that employment practices in the pharmaceutical industry have changed recently, with an increasing preference in that industry to hire researchers that have already completed a formal Ph.D. program. On the other hand, the traditional practices appear to persist in electronics firms.

employees received both training and a credential that helped them advance within their organizations.

Not surprisingly, the lengthy association of corporate researchers with university scientists often generated a number of co-publications. However, it was clear from our interviews that many of these co-publications were more reflective of the research agenda of the sponsoring scientist than they were of the strategic technological activity of the sponsoring firm. From the point of view of the firms, the time their employees spent in these corporate labs was more a matter of their general training and development than it was a strategic partnering with local professors to produce core technology for the firm.

Given these concerns, it is perhaps not surprising to observe that the pattern of co-authorship for firms in our data set is quite different from the patterns in their patent citations to science. Table 5 provides some preliminary evidence on this point drawn from the distribution of co-authorships and patent citations to science for four leading Japanese high-technology firms. In this table, we aggregate data from publications co-authored between the firm and a university and publications co-authored between a firm and other institutions, including other private firms. However, the pattern in the data is essentially the same if we restrict our analysis to academic co-authorships. It can be seen clearly that researchers associated with Canon, Matsushita, Sankyo, and Takeda co-author overwhelmingly with other Japanese researchers. In fact, this treatment understates the degree to which co-authorship is concentrated in Japan because we consider here only cases in which authorship of the article involves at least one person from the firm and one other individual form outside the firm. The largest number of corporate publications for most of these companies are generated by teams of in-house researchers that do not include an external co-author.[51]

On the other hand, for each firm, the articles most frequently cited in patent documents are mostly foreign, and, in fact, mostly American. Naturally, we would like to believe that our analysis based on patent citations to science reflects "using science" more accurately than the publication data. That is, we would like to think that the geographic distribution of patent citations to science is broadly reflective of where the most influential original science is coming from.

We have found that interviews with R&D managers generally tend to support this view, in the following sense. The patterns we find in the data on patent citations to science tend to correspond closely to where managers think the most influential new scientific developments are coming from.[52] In fact, when we explained what we meant by the term "using science," the response was virtually universal that the source of this kind of knowledge spillover still tends to be disproportionately foreign (and disproportionately American) research universities.[53] This pattern of interview responses is consistent with other survey evidence suggesting that the preference for working with "local" universities is much weaker when firms are seeking to apply basic or recent science to their R&D activities.[54] On the other hand, firms acknowledged a strong preference for local universities when it came to "using scientists." As for collaborative implementation, R&D managers generally stressed that they tended to work with both

---

[51] A more comprehensive comparison of the patterns of co-authorship and the patterns generated by the patent citation to science data is the focus on ongoing research.

[52] That being said, a number of managers also noted that specialized patent attorneys and U.S. patent examiners also had an impact on the citations appearing in their patent documents, reinforcing the need to use caution in interpreting our data.

[53] This is also consistent with the interview-based evidence presented by Kneller (2003) regarding recent developments in the Japanese pharmaceutical industry.

[54] Again, see Mansfield and Lee (1996) and Adams (2001).

Japanese and foreign (especially American) universities. The degree of formal collaboration with Japanese universities has increased in the most recent years, in part due to government reforms and in part due to a changing mindset on the part of Japanese universities.

Another potential challenge to our results and their interpretation comes from the work of Tamada et. al. (2003a, 2003b), to which we have already referred in the text. In an impressive feat of data analysis, these researchers managed to combine electronic data on all patents published in Japan from 1995-1999 into a single electronic data base. The authors then obtained manageably small random samples of patents (about 300 patents) in four clusters of technology identified by Japan's recent science promotion policies as areas of priority for public support: biotechnology, nanotechnology, IT, and environmental technology. Given the very large number of IT-related patents in Japan, the authors limited themselves to essentially two IPC codes, acknowledging that these do not cover the full scope of patenting by Japanese IT firms.

Having identified these patents, the authors then identified all references to scientific articles on the "front page" *and* in the main text of the patent. They then made extensive efforts to identify the authors and institutional affiliations of the researchers cited in these patent documents. As they correctly note in their articles, the legal function played by patent citations under U.S. law may introduce noise, even bias, into the patterns of knowledge flow traced out by the citations to papers in these patents. Their data, which include the citations made in the claims of the patent, provide an alternative window into the connection between science and technology that is plausibly not contaminated by these institutional biases. On the other hand, the lack of a requirement to disclose prior art in Japan raises the possibility that the citations made in Japanese patent documents are incomplete.

Like us, Tamada et. al. (2003a, b) find that the number of patent references to scientific articles is much higher in "biotechnology" patents than in any other class. This strengthens our contention that the degree of science linkage implied by U.S. patent citations to science is not an artifact of U.S. PTO-enforced citations practices. Furthermore, regardless of the nationality of the inventor, Japanese patents tend to cite far more academic articles with U.S.-based authors than those of any other group. Thus, their research confirms the overwhelming importance of American science in this key technology category.

However in other high-technology fields, the relative impact of American science was much less pronounced. For instance, in nanotechnology, American articles were cited only slightly more frequently than Japanese articles. In the other two categories of technology, citations to Japanese articles significantly outnumbered citations to American ones. This finding contrasts sharply with our finding from U.S. data that American science tends to be more frequently cited across multiple categories of technology. Why does this discrepancy exist?

Clearly, it is possible that the citations found in U.S. patent documents of Japanese firms reflect the influence of American patent attorneys and patent examiners. That is, citations are added by parties other than the inventor, and these added citations tend to be disproportionately American. This could exaggerate the role American science plays in the R&D of Japanese firms. On the other hand, our own discussions with American patent attorneys suggest that, while patent attorneys may add citations to patents unknown to the inventor, they are much less likely to add citations to the academic literature, because they are often less knowledgeable about the scientific literature than the inventor. Perhaps more to the point, when we asked Japanese R&D managers, even those outside of the pharmaceutical industry, where the scientific ideas that have the most impact on their research come from, the universal response was that American universities and American scientists were disproportionately more important. This does not necessarily mean that our data are more accurate, but they do seem to be consistent with managers' perceptions regarding "using science."

This leads us to consider another potential explanation for the discrepancy between our findings and those of Dr. Tamada and his collaborators: the samples of patents used are quite different. As we noted earlier in our reference to the data displayed in Figure 3, Japanese firms, particularly those in the electronics industry, generate large numbers of patents that the firms themselves do not consider sufficiently valuable to apply for patent protection overseas. That figure suggests that, out of a randomly drawn sample of 100 patents, only 16 will be considered novel or valuable enough to be patented overseas. To the extent that truly novel and commercially valuable innovations are under-represented in the random samples used by Tamada et. al. (2003, 2003), the true impact of American science on this kind of more fundamental Japanese invention may be similarly underestimated. A better test would be to compare the citation patterns found in the U.S. and Japanese versions of patents selected by the firms to be protected overseas, as well as in Japan.

X. Conclusions and Policy Implications

In this paper, we have sought to obtain a better understanding of the changing linkage between "science," particularly frontier academic research conducted at universities in Japan and elsewhere, and the efforts by Japanese firms to create commercially useful new technology. We began this study with the observation that firms interact with universities in many different kinds of ways, and we frankly acknowledged that our empirical approach will only capture some of these modes of interaction. To briefly summarize our discussion of this point, we categorized university-industry research interaction into four types: the use of relatively new, "breakthrough" science in early-stage basic industrial R&D ("using science"), the use of predominantly local professors in order to obtain advice concerning the routine or incremental application of well-established engineering principles or "old science," ("using scientists"), formal collaboration with university professors to apply new science to industrial products or processes ("collaborative implementation"), and the licensing of university inventions.

We observed that the latter category has been limited in its importance in Japan, even today. Furthermore, according to some measures, formal collaborative implementation with Japanese universities remains at a limited level.[55] It is widely acknowledged that a long tradition exists in Japan, albeit a largely informal one, of firms "using scientists" in their incremental innovations. However, this mode of interaction may be insufficient for firms in globally competitive high-tech industries seeking to compete with rivals in Europe, the U.S., and elsewhere in Asia through the development of fundamentally new products or processes. Some of the difficulties Japanese firms in

---

[55] Official government statistics suggest a level of industrial support in Japan that is lower than that in the U.S. Some of this evidence is discussed in Walsh and Cohen (2004).

industries like electronics or pharmaceuticals have encountered over the course of the 1990s have been attributed to insufficiently strong linkages between universities and firms, limiting the effectiveness of their "use of science" in industrial invention.

To investigate this situation empirically, we have constructed an original data base that captures in an unusually rich way the technological activities of more than 300 of Japan's most important technology intensive firms and the interaction between this technological development and scientific research. In particular, we aimed to construct a data base that could measure, at least to some extent, "using science." At the core of our data base is a complete set of citations linking the U.S. patents of our sample of Japanese firms with the scientific articles cited in these patents. In principle, these patent citations to science can provide us with a useful measure of the linkage between science and technology at a highly disaggregated level. Along with the data on patent citations to science, we include firm-level data on R&D spending, output, conventional inputs such as capital and labor, measures of the firm's network of research subsidiaries in the United States, and measures of the firm's network of research alliances, broadly defined, with U.S. firms and research institutions.

Econometric analyses of these data suggests that, like American firms in technology-intensive industries, Japanese firms seem to have changed their approach to R&D in a way that is more connected to recent developments in academic science. The beginnings of this shift in the nature of R&D are evident in the mid-to-late 1980s, but it seems to have continued through much of the 1990s. Interestingly, the shift began long before the implementation of many measures in Japan designed to promote "sangaku renkei" vis-à-vis Japanese institutions. As in America, this change has been most dramatic in the pharmaceutical industry. In striking contrast to some of the more pessimistic assessments of the state of university-industry interaction in Japan, we find evidence of an increasingly strong linkage between Japanese technology and science, broadly defined. Analysis of individual citation data reveals that this science tends to be quite recent in origin.

Much of this science also originates outside Japan, with a significantly large portion of cited articles having their origins in the United States. While the measured impact of U.S. science could be, in part, a reflection of measurement error or even bias in the patent citation data used, other recent studies referred to in the body of the paper and the opinions of interviewed Japanese R&D managers themselves suggest that this finding has a basis in reality, and that is particularly true in more "science-driven" fields such as biotechnology. Because much of the pathbreaking science occurs outside Japan, the strategic use of this science requires firms to forge close connections to foreign science centers.

Our econometric analysis reveals a connection between these efforts, undertaken at the firm level, and the number of science citations appearing in firm patents. The good news for Japan is that neither the alleged weaknesses of Japanese university science nor the alleged barriers to interaction between Japanese universities and Japanese firms have fully prevented Japanese multinationals from exploiting the opportunities for "using science." Japanese R&D managers expect that, for the foreseeable future, foreign institutions will continue to be an important source of breakthrough science, and their firms continue to make the necessary investments required to tap this knowledge. Clearly, these investments require a certain scale of operations in order to be feasible. The relative difficulty small firms in Japan face in tapping distant sources of scientific knowledge is one of many factors likely to hinder the growth of Japanese "high-tech" venture firms for some time to come. A public policy implication grows out of this reality: it may be counterproductive for the Japanese government to seek to promote ties with local universities at the expense of firms' existing ties with foreign universities.

Econometric analysis at the firm level reveals a surprisingly strong and robust connection between the "use of science" in firm invention, as measured by our patent citation data, and research productivity. We measure this impact in two ways using two different measures of inventive outcomes: citation-adjusted patent counts and total factor productivity (TFP). We find that increases in the propensity to cite science lead to increases in both quality-adjusted patenting and TFP. While the estimated coefficients are not so large, the implied impact of changes in "use of science" on innovative output is quite substantial. The existence of this linkage between science citation measures and research outcomes helps validate our use of these data as measures of "using science."

Because we also possess data on the scientific publications of a large fraction of our sample firms, we have also presented a limited comparison of the patterns suggested by co-authorship. It is evident that these patterns are quite different from the patterns generated by patent-to-article citation data. We have argued in the text that publications in general, and publications co-authored with Japanese university professor in particular, may be substantially less reflective of leading firms' strategic R&D activities than some of the recent literature has presumed. Further analysis of publication data is the subject of ongoing research.

Although Japanese R&D managers noted the importance of foreign science, they also pointed to an increasing level of interaction between Japanese firms and Japanese universities. While in the past, much of this interaction occurred in an informal way, our interviewees have consistently stressed that this has changed dramatically over the last five years. Unfortunately, these changes are unlikely to be fully captured in the data used in this paper. Interaction between Japanese industry and Japanese universities has become more formal, and these more formal kinds of interaction, such as formal contract research and formal collaboration through a joint research center, are now considered relatively more important than the more traditional informal modes of interaction that were prominent in the past. While this kind of formal "collaborative implementation" is less expensive when pursued with local universities, managerial interviews and government statistics make clear that Japanese firms also undertake these collaborative partnerships with foreign institutions.

That being said, few interviewees thought that university patents and formal licensing contracts associated with those patents were a particularly important channel of technology transfer from domestic universities, and this was an important channel of technology transfer from foreign universities only in a limited number of cases. Our empirical results provide indirect support for this position, as they indicate that the increasing linkage between science and industrial technology considerably preceded growth in formal university patenting or licensing in Japan. In fact, there was a view that, although the number of patents generated by universities is increasing, relatively few of these patents actually protect valuable technology. It is not clear that the recent government focus on the promotion of university patenting and licensing will act as a major stimulus to the degree of interaction between universities and industries in Japan.

In addition, few interviewees thought that university-affiliated start-ups in Japan were currently an important channel of knowledge transfer. There were exceptions to this general rule, but most interviewees were skeptical that small Japanese biotech companies or start-ups in other sectors would make a major contribution to the industrial application of new science in the near future. Concerns voiced by the interviewees on this score are echoed in other recent studies.[56] It is not clear that setting a target for the number of gakuhatsu ventures, without regard to the quality of the technology they possess, is the right public policy. Again, our empirical results provide some indirect support for this skeptical position. We find a reasonably strong and robust relationship between "using science" and firm size. The increase in firm connection to science we measure in our data is not plausibly connected to the growth of Japanese high-tech startups, and they seem to play little role in mediating the flow of new scientific knowledge to industrial R&D over our sample period.[57]

We conclude with the same observation we made at the beginning. There are many different kinds of sangaku renkei. Tracking them requires the use of different measurement techniques. We believe that the evidence provided in this paper suggests that patent citations to papers may provide a relatively good measure of "using science." They probably do not do a very good job of measuring "using scientists," and they may only partly reflect collaborative implementation. To get a full picture of how Japanese firms are interacting with universities in Japan and outside Japan, we need to use a

---

[56] See the interview-based evidence presented by Kneller (2003).

[57] On the other hand, Kneller (2003) provides evidence that *American* biotech start-ups have functioned as important strategic partners for Japanese pharmaceutical firms.

variety of empirical approaches that capture all of these dimensions of sangaku renkei. That kind of comprehensive data building project is beyond the scope of this paper. However, we can point to efforts by a number of Japanese scholars, including Professor Akira Goto of the University of Tokyo, Professors Sadao Nagaoka and Yosuke Okada of Hitotsubashi University, and Dr. Schumpeter Tamada of RIETI, to create precisely this kind of multidimensional approach to the study of sangaku renkei in Japan. We hope that the results presented herein provide a modest contribution to this larger effort.

Bibliography

Adams, James, 1990, "Fundamental Stocks of Knowledge and Productivity Growth," *Journal of Political Economy* 98: 673-702.

Adams, James, 2001, "Comparative Localization of Academic and Industrial spillovers," *Journal of Economic Geography* 2: 253-278.

Adams, James and Zvi Griliches, 1998, "Research Productivity in a System of Universities," *Annales d'Economie et de Statistique* 49/50, pp. 127-162.

Agrawal, Ajay, 2001, "Research on University-to-Industry Knowledge Transfer: Framework of Existing Literature and Future Questions," *International Journal of Management Reviews*.

Agrawal, Ajay and Iain Cockburn, 2003, "The Anchor Tenant Hypotheses: Exploring the Role of Large, Local, R&D-Intensive Firms in Regional Innovation Systems," forthcoming in the *International Journal of Industrial Organization*.

Agrawal, Ajay and Rebecca Henderson, 2002, "Putting Patents in Context: Exploring Knowledge Transfer from MIT," *Management Science*, Vol. 48, No. 1.

Arison, T., C. Fred Bergsten, E. Graham, and M. C. Harris (eds.), 1992, *Japan's Growing Technological Capability: Implications for the U.S. Economy*, Washington, D.C.: National Academy Press.

Arora, Ashish and Alfonso Gambardella, 1990, "Complementarity and External Linkages: the Strategies of the Large Firms in Biotechnology," *Journal of Industrial Economics*, Vol. 38, pp. 361-379.

Arora, Ashish and Alfonso Gambardella, 1994, "The Changing Technology of Technological Change: General and Abstract Knowledge and the Division of Innovative Labor," *Research Policy*, Vol. 23, pp. 523-532.

Arora, Ashish, Andrea Fosfuri, and Alfonso Gambardella, 2001, *Markets for Technology: The Economics of Innovation and Corporate Strategy*, MIT Press.

Audretsch, David and Paula Stephan, 1996, "Company-Scientist Locational Links: The Case of Biotechnology," *American Economic Review*, Vol. 86, No. 3.

Barnes, Michael, David Mowery, Arvids Ziedonis, 1998, "The Geographic Reach of Market and Nonmarket Channels of Technology Transfer: Comparing Citations and Licenses of University Patents," working paper.

Bessen, James and Robert Hunt, 2003, "An Empirical Look at Software Patents," unpublished working paper.

Branstetter, Lee (2000a), "Is Foreign Direct Investment a Channel of Knowledge Spillovers? Evidence from Japan's FDI in the United States," NBER WP no. 8015.

Branstetter, Lee, 2003, "Exploring the Link Between Academic Science and Industrial Innovation," unpublished working paper.

Branstetter, Lee and Yoshiaki Nakamura, 2003, "Has Japan's National Innovative Capacity Declined?" in A. Kashyap, J. Corbett, M. Blomstrom, and F. Hayashi, (eds.), *Structural Impediments to Growth in Japan*, 2003, University of Chicago Press and NBER.

Cockburn, Iain and Rebecca Henderson, 1998, "The Organization of Research in Drug Discovery,"*Journal of Industrial Economics*, Vol XLVI, No. 2.

Cockburn, Iain and Rebecca Henderson, 2000, "Publicly Funded Science and the Productivity of the Pharmaceutical Industry," paper prepared for the NBER Conference on Science and Public Policy.

Cockburn, Iain, Rebecca Henderson, and Scott Stern, 1999, "The Diffusion of Science Driven Drug Discovery: Organizational Change in Pharmaceutical Research," NBER Working Paper No. 7359.

Cohen, Wesley, Richard Florida, Louis Randazzese, and John Walsh, 1998, "Industry and the Academy: Uneasy Partners in the Cause of Technological Advance," in R. Noll, ed., *Challenges to the Research University*. Washington, D.C.: Brookings Institution

Cohen, Wesley and Daniel Levinthal, 1989, "Innovation and Learning: The Two Faces of R&D," *Economic Journal*, no. 99, pp. 569-596.

Darby, Michael and Lynne Zucker, 2003, "Grilichesian Breakthroughs: Inventions of Methods of Inventing and Firm Entry in Nanotechnology," NBER working paper. 9825.

DeLong, J. Bradford, 2001, "Do We Have a 'New' Macroeconomy?," *Innovation Policy and the Economy,* Vol. 2, MIT Press.

Evenson, Robert and Yoav Kislev, 1976, "A Stochastic Model of Applied Research," *Journal of Political Economy*, Vol. 84, pp. 265-282.

Faulkner, Wendy and Jennifer Senker, 1995, *Knowledge Frontiers: Public Sector Research and Industrial Innovation in Biotechnology, Engineering Ceramics, and Parallel Computing*, Oxford: Clarendon Press.

Fleming, Lee and Olav Sorenson, 2001, "Science as a Map in Technological Search," working paper.

Gambardella, Alfonso, 1995, *Science and Innovation: The U.S. Pharmaceutical Industry during the 1980s*, Cambridge: Cambridge University Press.

Gomes-Casseres, Benjamin, Adam Jaffe, and John Hagedoorn, (2003), "Do Alliances Promote Knowledge Flows?" working paper.

Gordon, Robert J., 2000, "Does the 'New Economy' Measure up to the Great Inventions of the Past?" NBER Working Paper no. 7833.

Gordon, Robert J., 2002, "Technology and Economic Performance in the American Economy," NBER Working Paper no. 8771.

Goto, Akira, 1993, *Nihon no Gijutsu Kakushin to Sangyou Soshiki*, Tokyo: University of Tokyo Press.

Goto, Akira, 2000a, "Japan's National Innovation System: Current Status and Problems," *Oxford Review of Economic Policy*, vol. 16, pp. 103-113.

Goto, Akira, 2000b, *Innovation and the Japanese Economy* (in Japanese), Iwanami Press, Tokyo.

Goto, Akira and Hiroyuki Odagiri, (eds.), 2003, *Science-Based Industries* (in Japanese), NTT Publishing Company, Tokyo.

Harhoff, Dietmar, Francis Narin, F. M. Scherer, and Katrina Vopel, 1999, "Citation Frequency and the Value of Patented Inventions," *Review of Economics and Statistics*, August 1999, pp. 511-515.

Hausman, Jerry, Bronwyn Hall, and Zvi Griliches (1984), "Econometric Models for Count Data with an Application to the Patents-R&D Relationship," *Econometrica*, Vol. 52 (4), pp. 909-938.

Henderson, Rebecca and Iain Cockburn, 1996, "Scale, Scope, and Spillovers: the Determinants of Research Productivity in Drug Discovery," *Rand Journal of Economics* 27, pp. 32-59.

Henderson, Rebecca, Adam B. Jaffe, and Manuel Trajtenberg, 1998, "Universities as a Source of Commercial Technology: A Detailed Analysis of University Patenting, 1965-1988," *Review of Economics and Statistics*, 119-127.

Hicks, Diana, 1993, "University-Industry Research Links in Japan," *Policy Sciences*, vol. 26, pp. 361-395.

Hicks, Diana, Tony Breitzman, Dominic Olivastro, and Kim Hamilton, 2001, "The Changing Composition of Innovative Activity in the US – A Portrait Based on Patent Analysis," *Research Policy* 30, pp. 681-703.

Iwasa, Tomoko and Hiroyuki Odagiri (2002), "The Role of Overseas R&D Activities in Technological Knowledge Sourcing: An Empirical Study of Japanese R&D Investment in the U.S.," Discussion Paper no. 23, National Institute of Science and Technology Policy (NISTEP).

Jaffe, Adam, 1989, "The Real Effects of Academic Research," *American Economic Review*, 79 [5], pp. 957-70

Jaffe, Adam, Manuel Trajtenberg, and Rebecca Henderson, 1993, "Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations," *Quarterly Journal of Economics,* Vol. CVIII, No. 3.

Jaffe, Adam and Manuel Trajtenberg, 2002, *Patents, Citations, and Innovations: A Window on the Knowledge Economy*, MIT Press.

Jaffe, Adam and Manuel Trajtenberg, 1996, "Flows of Knowledge from Universities and Federal Labs: Modeling the Flow of Patent Citations over Time and across Institutional and Geographic Boundaries," NBER working paper no. 5712.

Jaffe, Adam, Michael Fogarty, and Bruce Banks, [1998], "Evidence from Patents and Patent Citations on the Impact of NASA and Other Federal Labs on Commercial Innovation," *Journal of Industrial Economics*, Vol. XLVI, No. 2.

Japan Patent Office, 2003, *Patent Administration Annual Report* (in Japanese), Hatsumei Kyoukai, Tokyo.

Jensen, Richard and Marie Thursby, 1999, "Proofs and Prototypes for Sale: The Licensing of University Inventions," *American Economic Review,* 91, pp. 240-259.

Kenney, Martin, 1986, *Biotechnology: The University-Industrial Complex*, New Haven: Yale University Press.

Kneller, Robert, 2003, "Autarkic Drug Discovery in Japanese Pharmaceutical Companies: Insights into National Differences in Industrial Innovation," *Research Policy* 32: pp. 1805-1827.

Kobayashi, Shin-Ichi, 1998, "The Current Stage of the Industry-University Relationship," (in Japanese), *Kotou Kyoiku Kenkyuu Kiyou*, Vol. 16, p. 107.

Kobayashi, Shin-Ichi, 2003, "Science-based Industries and Universities, University-Industry Linkages, and Spin-offs," (in Japanese), in Goto, Akira and Hiroyuki Odagiri, (eds.), 2003, *Science-Based Industries* (in Japanese), NTT Publishing Company, Tokyo.

Kortum, Samuel, 1997, "Research, Patenting, and Technological Change," *Econometrica*, Vol. 65, pp. 1389-1419.

Kortum, Samuel and Joshua Lerner, 1998, "Stronger Protection or Technological Revolution: Which is Behind the Recent Surge in Patenting?" *Carnegie-Rochester Conference Series on Public Policy*, 48, pp. 247-304.

Kortum, Samuel and Joshua Lerner, 2000, "Assessing the Contribution of Venture Capital to Innovation," *Rand Journal of Economics*, 31, pp. 674-692.

Kortum, Samuel and Joshua Lerner, 2003, "Unraveling the Patent Paradox," unpublished working paper.

Lach, Saul and Mark Schankerman, 2003, "Incentives and Invention in Universities," unpublished working paper.

Lerner, Joshua and Paul Gompers, 1999, *The Venture Capital Cycle*, MIT Press, Cambridge.

Lerner, Joshua and Paul Gompers, 2001, *The Money of Invention*, Harvard Business School Press, Boston.

Lerner, Joshua and Paul Gompers, 2002, "Short-Term America Revisited? Boom and Bust in the Venture Capital Industry and the Impact on Innovation," *Innovation Policy and the Economy*, 3 pp. 1-27.

Lieberman, Marvin, 1978, "A Literature Citation Study of Science-Technology Coupling in Electronics," *Proceedings of the IEEE*, 36 [1], pp. 5-13.

Lim, Kwanghui, 2001, "The Relationship between Research and Innovation in the Semiconductor and Pharmaceutical Industries," working paper.

Mansfield, E., 1988, "Industrial R&D in Japan and the United States: A Comparative Study," *American Economic Review Papers and Proceedings*, vol. 78, no. 2. pp. 223-228.

Mansfield, Edwin, 1995, "Academic Research Underlying Industrial Innovations: Sources, Characteristics, and Financing," *The Review of Economics and Statistics* 77: 55-65.

Mansfield, Edwin and J. Y. Lee, 1996, "The Modern University: Contributor to Industrial Innovation and Recipient of Industrial Support," *Research Policy* 25: pp. 1047-1058.

Marquis, D. G. and T. Allen, 1966, "Communication patterns in Applied Technology," *American Psychologist*, 21, pp. 1052-1060.

Motohashi, Kazuyuki, 2001, "Survey on Japan's National Innovation System," (in Japanese) in "Report on Japanese National Innovation System Research, RIETI, Tokyo, Japan.

Motohashi, Kazuyuki, 2004, "Economic Analysis of University-Industry Collaboration: The Role of New Technology Based Firms in Japanese National Innovation Reform," working paper.

Mowery, David, Richard Nelson, Bhavin Sampat, and Arivds Ziedonis, 1998, "The Effects of the Bayh-Dole Act on U.S. University Research and Technology Transfer: An Analysis of Data from Columbia University, the University of California, and Stanford University," working paper

Murray, Fiona, 2002, "Innovation as Overlapping Scientific and Technological Trajectories: Exploring Tissue Engineering," *Research Policy*, vol. 31.

Murray, Fiona and Sarah Kaplan, 2001, "The Role of Social Evidence in Shaping a Technological Discontinuity: The Evolution of Biotechnology," unpublished working paper.

Nagaoka, Sadao, 2004, "Evaluating R&D Management of Firms Using Patent Citations," working paper.

Narin, Francis, Kimberly Hamilton, and Dominic Olivastro, 1997, "The Increasing Linkage Between U.S. Technology and Public Science," *Research Policy* 197: 101-121.

National Academy of Engineering, 1987, *Strengthening U.S. Engineering through International*

Cooperation: Some Recommendations for Action, Washington, D.C. : National Academy Press.

National Science Foundation, 2002, *National Science and Engineering Indicators*.

Odagiri, Hiroyuki, 1999, "University-Industry Collaboration in Japan: Facts and Interpretations," in L. Branscomb, F. Kodama, and R. Florida, (eds.), *Industrializing Knowledge: University-Industry Linkages in Japan and the United States*, MIT Press, Cambridge, MA, pp. 269-306.

Odagiri, Hiroyuki, 2001, "Transactions Costs and Capabilities as Determinants of the R&D Boundaries of the Firm: A Case Study of the Ten Largest Pharmaceutical Firms in Japan," Discussion Paper no. 19, NISTEP and MEXT.

Office of Technology Transfer, University of California, 1997, Annual Report: University of California Technology Transfer Program. Oakland, CA: University of California.

Okada, Yosuke, 2002, "Technological Position, Cooperative Research, and Patenting Activity of the Japanese Biotechnology New Firms," working paper.

Okimoto, Daniel and Gary Saxonhouse, 1987, "Technology and the Future of the Economy" in *The Political Economy of Japan, Volume 1: The Domestic Transformation*, K. Yamamura and Y. Yasuba (eds.), Stanford, CA: Stanford University Press.

Pechter, Kenneth, 2000, "Empirical Support for Significant University-Industry Linkage in Japan," Management in the 21st Century, Proceedings of the 2000 IEEE International Conference on Management of Information and Technology, Singapore.

Pechter, Kenneth, 2001. "Comparative Policy Analysis Under Conditions of Innovation-Driven Change: Assessment of the University-Industry Linkage in Japan and the United States," Change Management and the New Industrial Revolution, Proceedings of the 2001 IEEE Engineering Management Society International Engineering Management Conference, Albany, NY.

Posen, A., 1998, *Restoring Japan's Economic Growth*, Washington, D.C.: Institute for International Economics.

Price, Derek, 1965, "Is Technology Historically Independent of Science? A Study in Statistical Historiography," *Technology and Culture*, 6, pp. 553-568.

Rosenberg, Nathan and Richard Nelson, 1994, "American Universities and Technical Advance in Industry," *Research Policy*, 23, pp. 323-348.

Sakakibara, Mariko and Lee Branstetter, 2001, "Do Stronger Patents Induce More Innovation? Evidence from the Japanese 1988 Patent Reforms," *RAND Journal of Economics*, vol. 32, no. 1, pp. 77-100.

Schmookler, Jacob, 1966, *Invention and Economic Growth*, Cambridge, MA: Harvard University Press.

Shane, Scott, 2000, "Prior Knowledge and the Discovery of Entrepreneurial Opportunities," *Organization Science*, 11, pp. 448-469.

Shane, Scott, 2001, "Technological Opportunities and New Firm Creation," *Management Science*, 47, pp. 205-220.

Sherwin, C. W. and R. S. Isenson, 1967, "Project Hindsight," *Science*, 156, pp. 1571-1577.

Sorenson, Olav and Lee Fleming, 2001, "Science and the Diffusion of Knowledge," working paper.

Stephan, Paula, 1996, "The Economics of Science," *Journal of Economic Literature* 34: 1199-1235.

Stern, Scott, 1999, "Do Scientists Pay to Be Scientists?" NBER Working Paper No. 7410.

Tamada, Schumpeter, Fumio Kodama, and Kiminori Genba, 2003a, "The Measurement of Science Linkage in Four Important Technology Areas" (in Japanese), RIETI Discussion Paper 03-J-016.

Tamada, Schumpeter, Fumio Kodama, and Kiminori Genba, 2003b, "The Sources of Patented Knowledge" (in Japanese), RIETI Discussion Paper, 03-J-017.

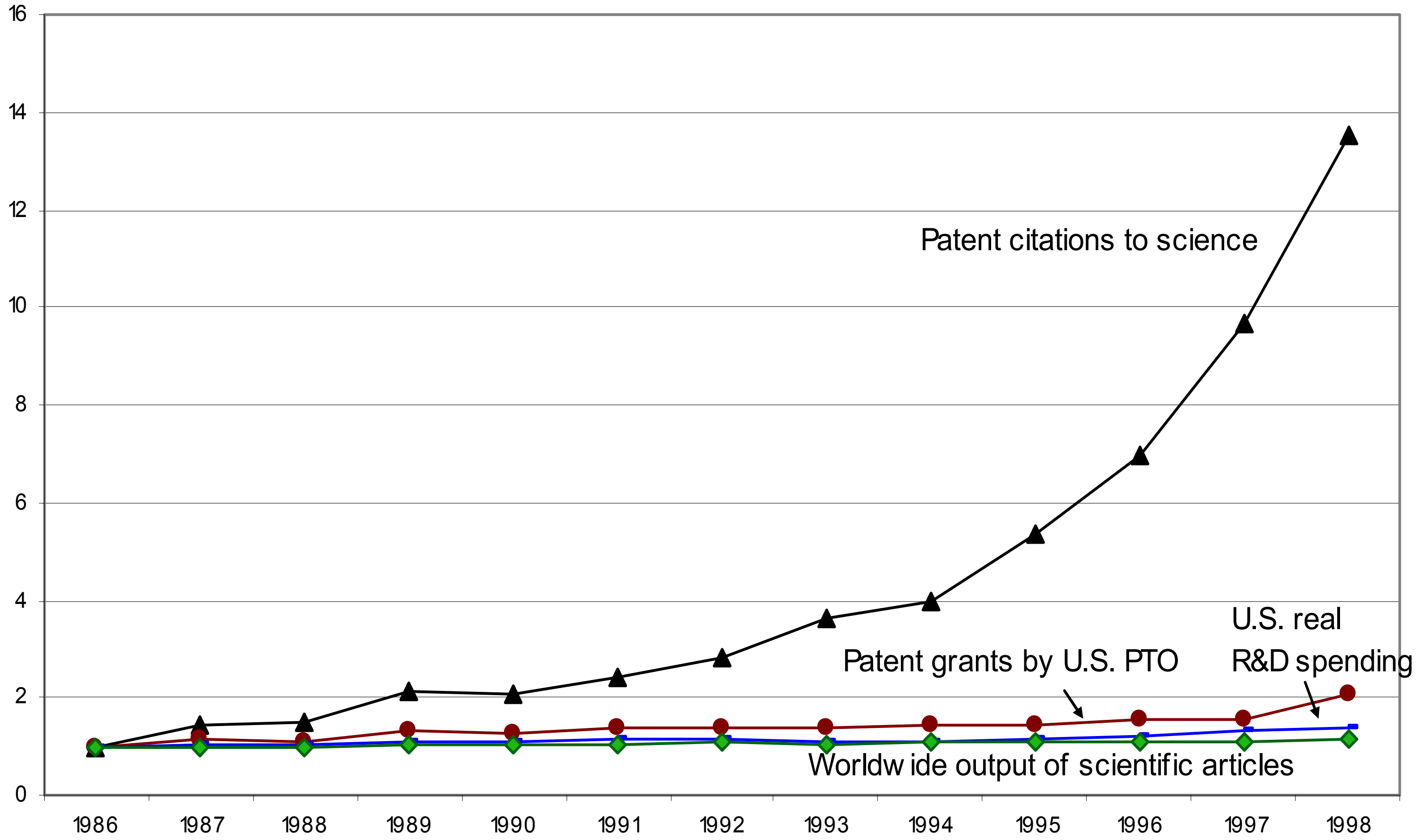
Thursby, Jerry and Marie Thursby, 2002, "Who is Selling the Ivory Tower? Sources of Growth in University Licensing," *Management Science*, 48, pp. 90-104.

Walsh, John and Wesley Cohen, 2004, "Does the Golden Goose Travel? A Comparative Analysis of the Influence of Public Research on Industrial R&D in the U.S. and Japan," working paper.

Zucker, Lynne, Michael Darby, and Michael Brewer, 1998, "Intellectual Capital and the Birth of U.S. Biotechnology Enterprises," *American Economic Review*, 88: 290-306.

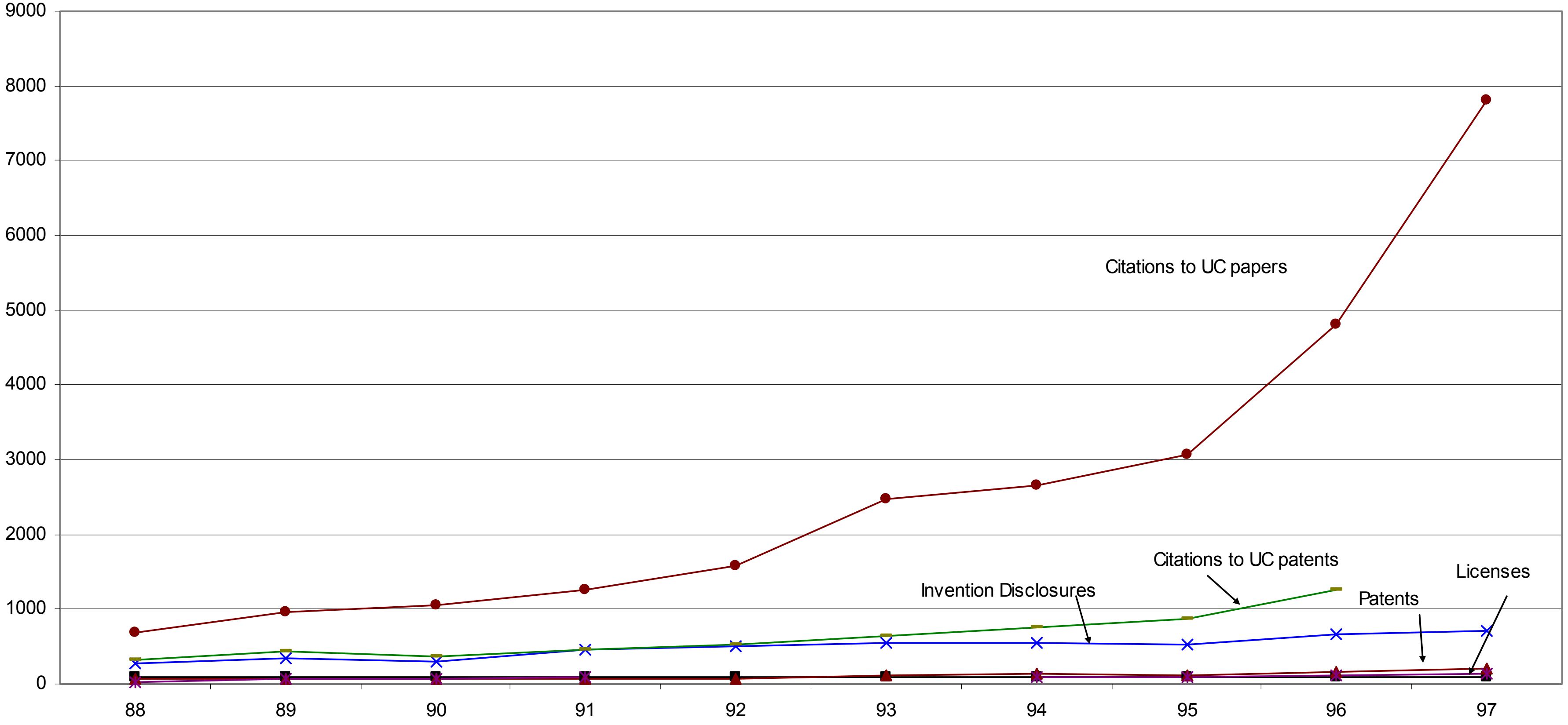
Figure 1 Patent Citations to Academic Science

Series are scaled so that 1986 values are equal to 1



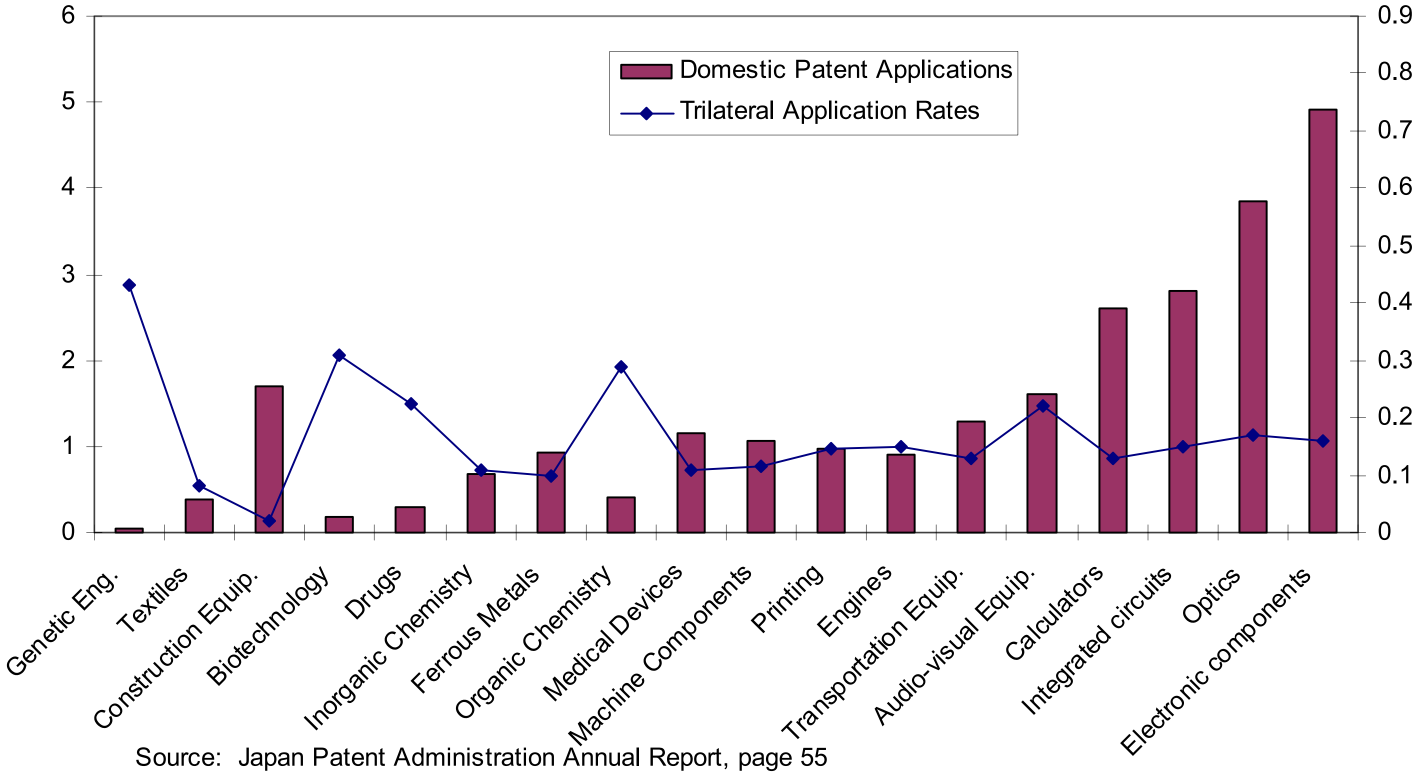
Source: *U.S. National Science and Engineering Indicators*, 2002

Figure 2 Citations to UC papers vs other indicators



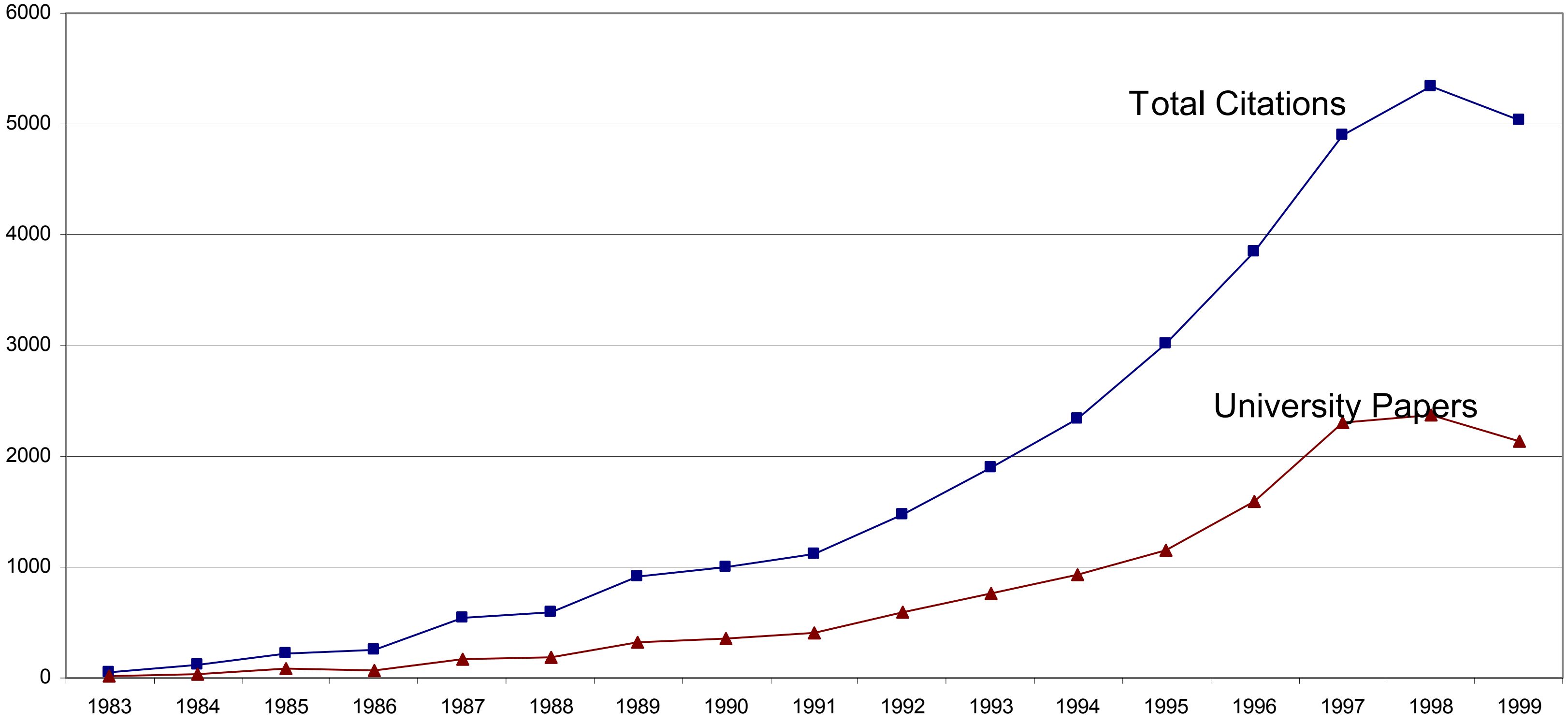
Source: University of California, AUTM survey, NBER Patent Citation Database, and authors' calculations

Figure 3 Japan's International Patent Application Percentage by Technology Class



Source: Japan Patent Administration Annual Report, page 55

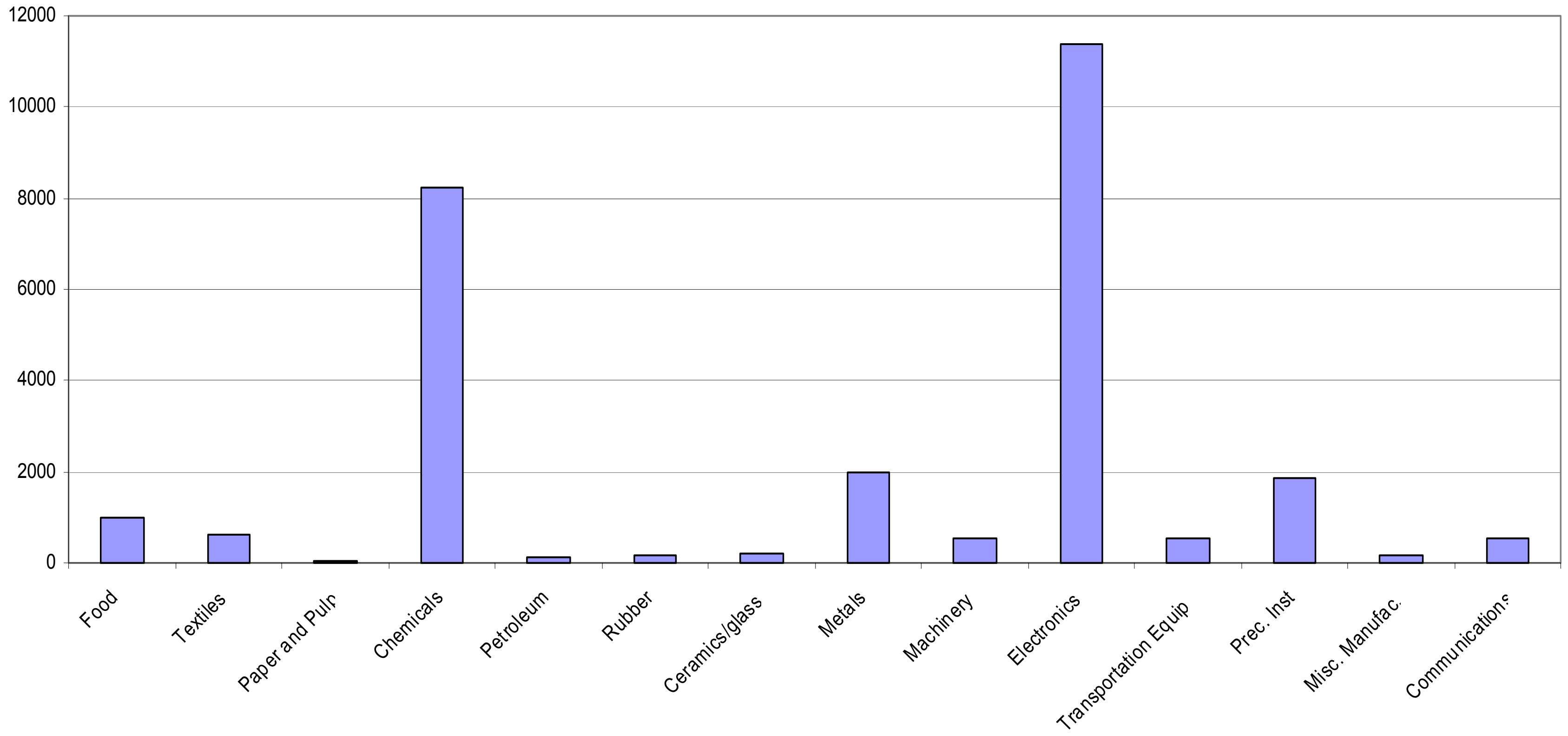
Figure 4 Growth in Japanese Patent Citations to Science



Source: Authors' calculations based on sample firm data

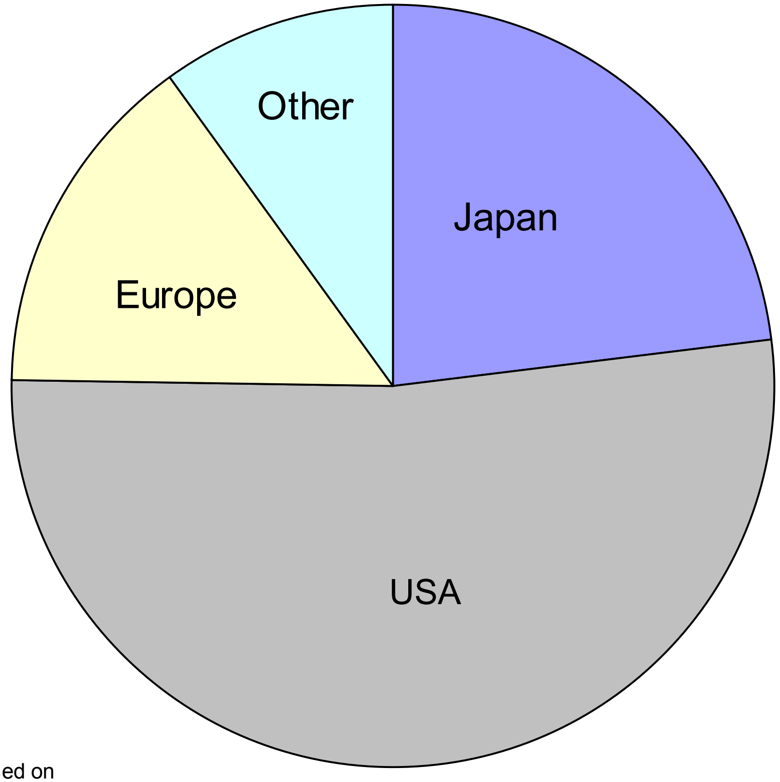
.

Figure 5   Distribution of Citations by Industry



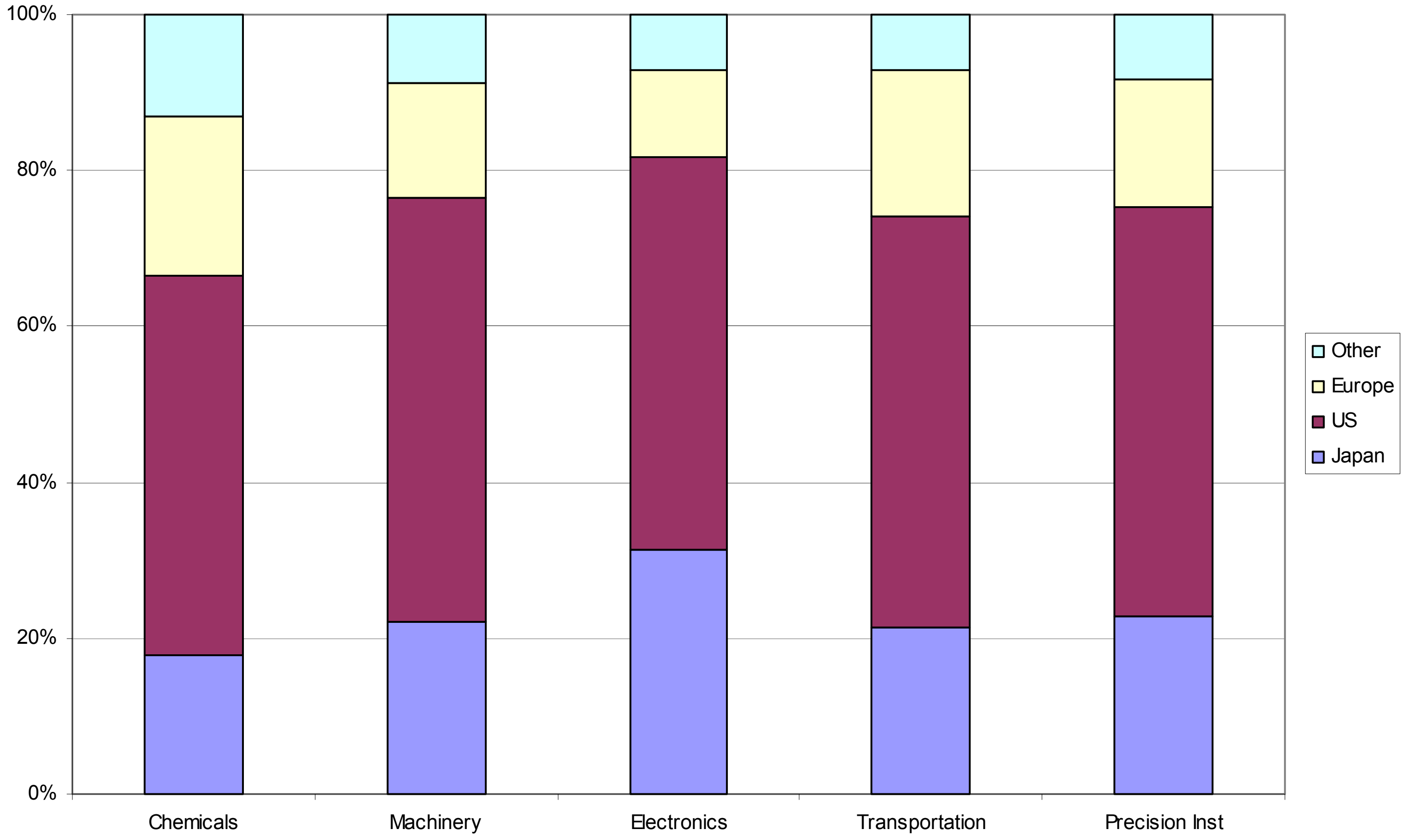
Source: Authors' calculations based on sample firm data

Figure 6 Geographic Distribution of Cited Authors



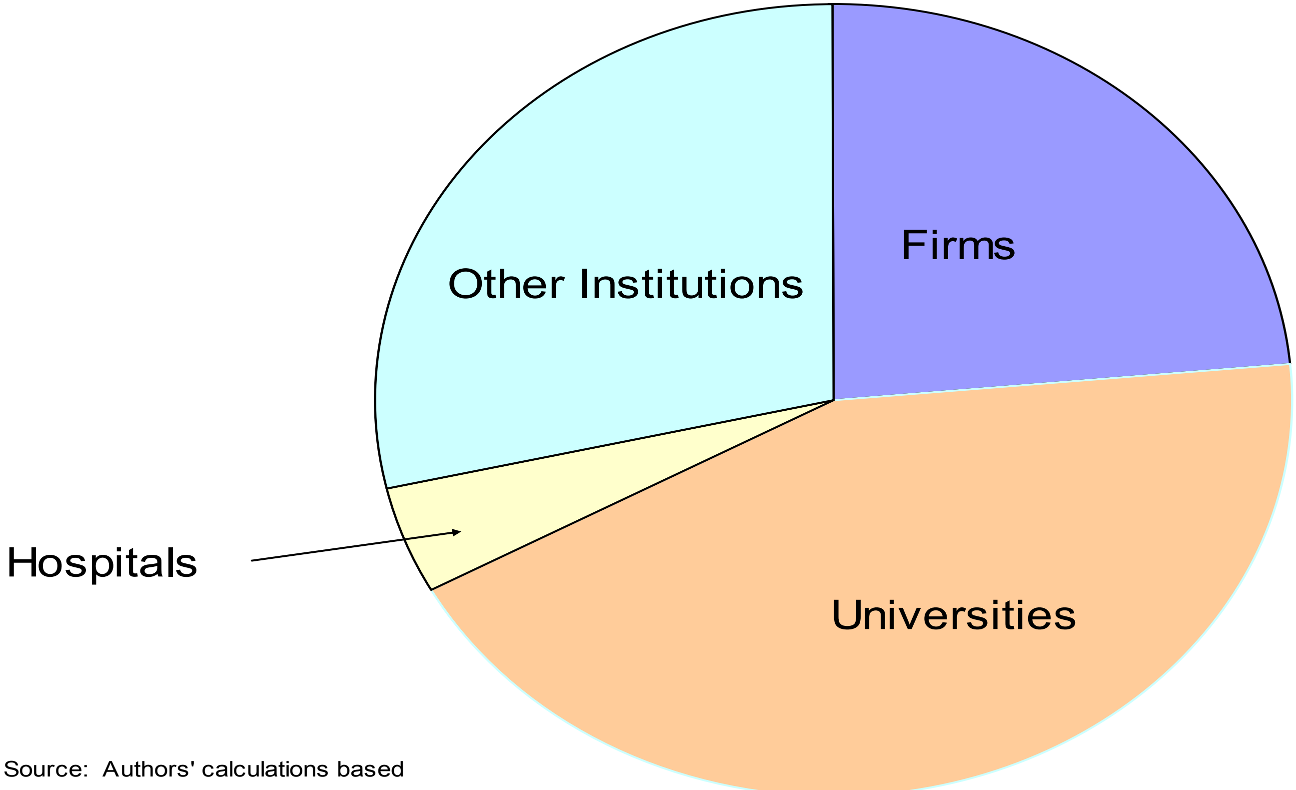
Source: Authors' calculations based on
sample firm data

Figure 7 Distribution of Cited Institutions by Industry and Nationality



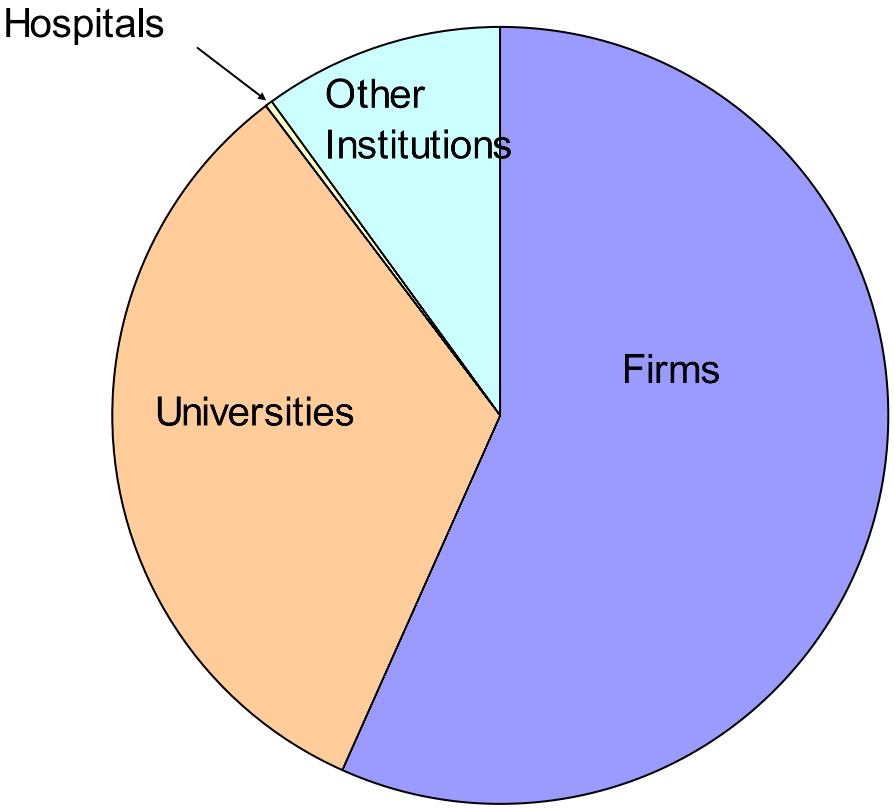
Source: Authors' calculations based on sample firm data

Figure 8 Distribution of Citations by Institution Type



Source: Authors' calculations based on sample firm data

Figure 9 Distribution of Japanese Citations by Institution Type



Source: Authors' calculations based on sample firm data

Figure 10 Distribution of Lags Between Paper Publication and Patent Application

Source: Authors' calculations based on sample firm data

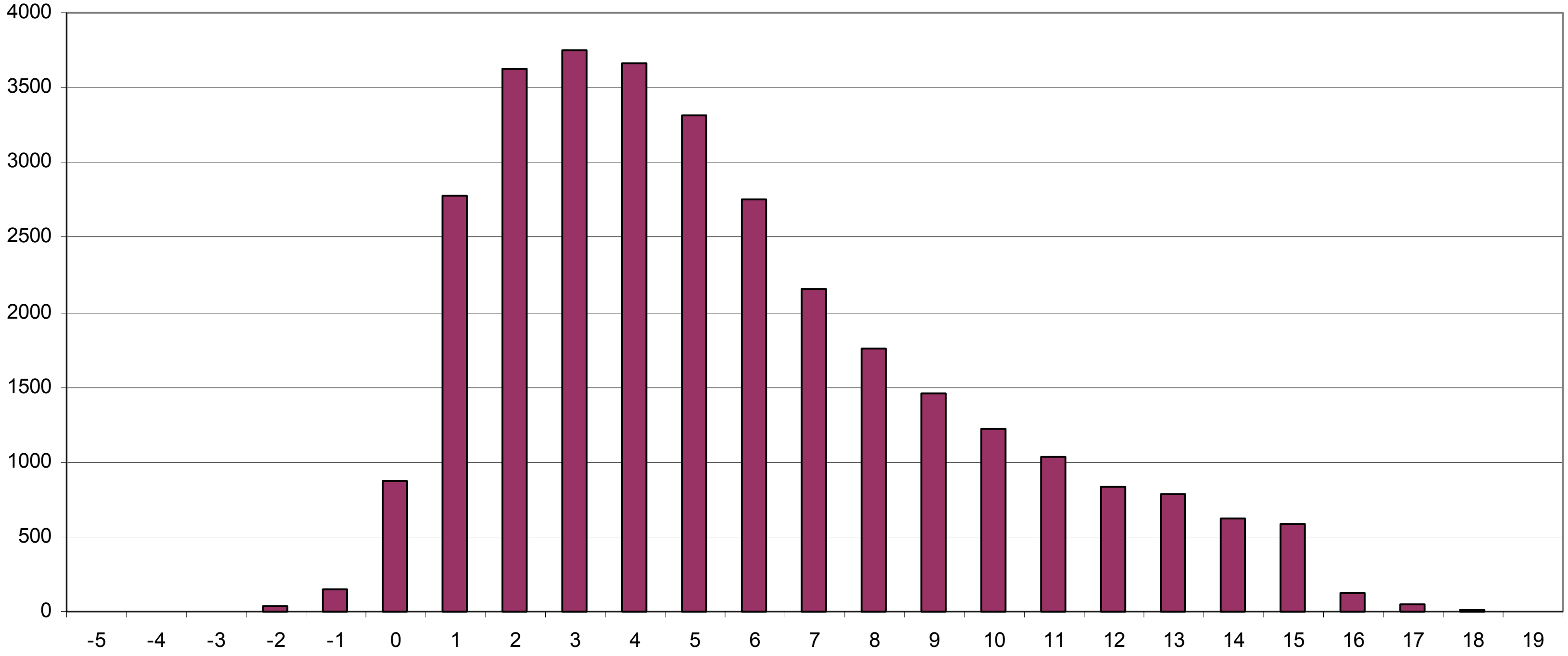
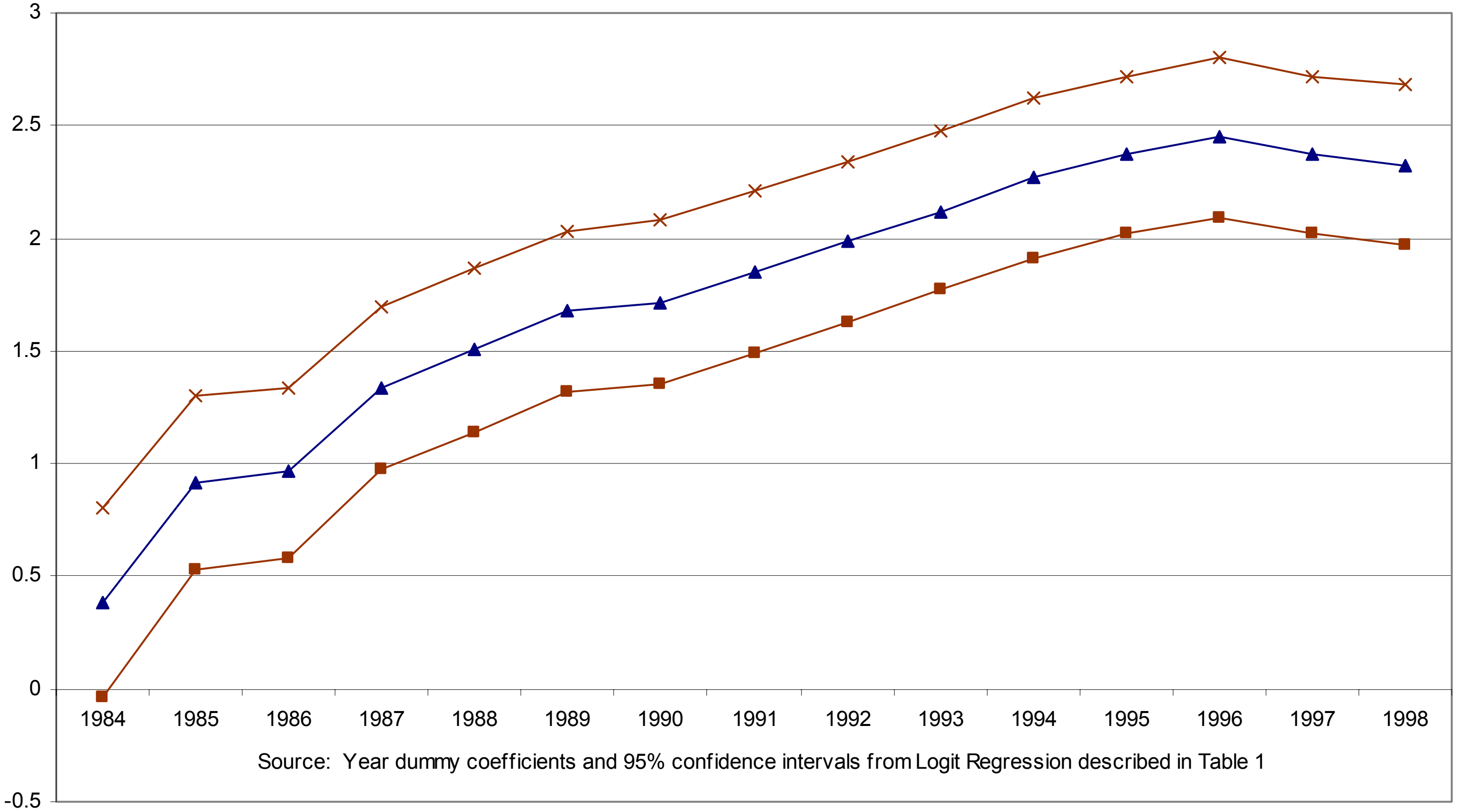


Table 1 Logit Regression Analysis

Variable	Coefficient
Chemicals	-.890 (.202)
Materials	-1.05 (.289)
Primary Metals	.217 (.205)
Machines	-1.67 (.209)
Electrical Machines	-.910 (.201)
Transportation Equipment	-2.59 (.212)
Precision Instruments	-1.17 (.202)
Pharmaceuticals	.993 (.207)
Sales	.106 (.053)
Overseas R&D subsidiaries	.051 (.027)
Research alliances	.132 (.016)
Log Likelihood	-33973.191

Figure 11 Growth in Patent Citations to Science
Controlling for Patent Numbers and Characteristics



Source: Year dummy coefficients and 95% confidence intervals from Logit Regression described in Table 1

Figure 12 Sangaku Renkei Indicators, 1983-2002

Source: Contract research expenditure and number of cooperative research pojrects are from MEXT w eb site. Dates of key reforms are
Kobayashi (2003). Left axis measures number of projects, right axis measures expenditure in 100 million yen.

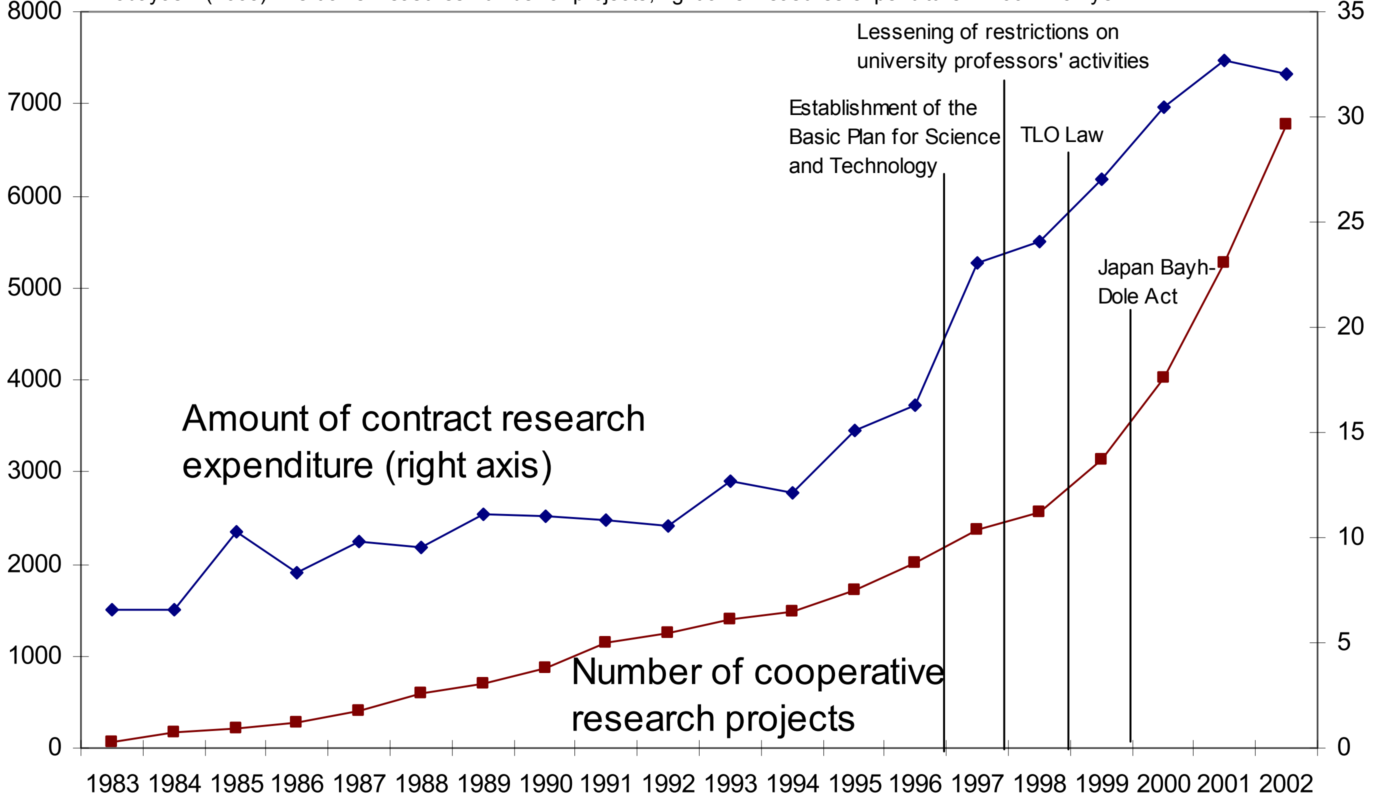


Table 2 Poisson and Negative Binomial Regressions

Regressions Undertaken at the Patent Level

Dependent Variable: Number of Citations to Science

Variable	Poisson	Negative Binomial
Late 1980s	1.54	1.53
	(.049)	(.058)
Early 1990s	2.27	2.26
	(.047)	(.058)
Late 1990s	2.77	2.75
	(.046)	(.057)
Pharmaceutical Ind.	1.97	2.07
	(.029)	(.077)
Other Chemicals	.174	.341
	(.026)	(.043)
Electronics	-.090	.015
	(.026)	(.045)
Sales	.144	.168
	(.011)	(.020)
Overseas R&D	-.109	-.066
	(.014)	(.024)
Alliances	.100	.082
	(.009)	(.016)
Log Likelihood	-76,579	-51,780

Table 3 The Impact of "Using Science" on Invention Quality

Firm-level fixed effects Negative Binomial Regressions
Dependent Variable: Citation-Adjusted Patent Output

Variable	(1)	(2)	(3)	(4)
Science Citations t-1	0.0072 (0.0106)			
Science Citations t-2		0.0419 (0.012)		
Science Citations t-3			0.0271 (0.0127)	
Science Citations t-4				0.0319 (0.0137)
R&D	0.0320 (0.0298)	0.0654 (0.0255)	0.1006 (.0275)	0.1218 (0.0061)
Patenting	0.4962 (0.0174)	0.3151 (0.0255)	0.2051 (0.0179)	0.1325 (0.0188)
Observations	3,030	2,977	2,929	2,728
Log Likelihood	-11,357	-11,348	-11,304	-10,508

Table 4 The Impact of "Using Science" on Productivity

Firm-level fixed effects linear regressions
Dependent Variable: Deflated Sales

Variable	(1)	(2)	(3)	(4)
Science Citations t-1	0.0189 (0.0044)			
Science Citations t-2		0.0172 (0.045)		
Science Citations t-3			0.0158 (0.0044)	
Science Citations t-4				0.0158 (0.0045)
R&D	0.0700 (0.0092)	0.0500 (0.0094)	0.0588 (.0095)	0.0840 (0.0098)
Patenting	0.0178 (0.0058)	0.0152 (0.0059)	0.0169 (0.0059)	0.0206 (0.0059)
Capital	0.1863 (.0.0168)	0.2208 (0.0175)	0.2017 (0.0173)	0.1844 (0.0175)
Employment	0.424 (0.0261)	0.4134 (0.0271)	0.4216 (0.0268)	0.3773 (0.0273)
Observations	3,281	3,235	3,178	2,948
R-squared	0.9048	0.9105	0.9089	0.9104

Table 5 Paper Co-authorships vs. Patent Citations to Science

Comparisons of geographic patterns for selected firms

(Numbers show percentage of co-authors or cited authors, respectively, in each geographic area)

		Canon	Matsushita	Sankyo	Takeda
Papers	Japan	85.31	81.42	81.75	76.62
	USA	6.94	12.09	9.82	17.83
	Other	7.75	6.49	8.43	5.55
Patent Citations to Science	Japan	21.3	34.8	19.1	27.9
	USA	51.7	43.9	55.1	53.2
	Other	26.9	21.3	25.8	18.9