Chapter 7

The Use of University Research in Firm Innovation

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Introduction

The Open Innovation paradigm focuses attention on the importance of firms' identification and use of ideas and knowledge from outside the boundaries of the firm. As documented by Chesbrough (2003a), firms in many industries have recognized the value of looking outside of their borders for ideas, knowledge, and sources of innovation. This value depends on the existence and depth of the knowledge landscape in which the firms operate. The characteristics of the knowledge landscape are determined by the knowledge flowing out of other firms and organizations and the intellectual property environment. With the exception of the Intel example that Chesbrough provides, the open innovation literature has focused primarily on the knowledge and ideas flowing out of firms, and the use of these ideas by other firms. In this chapter I will focus on another important source of knowledge and ideas useful to the innovation processes of firms: universities.

Many industries owe their technological foundation to federally-funded research performed in university labs (Fabrizio and Mowery 2005). The body of science that university-based research represents is an important and growing contributor to industrial innovation. University research is not automatically transferred to industry researchers. The transfer of this knowledge from universities to firms is affected by the appropriability regime, the nature of the knowledge, and the competencies developed by firms to identify and exploit this external knowledge (Teece 1986, Chesbrough 2003a).

Recent federal policy changes have altered the interface between U.S. universities and companies that make use of the research results generated at these universities. Specifically, policies embodied in the Bayh-Dole Act of 1980 allowed and encouraged universities to pursue formal intellectual property right (i.e. patent) protection to research results developed using federal funds, which at the time accounted for 70% of university research funding. As a result of this and related policies, patenting of university research results has exploded during the intervening decades.

During the same period, firms in many industries increased their reliance on research and technology developed outside of the firm (Chesbrough 2003a). Increased licensing activity, collaborative alliances, and outsourcing of research activities have highlighted the importance of effective knowledge transfer across the boundary of the firm. In this sense, study of the university-firm interface is one example of the more general knowledge transfer activity undertaken in several contexts. The recent substantial increase in formal property rights associated with university research in the United States provides a quasi-experiment that allows empirical investigation of the effect of increasing formal intellectual property (IP) rights on the use of university research in industrial innovation.

The goal of the Bayh-Dole Act was to promote commercialization of university research results that were seen as going to waste sitting on the shelves of university laboratories. The increased patenting and commercialization activity, however, brought with it concerns over increased secrecy, restrictions on follow-on research, and destruction of the open-science norms on which the institution of academic science relies. How has the increase in formal property rights altered the transfer of knowledge from universities to industry? How can firm managers position their firm to take advantage of the important contributions that reside in university research? Answering these questions contributes to the Open Innovation paradigm by shedding further light on how the use of external knowledge occurs, how it is affected by the prevailing IP regime, and what managers can do to improve performance in this regard.

In this chapter, I present empirical evidence relating to the impact of recent changes in the IP regime associated with university research results. Results suggest that the exploitation of openly published scientific research became more unequal across firms in technology areas experiencing the greatest increases in patenting by universities. This suggests that relative to the pattern of dissemination and exploitation of university research that existed in the absence of formal property rights, university research results were increasingly funneled for some firms at the expense of others as the assertion of IP increased. For firms attempting to take advantage of external knowledge from this important source, increasing IP associated with university research may limit their access to research inputs important to their innovation process.

Further evidence suggests that exploitation of openly published scientific research is in fact beneficial for at least one dimension of firm innovative performance. By examining the lag time between existing patented knowledge and the firm's new inventions building on that knowledge, I find evidence that as university patenting increased in a technology area, the length of this lag time increased. This suggests that the pace of knowledge exploitation by firms is slowing as universities are increasing their formal IP claims to their research results. Finally, I report evidence suggesting that firms that are exploiting more openly published scientific research experience a shorter lag time, consistent with innovative performance benefits associated with use of this external knowledge.

To successfully embrace the open innovation paradigm, firms must develop the ability to identify, assimilate, and make use of external knowledge and ideas. In the case of university-based research knowledge, publications and dissemination of research results have traditionally contributed to the knowledge landscape surrounding firms. However, seeking out and making effective use of this knowledge requires firm investments in building internal research expertise and collaborative networks with external scientists. This chapter considers evidence that suggests some of the research activities that enhance the ability of a firm to take advantage of public science.

The remainder of this chapter proceeds as follows. The next section describes several aspects of the university-industry interface, including the importance of university research in industry innovation, recent policy changes that have influences the intellectual property rights environment at this interface, and the expected implications of these changes for firms' use of university-based research result. The following sections empirically tests some of these implications and reports the results of the analyses with respect to both changes in the patterns of knowledge exploitation and how firms can enhance their ability to take advantage of university research. The final section concludes and discusses how this research relates to the open innovation paradigm.

University Knowledge and Industrial Innovation

An Important Source of External Knowledge

Public science supports the productivity of private science in many ways. Industry researchers across many industries rely on universities for research findings, instruments, experimental materials, highly trained human capital, and research techniques (Cohen, Nelson, and Walsh 2002). Industry researchers report that linkages with university researchers provide benefits in terms of keeping abreast of university research, gaining access to the university researchers' expertise, and receiving general assistant with problem solving (Rappert, Webster, Charles 1999). The successes and failures from basic research at universities provide information useful for guiding applied research in the direction of most promising opportunities, avoiding unfruitful areas, thereby increasing the productivity of applied research (David, Mowery, and Steinmueller 1992). Access to a stronger knowledge base facilitates more efficient and effective search for new innovations by firm researchers (Nelson 1982, Cockburn and Henderson 2002).

Existing studies have documented the reliance of industrial innovation on university-based research. Industrial patents heavily cite university-based published basic research, and the citation linkage between universities and industries has been growing over time (Narin and Olivastro 1991, Narin, Hamilton, and Olivastro 1997). Universities were reported to be the most important sources of external technologies by British and Japanese firms (Tidd and Trewhella 1997). In a studies of U.S. industry researchers, respondents report that approximately 10% of their product and process innovations could not have been developed without substantial delay in the absence of academic research inputs (Mansfield 1991, 1998).

Although all industries report some reliance on university research results, the importance of this research is particularly strong in some high-technology areas. Industries such as drugs, computers, semiconductors, and medical equipment consistently report the highest reliance on university-based research in their innovation processes (Cohen, Nelson, and Walsh 2002, Mansfield 1998).

In terms of the channels through which university research has historically reached researchers in industry, open publication of research results in the scientific literature dominates. Consistent with the expected importance of complementary, uncodified research results, more interactive channels of knowledge transfer (such as conferences, consulting, and informal interactions) are also important for effectively transferring university research results to industry (Cohen, Nelson, and Walsh 2002). Collectively, these studies highlight not only the importance of university science, but also the critical importance of informal, open, non-intellectual property related knowledge transfer mechanisms.

Traditional University Research Environment

University research has traditionally been held apart from private science research. The research performed at universities in generally taken to be more basic in nature (as opposed to applied, development-focus research), more important, and of larger impact than research performed by private companies (Trajtenberg, Henderson, and Jaffe 1997). The university research environment places a high value on dissemination of research results to promote the development of cumulative learning and technological progress. The institutions associated with university research support these norms and practices that sustain an open science environment.

The "open science" nature of academic research provides incentives for researchers that are consistent with the cumulative development of scientific knowledge (David 1998). The reputation-based reward system, associated priority claim, and review by peers support a system of rapid disclosure and broad dissemination of new research results by scientists. Rewarding a scientist for being first to discover encourages both inventive drive and disclosure. Disclosure and peer review allow validation of the research results. A reputation based reward system encourages dissemination of research and the production of meaningful, contributory science on which others will build. This avoids excessive duplication of research efforts, promotes information sharing, and allows the development of a strong public knowledge base from which following researchers can draw. Importantly, the open science system encourages both the dissemination of codified research results (through publication and the like) and the transfer of the complementary know-how that remains uncodified, through collaboration, interaction, and discussions between researchers. This system has clear benefits for open innovation, as it encourages contribution of research knowledge to the knowledge landscape from which firms can draw.

This system, treating new research results as public knowledge in order to strengthen the body of public knowledge, can be contrasted with a system of private science, characterized by restricting access to knowledge in order to appropriate rents from research (Dasgupta and David 1994, David 1998). The norms and rewards mechanisms of the two systems differ considerable, and result in different behaviors and outcomes. As I will return to below, the increasing focus on property rights, appropriation of rents, and commercialization on the part of university faculty and administrators has (perhaps unavoidably) brought some of the private science incentives into the traditionally open science research community of academia.

Changing Intellectual Property Regime

The Bayh-Dole Act of 1980 (The Patent and Trademark Amendments of 1980, Public Law 96-517) standardized the process by which universities could acquire patent protection for research conducted with federal funding. Before this policy, universities could obtain patent protection for research results only by applying to the federal government for permission to do so, and the university's activities were constrained by the case-by-case allowances of the government. The Act provided blanket permission and standardized procedures for universities to apply for patent rights covering the results of federally funded research, license the patents to interested firms, and collect royalty payments. In addition, the Act supported the negotiation of exclusive licenses to university patents resulting from federally funded research (Mowery and Ziedonis 2001). This policy change standardized the procedure for university patenting and in fact encouraged university patenting as a means to achieving technology transfer between university and industry (Mowery et al. 2001).

The motivation for the Bayh-Dole Act was to increase the commercialization of publicly funded research that occurred at universities and government labs. At the time, 70% of university research was federally funded, so policies affecting this portion of university research had a significant impact. The justification for increasing formal property rights to the outcomes federally funded research was based on the belief that many of these (potentially commercializable) research outcomes were going undeveloped due to a lack of property rights. In order to develop university research results into commercially viable products, significant investment on the part of the firm and continuing effort on the part of the university researcher are often required (Thursby, Jensen, and Thursby 2001). Without property rights, industry interests will not have the incentive to invest in the necessary development costs due to a fear of imitation or expropriation. In addition, university researchers had little incentive to participate in the commercial development of the technology in the absence of property rights. By granting formal intellectual property protection to federally funded university research results, allowing universities to license these results and collect royalty payments from the licensee firms, and providing an approbriability mechanism to the investing firms, the Bayh-Dole Act aimed to provide the necessary incentive structure to get more of the federally funded university research off the shelf (or out of the lab) and into industry (Henderson, Jaffe, and Trajtenberg 1998a, 1998b).

Stronger patent rights might well be expected to promote inter-organization knowledge and technology transfer. Patent rights and the associated disclosure and exclusion rights allow parties to negotiate over a clearly defined and specified piece of technology without the worry that potential buyers will walk away from the deal once they internalize the knowledge contained in the patent (Teece 1986). Formal IP associated with the codified portion of a technology also is expected to aid in the transfer of complementary tacit knowledge (Arora 2002). Strong patent rights also encourage specialization (Lamoreaux and Sokoloff 1999). Researchers can specialize in creation of intellectual assets, which they can then be compensated for through the licensing process. Licensees can specialize in the development, marketing, and delivery of the technology or associated product. By reducing the transaction costs associated with identifying and negotiating for technologies created outside of the firm, formal property rights may encourage firms to license and utilize technology from outside of the firm boundaries (Gallini 2002).

The response, in terms of the amount of university research protected by patents, was dramatic. In 1965, there were 96 U.S. patents granted to 28 U.S. universities. By 1992, nearly 1500 U.S. patents were granted to more than 150 U.S. universities (Henderson, Jaffe, and Trajtenberg 1998a, 1998b). Since 1975, the growth in the number of university-assigned patents granted by the United States Patent and Trademark Office has far outpaced the increase in the general population of U.S. patents (see Figure 1). Not surprisingly, the increase in university patenting has been concentrated in fields where licensing is a relatively effective mechanism for acquiring new knowledge (Shane 2004), such as drugs and medical, electronics, and chemical fields. Without the possibility of licensing the patented research results, university scientists and administrators lack sufficient incentives to patent the research results, and the traditional model of open publication without patenting prevails.

It is important to note that there were other changes that contributed to the overall increase in university patenting during this time. Patent protection generally was increased by the Federal Court Improvements Act of 1982, which created the Court of Appeals for the Federal Circuit to hear all patent case appeal. This court was broadly seen as favoring the patent holder in cases of infringement (Jaffe 2000, Gallini 2002). The Bayh-Dole Act was followed by a law in 1984 that expanded the patent rights of universities further and removed some restrictions contained in the Bayh-Dole Act. In part because of the Bayh-Dole Act, the number of universities with formal offices dedicated to technology transfer from universities grew following 1980. In addition, due to changes in technology, decreasing federal funding, and an increased focus on technology transfer, industry funding of university research increased as well (Henderson, Jaffe, and Trajtenberg 1998b). In fact, the increase in university patenting and license appears to predate the Bayh-Dole Act in some fields, such as the biomedical area, where university patenting grew significantly between 1975 and 1979 (Mowery et al. 2001). The growth in patenting in biotechnology areas was obviously associated with Court and U.S. Patent Office decisions that allowed discoveries such as gene sequences to be patented (Nelson 2001).[1] The Act, however, did encourage universities that had not

[1] For example, the 1980 U.S. Supreme Court decision in *Diamond v. Chakrabarty* extended patent protection to genetically engineered bacteria.

been involved in patenting previously to begin patenting their research outcomes (Mowery et al. 2001).[2]

These policy changes in the United States are more dramatic, but similar to, changes taking place in other developed countries. Cesaroni & Piccaluga (2002) and Geuna and Nesta (2004) describe the recent changes in European countries, including increased patenting by universities and more interactions between industrial and university researchers, but also point out that European universities in general are not as active as U.S. universities in either activity. As in the U.S., university patenting activity is concentrated in the biotechnology and pharmaceutical related fields. Collins and Wakoh (2000) document the recent regime changes in Japan, aimed at creating a system similar to the post-Bayh Dole environment in the United States. Although the existing empirical work and the results I report here primarily focus on the U.S. case, similarities among the policies in other developed countries suggest that the discussion and qualitative results presented here may be relevant to other regions.

Dasgupta and David (1994) warn of the potentially detrimental consequences associated with altering the norms established in the open science environment, for example in favor of property rights and commercialization of university science. By altering the system

[2] Several studies have examined the effect of the increase in patenting on the quality of university inventions. Quality of patents is typically proxied for using a count of the future patents that refer to the original patent as cited prior art. Patents relied upon more by follow-on innovation, the argument goes, are more important and of a higher "quality." Universities new to patenting received patents for inventions that were less important and less general, as compared to the patents of universities that were involved in patenting prior to the Bayh-Dole Act, but the patents of these "entrant" universities improved over time (Mowery and Ziedonis 2001, Mowery, Sampat, and Ziedonis 2002). Research has demonstrated that citations to university patents are coming with increasing lags, relative to other patents, but the overall quality (as measured with a count of citations to the patent) of the university patents is not decreasing over time (Sampat et al. 2003).

that so effectively produces and disseminates the body of public scientific knowledge, future innovation based on this knowledge may be inhibited. Some of these concerns, and evidence regarding their validity, are reviewed in the next section.

Implications for Industry Exploitation of University Research

Increased university patenting reflects an increase in the percentage of university research that is patented, while the underlying generation of university research has remained relatively stable (Henderson, Jaffe, and Trajtenberg 1998b). It is clear that many university research results are at an early stage of development and a patent and exclusive license are necessary to provide the incentives for industry development. However, in other cases, industry researchers have indicated that they would have utilized or developed the university research even in the absence of patent protection or an exclusive license. The industry researchers look down the road and recognize that their own inventions building on the university research would themselves be patentable, affording the necessary appropriation of rents. In this later category of cases, enforcing patent right to university research introduced a monetary transaction cost on the firms doing development. If exclusive licenses were also granted, follow-on development utilizing university research is (perhaps unnecessary) restricted. As Nelson (2001, p. 16) reflects after interviewing industry researchers, “my strong suspicion is that a good share of the technology transfer that has occurred would have proceeded as widely and rapidly as in fact it did, even if there had been no claiming of intellectual property rights by the university. And in some cases, it would appear that such claiming probably has made technology transfer more costly and time consuming for the firms involved.”

Markets and Transfer of External Knowledge

Maybe I don't need this section

The prevailing theory of how formal property rights influence the market for technology and knowledge assets is based on transferring the technology between parties both seeking to profit from it. Creating value from innovations and new technologies requires complementary assets to bring the innovation through development, commercialization, marketing, and distribution. The firm that generates the innovation often does not hold all of these pieces of the value chain in house, and therefore some inter-firm transactions are necessary and desirable. As the open innovation framework makes clear, the best way for a firm to gain value from innovations that do not fit the firm's own set of complementary assets is to look outside of the firm for a licensee or spin off to develop the innovation (Chesbrough 2003a).

In general, the market for technology or knowledge assets between organizations is assisted by the ability to protect the value of the knowledge asset from expropriation while also being able to effectively transfer the technology and related knowledge (Teece 1986). The protection of the technology, through formal IP rights or other contracting, allows the holders of the technology to reveal it to the potential buyer(s) without overwhelming threat of being copied once they reveal the knowledge.[3]

[3] The ability of others to imitate or duplicate the technology also depends on the characteristics of the technology, such as the complexity or tacitness of the related knowledge. For example, if understanding the technology requires scientists to work with the innovator and learn aspects of the related knowledge that would be difficult to capture in written description, it is considerably more difficult to copy the technology without this interaction. However, the same characteristics that make the knowledge easier to protect may also make it more difficult to transfer.

Viewing technology transfer from universities in this light provides some interesting insights. University researchers do not generally possess the complementary assets necessary to bring the often early-stage research results through development into a commercialized product that is marketed and distributed to consumers. The researchers tend to specialize in the creation of knowledge assets, the commercialization of which is typically left to other organizations. Therefore, in most cases the technology must be transferred a holder of complementary assets if development and commercialization is to occur.

The traditional open science environment of university research makes this transfer of knowledge assets a special case, since university researchers have different incentives than a firm that has generated an innovation or technology. University scientists seeking recognition or reputation rewards are not concerned with protecting their intellectual contributions – in fact, they openly publish and distribute their contribution in hopes that others recognize the value of their work and build upon it. Therefore, the from the traditional stance of university researchers, contribution to the knowledge landscape was not as plagued by IP concerns as one might expect in the case of firms generating knowledge assets.

The IP concerns come instead on the side of the firms to which the innovations are flowing. As described above, transferring and developing the university-based innovations often requires significant investment on the part of the firms, and firms may be hesitant to make these investments if the innovations which they are receiving are not protected by IP rights. The traditional model of openly publishing and disseminating university research results was therefore considered an impediment to effectively transferring university discoveries into commercial products. The hazard in this transaction falls on the acquirer of the technology, who does not want to be copied by competitor, rather than the originator of the technology. How does an increase in formal property rights affect transfer across this type of interface?

Increasing IP and Transfer of University Research to Industry

The historically differing norms between the academic environment and the private science carried out in industry have collided in the technology transfer process. In their survey of various stakeholders in the university-industry transfer process, Siegel et al. (2003) found that the dominant complaint of industry managers was a lack of understanding of corporate culture and norms by university technology licensing officials. Similarly, university technology licensing officials complained that their corporate partners failed to understand and appreciate the goals and norms of the university. The technology transfer process forces the inherent conflicts between open science and private science norms to the surface. Although the Bayh-Dole Act was intended to facilitate commercialization of university-generated technologies, there are several reasons for concern in terms of implications for knowledge being disseminated and available to industrial innovators.

One concern about the increased involvement of universities and university research in commercialization and technology transfer activities is the "contamination" of the academic norms system with norms from the private sector. One example of this was described in a recent Wall Street Journal article documenting the patenting activity at Columbia University (Wysocki 2004). Work by Columbia University researchers in the 1970s resulted in a method for inserting genes into the DNA of a cell, a technology which was very important to the burgeoning biotechnology industry. Columbia patented the discovery in the early 1980s and licensed the technology to several companies. The licenses resulted in payments of approximately $600 million to the university over the subsequent two decades. As the patent was reaching its expiration date in early 2000, Columbia took several steps to extend its lucrative payment stream. The university applied to Congress for an extension of the patent and was denied. The university also had secretly applied for a new patent in 1995 to cover technology very similar to the technology covered by the original patent. At the time that Columbia filed this second patent, patent applications were not publicly disclosed until they were granted, so Columbia was able to keep its second patent application secret and delay the granting of the patent by amending the application several time. The new patent did not issue until the first patent was expired (thus providing Columbia the longest period of patent protection for the new patent). When the new patent issued in 2002, Columbia demanded royalties based on the technology covered by the new patent from the firms using the technology covered in the original (now expired) patent. The companies challenged the royalty claim. Following noises by the judge that the companies were likely to prevail, Columbia withdrew their royalty claims, and the case was dismissed. Columbia is now fighting a separate challenge to the validity of the second patent.

This example demonstrates that some for-profit tactics, such as secrecy and strategic patenting, may be transferring to the traditionally open science domain of university research. More general concerns relate to the potential for limited availability of upstream university research and the destruction of norms that have supported the cumulative, open, and basic nature of scientific discovery associated with university research.

Fencing off upstream research

One concern that has been raised with respect to increasing university patenting is that downstream research will be stifled due to the unavailability of upstream research inputs, especially in complex industries that require many, potentially overlapping, IP-protected inputs (Heller and Eisenberg 1998). This "anti-commons" problem at worst leaves industry researchers unable to access the needed inputs to their own innovation process, and at best requires time consuming negotiations plagued by hold-up hazards.

First, because of the early-stage nature of many university inventions, exclusive licenses to patented university research have been favored in many cases. This necessarily limits to set of follow-on researchers to the sole licensee. Even university patents that are licensed on a non-exclusive basis still require the negotiation of licenses and potentially the payment of up-front and royalty fees, both which may restrict the set of follow on innovators relative to an open science environment. Stern and Murray (2004) find that following the grant of a patent covering university research that is also contained in a publication, citations to the publication are lower than would otherwise be predicted, suggesting diminished follow-on research associated with a patent on university research.

Second, increasing intellectual property concerns in an arena previously characterized by open knowledge sharing creates barriers and administrative burdens that can be a drag on innovation. Firm are forced to wade through the increasingly crowded and complicated intellectually property rights surrounding their own research and identify and negotiate access to relevant technologies. This process is time consuming and costly, and can slow down the research activity of the firm (Walsh, Arora, and Cohen 2003).

Industry researchers report difficulty negotiating for licenses or access to IP-protected university based research. In a significant number of cases, IP concerns presented an insurmountable barrier to firms joining with a university in a research partnership (Hall, Link, and Scott 2001). Industry researchers experience the increasing formalization of university technology transfer as detrimental to the (more effective) knowledge transfer through informal, collaborative channels (Rappert, Webster, and Charles 1999). One researcher in a biotechnology firm interviewed by Walsh, Arora, and Cohen (2003) reported that university patenting of research tools causes them to work around the university intellectual property, often slowing down their research progress. More generally, industry researchers in that study reported that high licensing fees or exclusive licenses to research tools could limit access to upstream university research and that wading through the increasingly complex intellectual property landscape to identify the relevant property rights added time to the research process.

Restricted Dissemination of University Research

Aside from property rights protection, increased patenting and commercialization activity by faculty members may be associated with less willingness to openly discuss and share research results and data within the scientific community. Louis et al. (2001) find that life sciences faculty members that are more involved in the commercialization of university research are more secretive about their research than other faculty members, all else equal. That is, they are more likely to deny requests for information about their research from other researchers. Faculty members in the biotechnology field with industry funding are more likely to keep research results secrecy to protect their proprietary value, more likely to take commercial applicability into account when choosing research projects, and more likely to produce research results that could not be published without the sponsors permission (Blumenthal et al. 1986).

This lack of willingness to share results, materials, and findings suggests an unraveling of the norms of the scientific community on which the progress of the academic system has been built. Recall that industry researchers report that publications are the most important source of university research that they rely on in their own research. In the absence of dissemination, peer review, and publication, dissemination of the important component of research knowledge than is contained in publications is restricted. In addition, less willingness of researchers to share results and collaborate means that the informal interactions critical to transfer of uncodified or unpublished research may be inhibited. This leaves all researchers seeking to build upon university science (including other university scientists as well as industry researchers) lacking an important resource. If researchers are left with only limited access to an important input to their innovation process, it is possible that industrial innovation may be hampered.

Implications for the University-Industry Interface

These potential negative consequences of increased university patenting have many far-reaching effects. The innovation system in the United States, as well as other regions that draw on research generated at U.S. universities, may suffer as access to important inputs to the innovation process are restricted. The possibility that some developments that would have occurred under the traditional (pre-Bayh-Dole) system will now not occur is impossible to test. However, it is possible to investigate changes in the pattern of use of university research as university patenting has increased.

In particular, if university research is becoming increasingly "fenced off" such that only those firms with license to the patented university research results may use and build upon university research, we would expect that the use of university research will become more restricted. That is, the use of university research will become more concentrated at some firms, leaving other firms without this input. In addition, if the increase in university patenting is inhibiting the transfer of university research result to firms, the innovation processes of firms may suffer. Given the importance of university research to the innovation processes in industry, limited access to this important input may result in slower exploitation of existing knowledge in new inventions by the firm. Empirical evidence relating to the consequences of the increase in university patenting on the transfer of research results from universities to industry is scant. In the following section, I draw on a large scale panel data set to make a first attempt to evaluate these concerns.

Empirical Evidence

University Patenting and Patterns of Knowledge Exploitation

How has the exploitation of university research results in firm innovation changed as university patenting has increased? In an effort to investigate the relationship between increasing university patenting and these concerns associated with knowledge transfer and industry innovation, I conduct a empirical investigation of patent activity during the 1975-1995 period. I use the information contained on the front page of each patent application to the U.S. Patent Office to examine the relationship between the growth of university patenting in a technology area and the exploitation of openly published scientific research in firms' inventions in that technology area. Specifically, I examine the citations to "non-patent" prior art listed on the patent. These citations list the prior art related to the invention covered in the patent, and they typically contain references to scientific journal articles, textbooks, and other codified, non-patent research reports.[4]

The number of these citations to openly published scientific work in each patent increased substantially in many fields during the same period as university patenting increased. For example, Figure 2 plots the average number of such citations per patent for patents in the main pharmaceutical patent technology class.[5] The upward trend in the number of these citations in industry patents is clear. Between 1980 and 1995 in this technology area, the percent of all U.S. patents that were university-assigned increased from about 2% to about 6%. The parallel increasing trends likely reflect both an increase

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[4] Citations contained on the front page of patent applications have been used in existing literature to evaluate the importance of a patent (Hall, Jaffe, and Trajtenberg 2000, Trajtenberg 1990), trace knowledge transfer and diffusion (Jaffe and Trajtenberg 1996), proxy for characteristics of the patented technology (Trajtenberg, Henderson, and Jaffe 1997), and compare the pace of innovation and obsolescence is an industry (Narin 1994), and a firm's closeness to science (Deng, Lev, Narin 1999).

[5] This Figure and Figure 3 use patents in international patent technology class A61K.

in the amount of university research in this area and an increased applicability of the university research results to the innovation processes in the pharmaceutical sector.

The concerns outlined about suggest that increased formal IP rights may be associated with less open dissemination of research result and increased limitations on the use of university research results in industry. If these concerns are true, we would expect that some firms (those with an advantage in terms of accessing university research or those that are able to gain access through licensing patented university technologies) will become increasingly advantaged relative to other firms. That is, if open dissemination, through publication, informal interaction, and other means, suffers as university patenting increases, university research results may become increasingly channeled to some firms relative to others. Again using the pharmaceutical patents as an example, Figure 3 displays the upward trend of the variance across firm of the average number of non-patent prior citations per patent. This suggests that during a period in which reliance on university science was increasing, some firms were exploiting this important knowledge source more than others, and the difference across firms increased over time as university patenting increased. This is consistent with a situation in which increasing formal IP to university patents is associated with more fencing off of university research results. The exploitation of scientific research results is becoming increasingly concentrated at some firms as university patenting increases in a technology area.

This trend not limited to the pharmaceutical sector. I use a panel data set containing information of all U.S. utility patenting assigned to firms over the 1975-1995 period in

620 World International Property Organization (WIPO) assigned international patent classes to evaluate the relationship between the amount of university patenting and the variance of citations to public science by firms in each technology class over time. For each firm that patented during this period, I calculate the average number of citations to non-patent prior art in the firm's patents in each technology class.[6] Then, for each technology class-year observations, I calculate the standard deviation of the number of non-patent citations across firms to arrive at a measure of the variance across firms in the technology class-year.

I use a technology-class fixed effects model to estimate the relationship between the percent of patents that are assigned to universities in the technology class and the variance of citation of public science across firms in the class. By controlling for technology-class averages, the fixed effect analysis effectively compares each technology class to itself over time. In the analysis, I also control for the number of firms in the technology class-year observations, because the variance could be affected by firms exiting or entering.[7]

Results of the fixed effect analysis of the variance of non-patent citations across firms are reported in column (1) of Table 1. The significant and positive coefficient on the university patenting variable suggests that as university patenting increased in a technology class, citation to public science became more unequal across the firms in that

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[6] In order to exclude only occasional patenters, I restrict this analysis to firms in the technology class with at least 21 patents over the 21 year period in each class.
[7] The relationship of the variance with the number of firms depends on where the entering or exiting firms fall in the distribution of the number of non-patent citations. I don't make any prediction about the sign of the relationship here, and simply include the number of firms as a control variable.

class (see Fabrizio 2005a for detailed description of the data construction and further results). In other words, the exploitation of public science in firms' inventions became increasingly concentrated at some firms relative to other firms in the same technology area as university patenting increased. This is consistent with the prediction of increased funneling of university research to a restricted set of firms. This evidence suggests that concerns over limiting use of patented university research and restricted dissemination of non-patented university research may be justified.

From an open innovation perspective, this suggests that increasing formal property rights may be detrimental to firms' use of previously openly disseminated research knowledge. As formal IP protection replaces a system of publication and sharing, it may become more difficult for firms to identify, assimilate, and make use of university research.

A natural next question is to ask is whether or not the restriction on use of university research has any measurable effect on firm innovation. One aspect of firm innovation is how quickly the firm develops new inventions based on existing input technologies. If dissemination and use of university research is being hindered by increasing formal property rights, and if the transfer that does happen is further slowed down due to the additional negotiation and contracting required through the technology licensing office, we might expect the industrial innovation would be slowed as well.

In order to investigate this concern, I estimate the relationship between the increase in university patenting and the amount of time that passes between existing knowledge and the new firm innovations that build on that knowledge. I construct a measure similar to the "technology cycle time" measure described by Narin (1994) by calculating the average number of years between the application year of a given patent and the years in which the patented "prior art" listed in that patent were granted. If a patent cites significantly older relevant prior art, it took longer for the inventors to build on the prior art in their new invention.

As an example, the distributions of this backward citation lag for patents applied for in 1985 in four technology classes are displayed in Figure 4. The distributions that peak quickly and drop off represent classes in which patents cite relatively recent prior art heavily, and do not cite older (now obsolete) prior art much. These two classes, Medical Preparations and Semiconductors, are classes that we would expect to be progressing at a relatively rapid pace in term of technological advance. The distributions of backward citation lags for patents in the other two classes, Stone Working and Hinges, are much flatter, suggesting a slower pace of advance and a longer period until technological obsolesces. In the following analysis, I examine changes in the backward citation lags of patents in each of the 620 technology class over time to evaluate changes in the pace of knowledge exploitation in each class.

By looking at this backward citation lag for all industrial patents across all technology classes for the 1975-1995 period, I evaluate whether the pace with which researchers developed new patented inventions slowed or sped up with increased university patenting. Analogous to the analysis above, I use a technology class fixed effects analysis to examine the relationship between changes in the university patenting in a given technology class and changes in the backward citation lags of patents in that class. Between-technology class differences are controlled for with the technology class fixed effect. In this analysis, the dependent variable is the average backward citation lag for patents by a given firm in a given technology class-year observation.[8] I control for various characteristics of the patents expected to affect the lag, including the average number of citations made and the number of patents in each technology class-year.

Results of this analysis, presented in column (2) of Table 1, demonstrate that the backward citation lag of firm patents increased as university patenting in the technology area increased, suggesting a slow down in the pace with which firm exploited existing knowledge in new inventions (see Fabrizio 2005a for more detail and further analysis). As university patenting increased, the time between the relevant existing knowledge and the firm's new patented inventions lengthened. This may reflect slow downs due to negotiation for rights to patented technologies or materials, time spent inventing around patented upstream technologies that a firm did not license, and slow down due a lack of research knowledge inputs.

If this apparent slow down is related to inaccessibility of university research, then we would expect that firms with an advantage in terms of accessing and exploiting university research would demonstrate some advantage with respect to the pace of knowledge exploitation. The evaluate this prediction, I re-estimate the model of the firm-class-year backward citation lag including the average number of citations to non-patent prior art in

[8] I use the same sample of patents here as in the variance regression for consistency.

the patents by the firm in each technology class-year observation. This variable reflects the firm's exploitation of public science in their inventions in that technology area and year.[9] Results, reported in column (3) of Table 1, demonstrate that firms whose patents contain more citation of non-patent prior art, suggesting more exploitation of public science, have patents with significantly shorter backward citation lags. In other words, exploitation of public science is associated with an advantage to firms while the overall effect of the increase in university patenting is to funnel public science to some firms relative to others and slow the pace of knowledge exploitation on average.

These results suggest that the pattern of knowledge transfer from universities to industry has changed as university research results are increasingly associated with formal intellectual property claims. In fields where university patenting has increased, there is evidence that university research is becoming increasingly funneled to some firms relative to others. This is consistent with concerns related to limiting dissemination and fencing off upstream research. In addition, the pace of knowledge exploitation evidence in industry inventions is slowing as university patenting increases. This is consistent with possible detrimental effects of limiting access to important upstream research, restricted dissemination of such research, and slower transfer due to lengthy negotiations over increasingly complex university intellectual property concerns. All of this evidence suggests that the contributions of university research results to the knowledge landscape are becoming increasingly privatized in the sense that their use is limited to those who secure contracts and pay licensing fees.

[9] Note that the inclusion of the technology class fixed effect controls for the average citations to non-patent prior art in each class. Therefore the firm-year level measure reflects differences across firms within each class.

Firm Research Strategies and Knowledge Transfer

If the increase in formal IP associated with university research results is associated with more funneling of university research to some firms relative to others, and access to university science is beneficial to firm innovation processes, what can firm managers do to improve their access to and use of university research results? How can firms gain value from university-based innovations?

Even without restrictions imposed by patent protection, use of external knowledge requires some investment by the firm. When university science is published in the open literature, the fact that research results are theoretically available for use by other researchers does not imply that all potential users are equally able to identify and make use of the research. In order to make use of the science generated by university scientists, firms must develop and maintain the ability to "plug in" to these research communities. The President of Centocor (a biotechnology firm now a subsidiary of Johnson & Johnson) recognized this need and the expected benefits when he stated that "Centocor should know about major research at least a year before it's published" by stressing collaboration and giving their scientists the freedom to make contacts and stay on top of relevant scientific research. In addition to finding out about new research results, contacts with university researchers may give a firm access to results that would not be published (such as lessons learned from failed experiments) and knowledge related to published research that can not or is not written down.[10] How a firm can develop its ability to identify and exploit public science is the subject of recent academic research that

[10] The codified information resulting from research, such as publications, patents, or blueprints, may not be sufficient for a researcher to recreate or implement the research results described. In many cases, additional tacit knowledge, held by the original researcher, is required (Dasgupta and David 1994).

evaluates the benefits of geographic proximity, founder experience, firm research, and collaboration for performance outcomes such as production of patents.

Geographic proximity to high quality university scientists enhances the firm's ability to capture the "spillovers" of knowledge from the university (Zucker, Darby, and Brewer 1998), but firms can also take an active role to develop their ability to exploit public science. The capability of a firm to identify, assimilate, and exploit external knowledge was termed "absorptive capacity" by Cohen and Levinthal (1989), who recognized that this ability requires some in-house research capability and expertise on the part of the firm researchers. Simply being aware of relevant basic research discoveries generated at a university necessitates the ability to understand cutting edge science, even if they research results are promptly published (Rosenberg 1990). The ability to assimilate and exploit such research results requires even more expertise, and may also require interaction with university scientists in order to fully understand and implement the research.

Several empirical studies demonstrate the significant positive effect of internal basic research on firm productivity (see for example Giliches 1986).[11] Most of these studies focus on the pharmaceutical and biotechnology sectors, because these are sectors in which reliance on published university-based research has been shown to be substantial

[11] Most of the studies of knowledge transfer from university to industry either take an aggregate look across many industries or explore in detail the firm activities in the pharmaceutical and/or biotechnology sectors. This industry selection is (in part) because it is a fertile context for such study: Reliance on published university-based research has been shown to be the highest in the pharmaceutical and biotechnology sectors (Cohen et al. 2002, McMillan 2000).

(Cohen, Nelson, and Walsh 2002, McMillan 2000). Gambardella (1992) find that pharmaceutical firms whose researchers produce more scientific publications also generate more patented inventions, controlling for the scale of firm R&D. Henderson and Cockburn (1994) find that for a small sample of large pharmaceutical firms, firms that promote researchers based on scientific publications and standing within the scientific community generate more important patents. In addition, pharmaceutical firms that collaborate with university scientists generate more important patents (Cockburn and Henderson 1998). Firms in the biotechnology sector that co-author scientific publications with top university scientists produce more patents and more important patents (Zucker, Darby, and Armstrong 2002). These findings suggest some inventive performance benefits associated with a firm's investment in basic science research, the scientific focus of its research culture, and the collaborative connections developed through researcher interactions.

These studies interpret the superior innovative performance as a benefit of superior absorptive capacity stemming from the internal basic research and university collaborations of the firm. Liebeskind et al. (1996) provide some support for this with a case study of two biotechnology firms. The authors find that the firms rely on social network connections as the dominant channel for transfer of scientific knowledge from universities. This suggests that there are advantages to being well connected to the scientific community.

In order to evaluate the relationship between firm research activities and the firm's exploitation of public science, I again explore the citation to public science in firm's patents. By focusing on firms in the pharmaceutical and biotechnology sectors, I am able to collect more detailed firm level data to investigate whether there is direct evidence that firms investing in particular research strategies possess superior absorptive capacity with respect to public science.

Following the existing empirical literature, I proxy for firm basic research expertise with a count of the number of scientific publications generated by each firm in each year. I proxy for the collaborative focus of the firm with the percentage of these publications that were co-authored with a university researcher.[12] Controlling for the size, research expenditures, research intensity, and age of the firm, I estimate the relationship between the number of non-patent citations in a firm's patents and that firms basic research focus and collaborative research efforts (see Fabrizio 2005b for more detail regarding the sample, method, and results). Results of a negative binomial estimates, reported in column (1) of Table 2, indicate that pharmaceutical and biotechnology firms investing more in basic research and collaborating more with university scientists do cite more public science in their patented innovations, consistent with the prediction that these activities enhance the firm's absorptive capacity. Also note that being farther away from a research university is associated with less exploitation of public science in the firm's

[12] It is important to remember that these measures, publications and collaborations, are indicator variables that represent the underlying organization routines and strategy of the firm. Firms that generate more publications are doing more basic science, but they also are likely to promote individual scientific inquiry, value scientific contributions, and build organizational practices the support the sharing of knowledge both with and across firm boundaries. Firms that collaborate with university researchers are also likely to build informal networks both within and across the boundaries of the firm. All of these unobserved characteristics likely contribute to the effects attributed to the indicator variables here.

innovations, consistent with the diffusion benefits associated with geographic proximity noted in other studies.

In order to explore the potential diminishing returns to additional collaborations, I also estimate this model including the square of the collaborations variable. Results of that estimation are reported in column (2) of Table 2. The relationship does in fact demonstrate diminishing returns. Holding all other variables constant at their mean, the maximum number of citations to non-patent prior art is reached by collaborating with university scientists on about 60% of a firm's published research projects. A firm that generates publications only when the researchers are collaborating with a university does not exploit public science as much as a firm that generates some publications without university co-authors. This suggests that a firm can not rely solely on external collaborations as a means to incorporate public science. The firm researchers also need to develop a level of scientific ability and expertise in order to most effectively assimilate and exploit public science research results.[13]

In light of the evidence described above relating to the changes brought about by the significant increase in university patenting, it is of interest to explore how the apparent benefits of these firm research activities change with the change in IP regime. Because all firms in this sample are (potentially) drawing from the same fields of university research,

[13] As described in Fabrizio 2005b, results utilizing a model with firm level fixed effects suggest that an increase in publication activity or an increase in collaborations with university scientists by firm researchers is associated with an increase in citation to public science, as would be expected if these activities enhance the absorptive capacity of the firm. As a firm increases its internal basic research activities or builds its network of collaborations with university scientists, its exploitation of public science increases as well.

cross-class analysis of changes in university patenting is not possible here. Instead, I examine whether there is any difference in the relationship between firm research activities and the citation of non-patent prior art before and after 1985.[14]

The final column of Table 4 reports the results of the analysis including the pre- and post-1985 indicator variables interacted with the publications and collaborations variables. The basic science research of the firm, as represented by the number of publications generated by firm researchers, provides significantly more benefits, in terms of the number of non-patent citations, during the pre-1985 period.[15] The coefficient on collaborations with university scientists, as reflected in the co-authored publications, is only significant in the post-1985 period. These results suggest that, relative to the 1975-1985 period, the basic scientific expertise of the firm is less important and the collaborations with university scientists are more important during the 1986-1995 period. This is consistent with increasing importance of connections with university scientists, in order to gain access to university research and participate in licensing, as university patenting increased. Internal expertise may become less important as IP protection limits the use of university research results.

These results demonstrate that by investing in certain organizational and research practices, firm managers in the biotechnology and pharmaceuticals sectors can enhance the ability of the firm to identify, assimilate, and exploit the public science research

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[14] Although 1985 is an arbitrary break point, the increase in university patenting is most dramatic following 1985, and this is when the greatest increase in the variance in citations to non-patent prior art across firms occurs.

[15] The equality of the coefficients on the pre-1985 and post-1985 publications variable is rejected at the 1% level.

available in the open literature. These research activities appear to be associated with superior knowledge transfer from a knowledge source that is particularly important in this sector. However, the usefulness of the research activities for sourcing external knowledge may depend on the IP regime in which the firm operates. Being able to effectively scan the scientific literature for useful research results becomes less important as the use of more of these results is restricted by patenting.

Conclusions

University-based research forms an important input to the research and innovation processes in many industries. Recent policy changes, increasing industry funding of university science, and technological changes have contributed to a substantial increase in the portion of university research results being patented. Although motivated by a desire to generate more commercial applications of university research results, the increase in patent protection to university research has drawn concern. In a system of cumulative innovation, where many current developments rely heavily on prior innovations, access to upstream university science is critical to the industrial development process. If the increase in patent protection hinders the availability or transfer of university research to firms, there is the potential for detrimental effects on industrial innovation.

Evidence presented here looks for the first time at changes in the pattern of exploitation of public science as university patenting increased. Evidence suggests that as university patenting increased in a technology area, exploitation of public science became increasingly concentrated at some firms relative to others. On average, the pace of knowledge exploitation evidence in industrial patents has slowed as university patenting increased, but firms that are exploiting public science more in their patents appear to be at an advantage in this regard. Overall, this evidence is consistent with increasing fencing off of university research, a slow down in knowledge transfer, and restricted dissemination of public science as university patenting increases.

As the open innovation framework highlights, firms in many industries are increasingly reliance on external knowledge and ideas in their innovation processes. One important source of these knowledge assets is university-based research. The open innovation literature suggests that the market for technologies and know-how across firm boundaries is assisted, and even depends upon, protection of intellectual property rights. This conceptualization assumes that the owners of the knowledge assets seek to protect the appropriable rents from their innovation. Therefore, they will not disclose the innovation to potential buyers if the risk of imitation is too high. Formal IP protection in this context facilitates contracting for and transfer of knowledge assets.

However, in the special case of university research, the increase in formal intellectual property protection is replacing a system of open disclosure and rapid dissemination of research results. Formal intellectual property rights in this environment have altered the norms and incentives of university researchers. University researchers and administrator have become more interested in capturing some of the rents from their innovations. IP protection may have the benefit of encouraging firm investment in university technologies, but also has the downside of fencing off upstream university research, slowing down technology transfer, and creating incentives for secrecy among university researchers.

From the perspective of a firm attempting to identify and exploit relevant public science, there is evidence that proactive strategies of managers may enhance that firm's ability to do so. Locating close to a knowledge source appears to promote knowledge transfer. However, location is not enough. By developing internal research expertise related to basic science research, firm researchers are able to better identify and make use of relevant public science. In addition, controlling for the amount of research performed by the firm, collaborations between firm and university researchers appears to enhance the transfer of public science knowledge to the firm.

These results highlight the fact that increased patenting does not by itself solve the knowledge transfer problem. Even in the biotechnology and pharmaceutical sectors, where patenting is seen as an important mechanism to appropriate rents from an innovation and an important source of information about public research (Cohen, Nelson, and Walsh 2002), patenting university research results does not by itself assure technology transfer to industry. Interaction between university researchers and industry researchers, as well as continued investment in basic science by firms, is important to the knowledge and technology transfer process.

The need for effective transfer of external knowledge across firm boundaries extends beyond firms acquiring knowledge from public science research. Alliances, research consortia, and licensing all include the potential for knowledge transfer. Evidence presented here with respect to universities may suggest that firms seeking effective knowledge transfer in another context would be well served by developing some related expertise and interacting with researchers working in the other firm.

Figure 1
The Increase in University Patents Has Outpaced Growth in Patenting

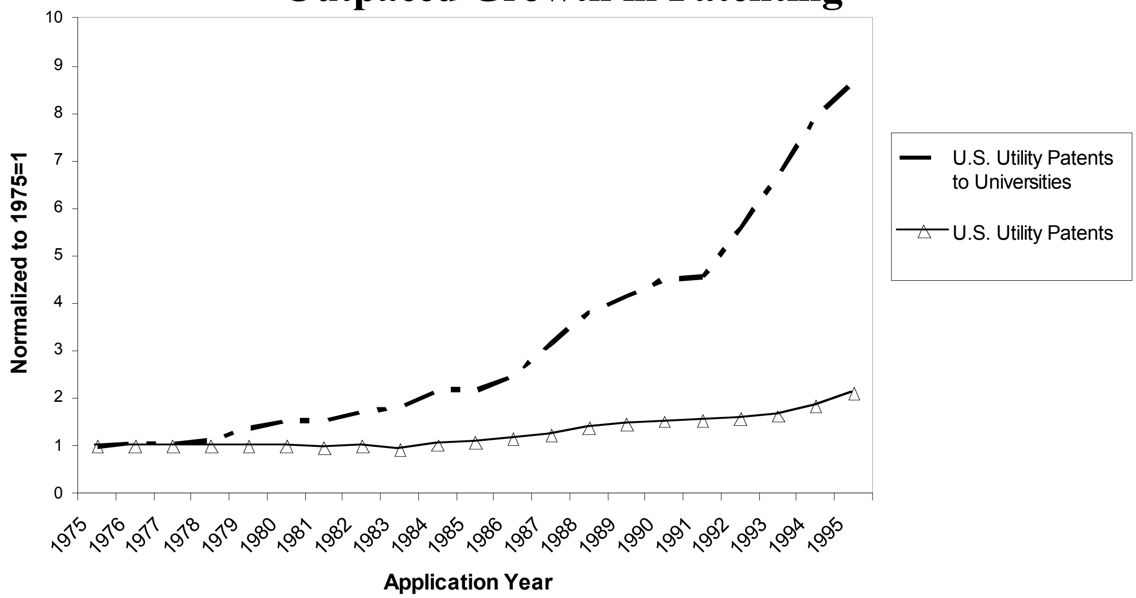

Figure 2
Citations to Non-Patent Prior Art Increased
Pharmaceutical Patents Example

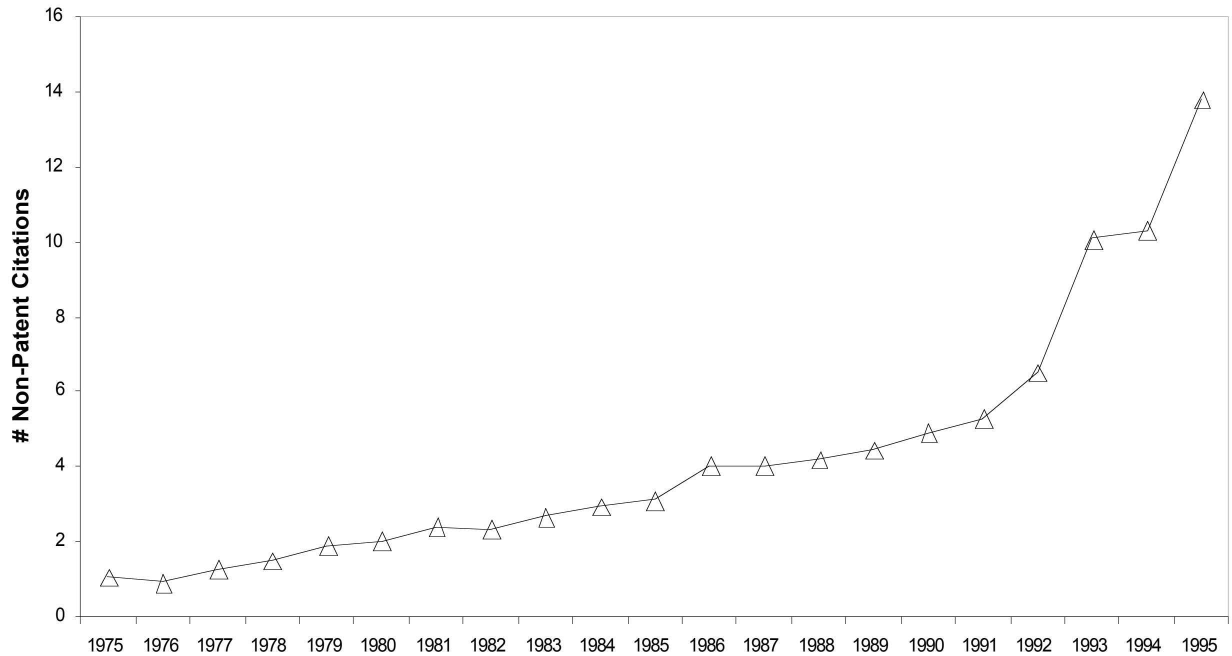

Figure 3
Inequality of Non-Patent Citations Across Firms Increased
Pharmaceutical Patents Example

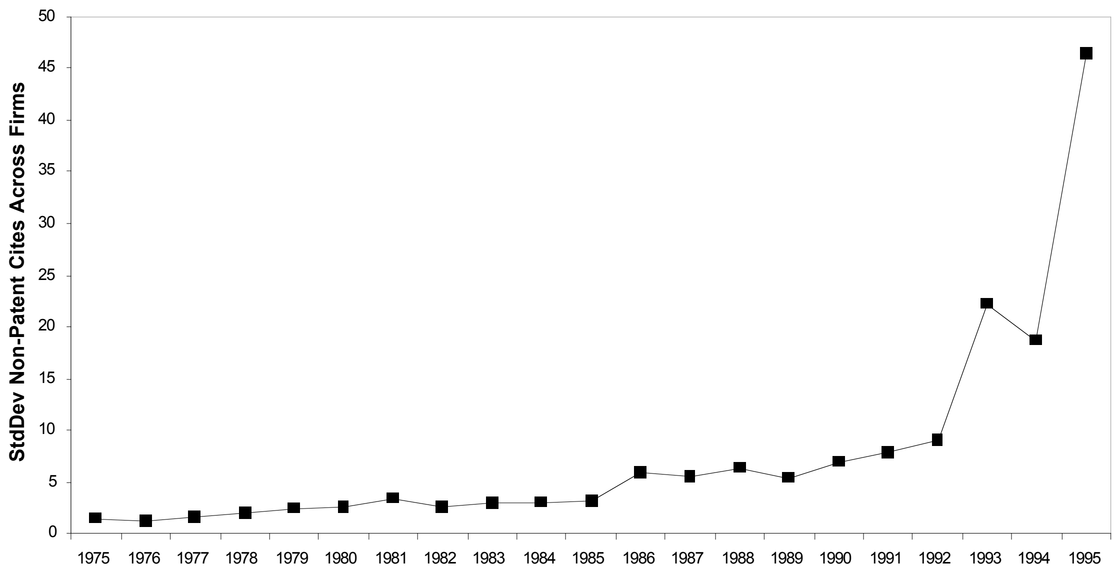

Figure 4
Distribution of Backward Citation Lags for Patents in Four Classes in 1985

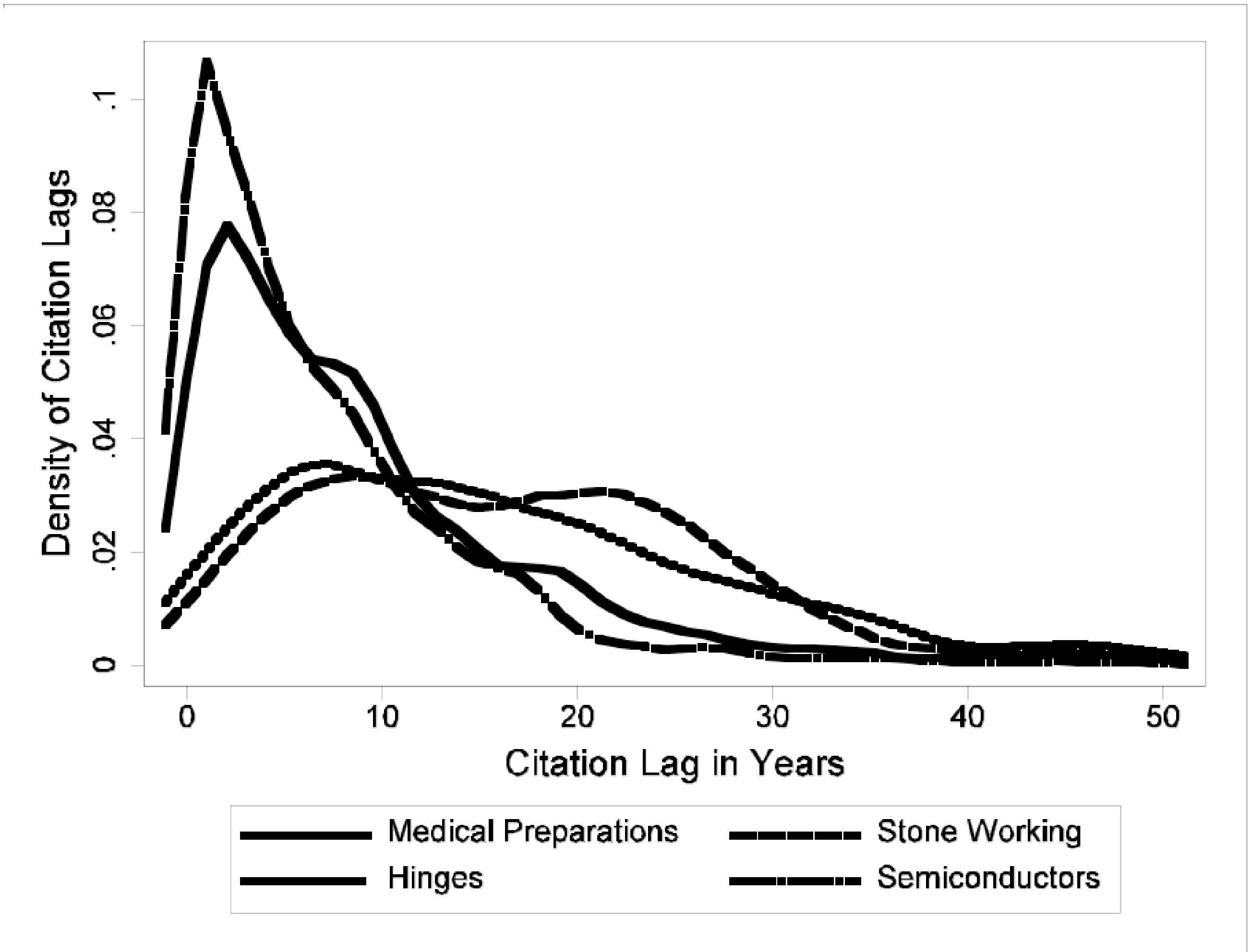

Table 1
Effects of Increased University Patenting
1975-1995

Dependent Variable:	Variance of Citations Across Firms	Backward Citation Lag	Backward Citation Lag
	(1)	(2)	(3)
University Patenting$_{k,t}$	11.38** (2.36)	4.72** (0.92)	5.35** (0.98)
# Firms$_{k,t}$	0.01** (0.001)		
ln(non-patent cites/patent)$_{j,k,t}$			-0.04** (0.01)
ln(cites/patent)$_{j,k,t}$		0.33* (0.02)	0.34** (0.02)
ln(# patents in class)$_{k,t}$		-0.06** (0.02)	-0.06** (0.02)
Constant	0.53** (0.03)	1.78** (0.10)	1.75** (0.11)
Tech. Class FE	YES	YES	YES
# Observations	6,373	112,103	112,103

*significant at the 5% level ** significant at the 1% level
subscripts: j: firm, k: class, t: year

Robust standard errors (clustered by technology class) in parentheses.
All equations include year fixed effects and technology class fixed effects.

Eq (1) is at the technology class-year level, with 6,373 observations. Variance of Citations Across Firms is the natural log of the standard deviance of the average number of non-patent citations per patent across firms in the technology class-year.

Eq (2) & (3) are at the firm-technology class-year level, with 112,103 observations. Backward Citation Lag is the average number of years between the application year of the patent and the grant year of the cited patents for patents of a given firm in a given year in a given technology class.

University Patenting is the cumulative percent of patenting in the technology class assigned to universities.
#Firms is the number of firms in the technology class-year observation.
Non-patent cites/patent is the average number of non-patent citations per patent for the firm-year-class observation.

Table 2
Firm Basic Research and Collaborations are Associated with More Citations to Public Science

Dependent Variable:	#Citations	#Citations	#Citations
	(1)	(2)	(3)
% Pubs w/UnivCo-Author$_{j,t}$	0.94* (0.39)	2.51** (0.80)	
% Pubs w/UnivCo-Author$_{j,t}^2$		-2.09** (0.76)	
# Pubs/100$_{j,t}$	0.08* (0.03)	0.08* (0.03)	
% Pubs w/UnivCo-Author$_{j,t}$*Pre1985			0.70 (0.51)
% Pubs w/UnivCo-Author$_{j,t}$*Post1985			1.07** (0.37)
# Pubs/100$_{j,t}$*Pre1985			0.30** (0.08)
# Pubs/100$_{j,t}$*Post1985			0.07* (0.03)
ln(#claims)$_i$	0.04 (0.03)	0.04 (0.03)	0.04 (0.02)
% self-citations$_i$	-0.40** (0.13)	-0.40** (0.13)	-0.40** (0.13)
ln(Min. Distance to Univ.)$_j$	-0.11* (0.06)	-0.11* (0.06)	-0.13* (0.06)
Foreign Firm Dummy$_j$	-0.44** (0.16)	-0.44** (0.15)	-0.49** (0.16)
ln(R&D/Employee)$_{j,t-1}$	0.11 (0.11)	0.09 (0.11)	0.07 (0.11)
ln(Employ)$_{j,t-1}$	0.08 (0.08)	0.06 (0.07)	0.05 (0.08)
Firm Age$_{j,t}$	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Biotech Dummy$_j$	1.38** (0.33)	1.40** (0.32)	1.33** (0.33)
# Observations	27,246	27,246	27,246

*significant at the 5% level ** significant at the 1% level
subscripts: i: patent, j: firm, k: class, t: year

All equations are estimated at the patent level, including all patents for the 82 pharmaceutical and biotechnology firms in the sample. Robust standard errors, clustered by firm, are reported in parentheses.
All equations include year fixed effects.