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University-to-industry knowledge transfer: literature review and unanswered questions

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This paper reviews the economic literature concerning university-to-industry knowledge transfer. Papers on this topic are divided into four categories. Research in the 'firm characteristics' category focuses directly on company issues, such as internal organization, resource allocation, and partnerships. In contrast, research in the 'university characteristics' stream pays little attention to the firms that commercialize inventions, but rather focuses on issues relating to the university, such as licensing strategies, incentives for professors to patent, and policies such as taking equity in return for intellectual property. The 'geography in terms of localized spillovers' stream of research considers the spatial relationship between firms and universities relative to performance in terms of knowledge transfer success. Finally, the 'channels of knowledge transfer' literature examines the relative importance of various transfer pathways between universities and firms, such as publications, patents, and consulting. Each of these research streams is discussed and key papers are described highlighting important methodologies and results. Finally, an outline of topics requiring further research in each of the four categories is offered.

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Introduction

This essay provides a review and commentary on the literature concerning university knowledge transfer. The economic importance of this issue provides significant motivation for deepening our understanding of the knowledge transfer system. It is well understood that the creation and application of new knowledge is the primary factor that drives economic growth. It is also commonly accepted that universities are an important source of new knowledge, especially in the areas of science and technology. Thus, it is important to build as clear a picture as possible of the mechanisms by which university science moves into the economy.

Evidence suggests that even knowledge transferred through the formal university technology transfer channel, patenting, which many scholars argue represents only a small fraction of the total economically valuable

transfer from universities, is quite significant. For example, the Association of University Technology Managers (AUTM) estimates that the licensing of innovations made at academic institutions contributed over US$40bn in economic activity and supported more than 270,000 jobs in the fiscal year 1999.[2]

Perhaps the two most active areas of university knowledge transfer are the life sciences and electronics, including electrical engineering and computer science. Examples of notable successes in these two areas include the innovation by Stanley Cohen (Genetics and Medicine, Stanford) and Herbert Boyer (Biology, UC San Francisco) for the process of making recombinant DNA using gene-splicing, and the innovation by Tom Leighton (Electrical Engineering and Applied Mathematics, MIT) and his colleagues of a set of algorithms for intelligently routing and replicating content over a large network of distributed servers without relying on centralized servers.

The Cohen-Boyer invention is often referred to as the cornerstone of the biotechnology industry; at the time of its expiration on 12 December 1997, the patent was being licensed by 380 firms and, during its 15-year lifetime, attracted a total of approximately 480 licensees. Professor Leighton's innovation led to the founding of Akamai Inc., which launched its first commercial service in April 1999 and achieved a remarkable market capitalization of US$35bn by December of the same year.[3] Owing to its significant economic impact, both primary and secondary, it is clear that university knowledge transfer warrants much effort towards a deeper understanding.

The objective of this paper is to construct a general framework of the research in this area by: (1) providing an overview of the various related streams of research and how they fit together; (2) presenting a survey of the literature associated with each of these streams, including highlights from key papers; and (3) offering a view forward in terms of directions for future research. The framework presented here categorizes the research on this topic into four categories: firm characteristics; university characteristics; geography in terms of localized knowledge spillovers; and channels of knowledge transfer.

The relationships between these streams of research may be considered as follows. Research in the *firm characteristics* category focuses on issues relating to the firm, such as internal organization, resource allocation, and partnerships. In contrast, research in the *university characteristics* stream pays little attention to the firms that commercialize inventions, but rather focuses on issues relating to the university, such as licensing strategies, incentives to patent, and policies regarding taking equity in return for intellectual property. The *geography in terms of localized spillovers* stream of research considers the spatial relationship between firms and universities relative to performance in terms of knowledge transfer success. Finally, the *channels of knowledge transfer* literature examines the relative importance of various transfer pathways between universities and firms, such as publications, patents, and consulting. Each of these research streams is discussed below and key papers are described highlighting important methodologies and results.

Firm Characteristics

There is a small but growing literature concerning the characteristics of the firm that influence its ability to utilize externally generated scientific knowledge, such as that which is transferred from universities. This branch of research originates from a pair of papers by Cohen and Levinthal (1989, 1990) that introduce the concept of 'absorptive capacity'[4] and argue that a firm's ability to apply university research for its own commercial gain is a function of its investment in R&D. Cockburn and Henderson (1998) build on this notion but add that the degree to which firms are ''connected'' to universities is also important for utilizing knowledge spillovers. Lim (2000) restructures the above two

concepts and argues that the absorptive capacity of firms is primarily a function of its connectedness, of which its investment in R&D is just one of several components.

Zucker *et al.* (2000) investigate the importance of connectedness to firms by examining their location decisions relative to star university scientists. Shane and Stuart (2000) study university start-up firms and examine the importance of connectedness, not with the scientific community in this case, but rather with the venture capital community. Ziedonis (1999) does not consider connectedness, but rather examines the firm's related knowledge assets and its ability to evaluate external technology in terms of its likelihood of licensing a particular technology and its likelihood of taking an option prior to licensing. Finally, Audretsch's (2000) study is not at the level of the firm but rather of the individual as he investigates the extent to which university entrepreneurs are systematically different from other entrepreneurs. These papers are now described.

Cohen and Levinthal introduce and develop the concept of absorptive capacity and argue that this characteristic of the firm is strongly related to its prior related knowledge generated by in-house R&D. The authors present a model in which a firm's absorptive capacity is a function of its investment in R&D. They apply this model to test predictions relating a firm's investment in R&D to the knowledge underlying technical change within an industry.

The authors utilize a cross-sectional data set constructed from a survey of R&D lab managers in the American manufacturing sector. They regress R&D intensity, measured by the R&D-to-sales ratio, on various measures of technological opportunity and appropriability. Technological opportunity is measured by the importance of 11 basic and applied fields of science and the importance of external sources of knowledge to technical progress in a line of business, as indicated by respondents on a seven-point Likert scale. Appropriability is measured by the perceived effectiveness of patents, secrecy, lead time, moving quickly down the learning curve, and complementary assets in protecting the competitive advantages of new processes and products.

The authors report ordinary least squares (OLS), generalized least squares (GLS), and Tobit regression results that support their two predictions. First, in the case of technological opportunity, the estimated coefficients for the impact of the applied sciences on R&D intensity are generally lower than those for the basic sciences, since the basic sciences are more relevant (of higher quality) and this knowledge has a more positive effect on R&D intensity. Secondly, the effect of increasing appropriability on R&D intensity is shown to be significantly greater in those industries in which the applied sciences are more relevant to innovation than the basic sciences. The authors conclude that these results support their hypothesis that R&D investments create a capacity to assimilate and exploit new knowledge.

Cockburn and Henderson argue that, while investments in in-house R&D are necessary for firms to develop their absorptive capacity to utilize knowledge spillovers, this alone is not enough. Firms must be connected to the open science community by being actively involved in sharing research results (publishing) and also engaged in research collaboration. They investigate the public–private science interface, focusing on the pharmaceutical industry, using both qualitative and quantitative measures. Their qualitative studies include both case histories and interviews. The case histories examine 21 drugs that two leading experts identified as having had the most impact upon therapeutic practice between 1965 and 1992. The authors reveal that public sector research was important in the development of 16, or 76%, of these drugs, implying that absorptive capacity was important in these cases. The authors also interviewed research scientists and managers from both the public and private sectors that both confirmed the importance of absorptive

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capacity in the classical sense, but also identified three additional factors perceived as being important for conducting leading-edge research within the firm. These include: (1) recruiting the best people; (2) rewarding researchers on the basis of their standing in the public rank hierarchy; and (3) encouraging them to be actively engaged with their public sector counterparts.

The authors address two related questions with their quantitative analyses concerning the concepts of connectedness, the organization of internal research, and research productivity. The concept of connectedness is introduced to express the degree to which the scientists at a firm are connected to their counterparts outside the boundary of the firm, including in other firms, universities, and National Institute of Health (NIH) research institutions, amongst others. They measure connectedness by the fraction of papers written by scientists at the firm that are co-authored with scientists outside the firm. They hand-code the institutions associated with co-authors into eight categories, the largest being 'self' (co-authors from the same firm), followed by 'university'.

The organization of internal research is measured on two dimensions. 'Pro-pub' is the perception of scientists of the degree to which their firm uses publication or individuals' standing in the wider scientific community as a basis for promotion and compensation, and is measured on a five-point Likert scale. 'Dictator' is the perception of scientists of the degree to which their management allocates research resources versus a peer-review committee system; this is also measured on a five-point Likert scale. Research productivity is measured by the number of important patents that are generated by the firm where important patents are defined as those patents that have been registered in at least two of the largest economic regions, including the US, Europe, and Japan.

Using the above approaches to operationalize the concepts of connectedness, internal organization, and research productivity, the authors first investigate the effect of firms' internal organization of research on the type of institutions with which they are likely to co-author. They regress the type of co-author on pro-pub and dictator, including a variety of control variables, using logit regression models. Their results suggest that pro-pub is positively associated with the probability of co-authoring with external institutions, especially universities. In contrast, dictator is negatively associated with the probability of co-authoring with external institutions.

The authors also investigate the relationship between connectedness and research productivity. They regress the natural logarithm of the number of important patents produced by a firm on the degree of connectedness, pro-pub, dictator, and a number of control variables, using OLS regression models. Their results indicate a positive relationship between connectedness and research productivity, which is arguably the most interesting finding reported in this paper. Their results also suggest that pro-pub is positively correlated with productivity, while dictator is negatively correlated.

Lim picks up from Cockburn and Henderson and argues that not only is connectedness important but that it is in fact the main ingredient for creating absorptive capacity. Internal R&D is but one mechanism to foster connectedness and it in turn generates absorptive capacity. The author identifies three additional mechanisms for fostering connectedness, including: (1) cultivating university relationships by way of sponsoring research, collaborating with faculty, and recruiting graduate students; (2) participating in research consortia; and (3) partnering with other companies that do related scientific research. The key issue investigated in this paper is whether firms are able to acquire and exploit externally generated scientific knowledge *without conducting in-house R&D*, but instead by being connected to the scientific community in other ways.

To study this issue, Lim conducts both quantitative and qualitative analyses of copper

interconnect technology that was discovered by IBM but quickly diffused to some, but not all, firms in the semiconductor industry. The author measures R&D by patent and publication counts and measures knowledge flows by patent-to-patent and patent-to-paper citation counts. With these measurement techniques, the author offers evidence to support a three-step logical argument. First, some firms depended on knowledge spillovers from IBM and other sources, and did not develop copper interconnect technology from their own R&D. The evidence presented to support this is: (1) all commercial processes to date use the damascene process developed by IBM; and (2) a large fraction of patents in this area belonging to firms other than IBM cite IBM patents and IBM papers. Secondly, firms' prior R&D was insufficient to account for absorptive capacity. The evidence presented to support this is the lack of publications and patents generated by many of the firms competing with this technology. Thirdly, the absorptive capacity of firms depends on connectedness. The evidence presented to support this is the variance in the time it took for firms to adopt the copper interconnect technology commercially. Firms that were able to adopt it quickly were connected in some way to IBM or other institutions that were familiar with the research on this topic but did not necessarily conduct their own R&D.

Further, Lim suggests that different types of absorptive capacity may exist within and across firms. The type of absorptive capacity depends on the mechanisms at work driving the connectedness. The author differentiates between disciplinary and domain-specific knowledge, and suggests that internal R&D may be best suited for generating absorptive capacity suited to the former while other methods are more suited to the latter.

Zucker *et al.* (2000) investigate the effect of star university scientists, who either left tenured positions to found firms or who remained in the university but established tight working relationships with their colleagues in private industry, on the performance of the firm. They investigate this phenomenon in the context of the bio-technology industry using data from the industry publication *Bioscan*. 'Star' scientists were identified as those that had published 40 or more genetic sequence discoveries in *GenBank*. The classification of the relationships between stars and firms is conducted by examining the affiliation of the authors associated with every article through 1989 reporting a gene-sequencing discovery written by a star.

Stars are categorized as 'affiliated' with a particular firm if they list that firm as their home institution in the article. Stars are categorized as 'linked' to a particular firm if one or more of their co-authors of the article are from that firm. The authors measure productivity on a number of dimensions and throughout the research and product development life cycle, including the number of patents granted, the number of products in development, and the number of products on the market. The primary result of this research is that the number of scientists who are tied to the firm, those that are either linked or affiliated, have a positive and significant effect on the productivity of the firm in all three major stages of research and product development.

Shane and Stuart examine the importance of initial resource endowments on particular major events in the growth of early-stage technology companies. Specifically, they investigate the importance of the founders' social capital in terms of their personal relationships with the venture capital community. The authors test for a relationship between the degree of the founders' social capital at the birth the firm and whether the firm: (1) raised venture capital financing; (2) experienced an initial public offering; or (3) failed. The authors conduct their experiment on a dataset comprising the life histories of 134 technology firms founded specifically to commercialize inventions from MIT during the period 1980–1996.

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The authors employ event-history methods to conduct their analysis. They carry out the analysis in two parts: (1) a set of piecewise constant models of the hazard of IPO and mortality; and (2) a set of piecewise constant models of the time until raising the first round of venture funding. The results from this study suggest that ventures with founders that have direct or indirect relationships in the venture capital community are more likely to receive venture financing and are less likely to fail. Also, firms that receive venture financing are, in turn, more likely to experience an initial public offering. Thus, the authors conclude that initial resource endowments, at least in terms of the social capital of its founders in the context of the venture capital community, do have significant influence on the likelihood of two major events in the growth process of young companies.

Ziedonis (1999) investigates two questions related to the issue of firms licensing technology from universities. First, he examines the extent to which the firm's related knowledge assets affect the likelihood that it will license a particular technology. Secondly, he examines the degree to which the firm's ability to evaluate external technology determines the manner in which it licenses, specifically whether the firm signs an option agreement prior to licensing. He uses a unique data set of 308 exclusively licensed patents related to inventions from the University of California and 291 firms that signed at least one secrecy agreement associated with these inventions.

The author employs a nested multinomial logit model as the econometric specification in this analysis. His results suggest that the following four characteristics of the firm's related knowledge assets increase the likelihood of licensing a technology: (1) the level of the firm's expertise, which is measured by the (log of the) citation-weighted number of firm patents in the same primary patent class as the patent under consideration; (2) whether the firm sponsored research leading to the licensed patent, which is measured by a dummy variable; (3) whether the firm previously licensed a patent in the same class, which is measured by a dummy; and (4) whether the university inventor has a fiduciary or other executive relationship with the firm, measured by a dummy. His results also suggest that firms with the characteristics described above will be less likely to take an option prior to licensing. This is consistent with theory since a higher level of related technical knowledge reduces uncertainty, resulting in a lower value of the option to the firm.

Audretsch (2000) examines whether entrepreneurs from university settings are different than their counterparts from industry. Specifically, the author suggests that university entrepreneurship will occur at a systematically later age for university scientists because the incentive and reward structures within the university system induce scientists to invest in developing an external scientific reputation by making research public via publication.

The author tests this hypothesis using a semiparametric hazard duration model to estimate the following covariates: (1) the cumulative citations of the scientist; (2) the number of other scientists who started biotechnology firms in the same geographic region; (3) the number of new biotech firms in the same geographic region; and (4) dummy variables indicating the career trajectory of the founders (university, industry, or mixed). The author conducts this experiment on a dataset of 101 founders associated with 52 biotechnology firms. His primary result suggests that university entrepreneurs are generally older and thus more scientifically experienced. The author emphasizes the importance of this finding in terms of policy implications given the prevalence of government programs specifically designed to foster and support entrepreneurial efforts, especially in the area of technology.

In terms of the applications for this work, these papers collectively suggest frameworks for contemplating firm strategies that may

influence absorptive capacity. Companies may experiment with various mechanisms (resource allocations) to increase their absorptive capacity such as modifying their patterns in: (1) recruiting graduate students; (2) hiring professors as consultants; (3) modifying internal incentives to publish or patent; (4) funding university research; (5) participating in research consortia; (6) sending company scientists to university labs as visiting scientists; and (7) engaging in collaborative research with university scientists that may result in co-authored publications or patents. Also, firms may experiment with metrics for both evaluating their connectedness to the greater research community, as well as calculating their ROI from investment in in-house research, including the intermediate step of absorptive capacity, not just research output.

At a conceptual level, it is interesting to note that the transfer of *tacit* knowledge, that which is costly or impossible to codify, is at the heart of the majority of this work. Connectedness is only important because the knowledge associated with an invention is not completely transferred in the codified form of patents or publications but rather requires some form of interaction between the inventor and the recipient firm. While there may be gains possible from increased efficiencies in transactions associated with codified knowledge, the focus on topics associated with tacit knowledge transfer suggests that this is the central issue, and it generates the majority of the variance in terms of firms' relative abilities to utilize university inventions effectively. Thus, research that contributes to our deeper understanding of tacit knowledge and how it is transferred would offer a worthy contribution to the work in this area.

University Characteristics

This stream of research focuses on university policies regarding intellectual property (IP), licensing strategies employed by university technology licensing offices, and characteristics of the actual inventor-professors. Most of the papers in this area refer in some way to the Bayh-Dole Act of 1980, which granted universities the right to license inventions that result from federally funded research. Economic scholars are interested in the effect this act has had on university policies concerning IP management and the incentives of professors to commercialize their research. In addition, there is considerable interest regarding whether the incentives created by Bayh-Dole have shifted the average type of research that is conducted at universities from basic to more applied science.

To this end, Henderson *et al.* (1998) investigate the change in quality of university patents since the act was passed. Thursby and Thursby (2000) develop a model to examine the extent to which the increase in university licensing is due to a change in the nature of research or just in the propensity to patent. Feldman *et al.* (2000) investigate the recent trend of universities that write licensing agreements involving equity rather than simply cash payments for the use of IP in an effort further to align the interests of the university with the firm. Jensen and Thursby (1998) examine the degree to which university inventions reported for licensing are at a very early stage, thus requiring the co-operation of the inventor by the licensee in order to develop a product successfully. Finally, Di Gregorio and Shane (2000) examine performance across university licensing offices and explore why some universities generate more new companies to exploit their intellectual property than others. Highlights from these five papers are discussed below.

Henderson *et al.* (1998) investigate the change in overall patent quality that accompanied the significant growth in university patenting during the period 1965–1988. To conduct this experiment, the authors use four sets of patents: (1) all university US patents granted between 1965 and mid-1992 (12,804 patents); (2) a 1% random sample of all US patents over the same time period (19,535); (3) all patents after 1974 that cited the university patents (40,859 patents); and (4)

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all patents after 1974 that cited the random sample patents (42,147 patents).

The authors compare university patents with a random sample of all patents along two dimensions. First, they construct a measure of patent 'importance' that involves a count of the number of patents that cite a particular patent. Secondly, they construct a measure of patent 'generality', which is a measure of the degree of concentration of citing patents across patent classes. The concept for the second measure is that patents that are more general will be cited across a greater variety of fields and hence the measure will indicate less concentration.

Their data illustrate that, while university patents used to be more highly cited and more general than a random sample of all patents, the difference has disappeared over time. This implies that, over the period examined, the rate of increase of important patents from universities was much less than the overall rate of increase in patenting. These results suggest that, while the Bayh-Dole Act seems to have successfully increased the propensity to patent, it has not resulted in a shift in the underlying rate of generation of commercially important inventions at universities.

Thursby and Thursby (2000) investigate the factors behind the rapid growth in university patenting and licensing activity. The motivation for this research is to determine whether the source of this growth is due to an increased willingness of professors to patent their inventions without a shift in the type of research itself or a much more fundamental change in the type of research to be more commercially oriented. The authors conduct this study by developing an intermediate input model where licensing is considered a three-step process, and then using non-parametric programming techniques on survey data from 65 universities to calculate the total factor productivity growth in each state.

The authors supplement the productivity analysis with survey data from firms that license university inventions. Their results suggest that the growth in licensing patented university inventions is driven primarily by an increase in professors' propensity to patent (on the supply side) and firms' propensity to outsource R&D by licensing (on the demand side), rather than a shift in the average type of research from more basic to applied.

Feldman *et al.* (2000) investigate the variance across university technology licensing offices in the degree to which they write licensing agreements involving equity, rather than traditional cash in the form of royalty payments, as a means for firms to pay for their use of university intellectual property. Specifically, the authors test the hypothesis that universities that are more experienced and successful at licensing are more likely to employ equity in their contracts, as this is a newer and more sophisticated means for engaging licensees. They test this hypothesis utilizing two data sources, including AUTM's annual survey and their own survey of 67 research universities.

The authors use Tobit models to estimate the effects of a variety of explanatory and control variables that are intended to measure the effects of experience, performance, and university characteristics on the fraction of deals closed by the university involving equity. They find three measures to have a positive and significant effect. These include: (1) the age of the technology transfer office measured in years; (2) the cumulative total licensing revenue; and (3) the average industrial research support. They also find that being a 'Carnegie I' institution (highest category of federal research support) has a negative effect on the fraction of equity deals. Their results show that experienced university technology transfer offices are more likely to use equity in certain situations because, although the use of equity is more complex than cash, it may increase the option value of some technologies and also improve the alignment between the university's interests and those of the firm.

Jensen and Thursby (1998) investigate the moral hazard problem associated with university inventors and the transfer of their inventions to industry. This research is

motivated by the debate over the Bayh-Dole Act and the associated royalty payments to inventors that result from the university's right to license federally funded research output under the Act. The authors utilize a dataset generated from a survey of 62 US research universities for which respondents were university licensing officers.

The most striking finding from this survey is that over 75% of the inventions licensed by these universities were in a very early, or embryonic, stage. That is, half of these inventions were only a proof of concept and, of the remaining half, over 50% were only a lab-scale prototype. The authors report that respondents believed 71% of the inventions licensed required co-operation between the professor and the licensing firm in order to commercialize a product successfully. This result underscores the importance of tacit knowledge transfer associated with early-stage inventions. The authors then present a theoretical model to illustrate conditions under which the development of an invention will not occur unless the inventor's income is proportional to the licensee's output by way of royalties or equity.

Di Gregorio and Shane (2000) investigate cross-university variation in new firm formation rates over the period 1994–1998. Specifically, they investigate the effects of: (1) the availability of local venture capital (number of local companies receiving funding from venture capitalists in a given year); (2) the commercial orientation of research (proportion of a university's sponsored research budget that was industry funded); (3) the intellectual eminence of faculty (the Gourman Report graduate school score); and (4) the university policies regarding taking equity in start-ups in lieu of royalty fees (minimum percentage of total royalties). The authors utilize survey data collected from university licensing offices by AUTM and supplement that with their own survey data of the same universities to gather information regarding their licensing policies. Their sample includes 101 universities and 530 start-ups.

The authors analyse the five-year period using generalized estimating equations (an extension of generalized linear models applied to longitudinal data) with a count of the number of new firms formed as the dependent variable, the explanatory variables described above, as well as several control variables. The results the authors report suggest that the two primary factors that have a positive effect on the rate of new firm formation are the intellectual eminence of professors and licensing contract flexibility such that start-ups may offer equity rather than cash to the university and inventors.

In terms of the applications for this work, these papers collectively suggest policy implications at both the university and federal level. Perhaps the greatest of these issues, in terms of impact on universities and firms, is the one concerning policies that restrict the commercialization of university research. Related policies generally involve two types of parameters: those that restrict by fiat the degree to which intellectual property created by university-employed professors may be controlled for commercial purposes, and those that create incentives (or disincentives) for professors to engage in activities associated with the commercialization of their research by way of patenting, consulting, or otherwise.

A variety of related questions have been explored both theoretically and empirically, especially since the passage of Bayh-Dole. This work also suggests policy implications associated with the university sponsorship of patent applications, given the findings that the quality of university patents appears to have decreased over time. The issue of universities taking equity in young firms, rather than licensing royalties, invokes a myriad policy considerations and, at the time of writing this paper, the practice is still too new to allow for the empirical investigation of most related questions. Finally, policies that appear to influence the number of start-ups that originate from a university have stimulated great interest and inspired much interaction across universities at the administrative level,

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particularly noticeable amongst technology licensing office directors. The rapid increase in AUTM membership across universities, and the association's increased attention to start-ups, provides some evidence of this.

From a more general perspective, it is interesting to note how the heavy focus on patent-related knowledge transfer has shaped this line of inquiry. This focus has resulted in intense scrutiny of the effects of the Bayh-Dole Act, related policies at individual universities that influence the incentives for professors to patent, and the consequent behavior of professors in terms of their research output. However, policies that affect the vibrant trade in scientific knowledge for commercial application that is not patented and does not flow through the university technology transfer office have been largely overlooked.

This may in part be due to the absence of policies, or at least policy enforcement, that address non-patent channels of knowledge transfer. In addition, value-added services are increasingly being offered by private sector organizations that indirectly compete with university transfer offices. These include services such as introductions to early-stage financiers, business advice, and customer contacts. Thus, some invention types such as software, which often do not lend themselves to patenting yet have direct commercial relevance, are frequently developed outside the radar of the technology transfer office. Policies that do, or could, address this phenomenon are potentially very important and offer a wide array of interesting research questions that would contribute greatly to this area of inquiry.

One additional note for readers who are new to this area concerns the asymmetry in transaction styles between firms and universities. For example, readers may be surprised at the simplicity of research questions associated with university policies concerning taking equity in return for intellectual property rights. Universities are often far less experienced in deal making than their private sector counterparts and are also subject to much greater restrictions due to their objectives and responsibilities that go well beyond profit maximization. As a result, universities behave quite differently from firms, even when they are engaged in business transactions. Our understanding of university–firm interactions is less developed than traditional firm–firm interactions and thus policy analysis concerning university-to-industry knowledge transfer may not rely upon the usual firm–firm interaction assumptions.

Geography in Terms of Localized Knowledge Spillovers

A stream of literature has developed at the intersection of the tacit knowledge concept in the information literature and the localized spillovers concept in the agglomeration literature. 'Tacit knowledge' includes those types of knowledge that are either impossible or costly to codify. As a result, the transfer of tacit knowledge generally requires direct interaction: in person, by phone, or through written correspondence. The literature in this area examines the effects of the implicit transaction costs associated with direct interaction that often influence the spatial relationships between the creator and recipient of tacit knowledge.

The papers in this area generally measure the variance in the levels of various knowledge inputs and hypothesized associated outputs and examine this relationship across geographic space. The inputs and outputs considered vary from study to study, as does the geographic unit of analysis. Jaffe (1989) relates the input 'federal research funding' to the output 'new patents issued' and examines the variance in this relationship across geographic space at the state level. Jaffe *et al.* (1993) relate the input 'original patents' to the output 'patents that cite the original patents' and examine the variance in this relationship across geographic space at the city level. Audretsch and Feldman (1996) relate the input 'local university research

funding' to the output 'local industry value-added' and examine the variance in this relationship across geographic space at the state level.

Zucker *et al.* (1998) relate the input 'number of local research stars' to the output 'number of new local biotech firms' and examine the variance in this relationship across geographic space at the economic region level. Branstetter (2000) relates the input 'scientific publications from the University of California' to the output 'patents that cite those papers' and examines the variance in this relationship across geographic space at the state level. Agrawal (2000) relates the input 'hours of interaction with the MIT professor associated with the patented invention' to the output 'likelihood or degree of success of commercializing the invention' and examines the variance in this relationship across geographic space in terms of distance measured in miles. Key findings reported in these papers are described briefly.

Jaffe (1989) was the first to examine geographically mediated knowledge spillovers. The author modified the knowledge production function approach introduced by Griliches (1979) to account for spatial and product dimensions. This conceptualization changed the observation from the traditional unit of the firm to the geographic level for an industry. The author chose the state as the geographical unit of analysis and patent counts as the knowledge output metric.

Results from this study indicate that patents occur in those states where public and private knowledge-generating inputs are the greatest. Even after controlling for industrial R&D, the results indicated that the knowledge generated at universities spilled over for higher realized innovative output. The author also reports results suggesting that university research appears to increase industry R&D that in turn increases the production of patents.

Jaffe *et al.* (1993) investigate the degree to which knowledge spillovers are geographically localized. They conduct this experiment by examining patent citations of patents. Specifically, they compare probabilities of patents citing prior patents that are associated with inventors from the same city with a randomly drawn control sample of cited patents. The authors report results suggesting that the citations are significantly more localized than the controls after adjusting for organizational types, such as universities. These results hold when the data are aggregated for analysis at higher geographic levels.

Audretsch and Feldman (1996) test the theory that innovative activity will cluster in regions where knowledge spillovers are the most prevalent. This would be consistent with expectations in terms of the knowledge production function. The authors calculate Gini coefficients for the geographic concentration of innovative activity to test this relationship. They report results that indicate the relative economic importance of new knowledge to the location and concentration of industrial production. Even after controlling for the geographic concentration of production, the results suggest a greater propensity for innovative activity to cluster spatially in industries in which industry R&D, university research, and skilled labor are important inputs.

Zucker *et al.* (2000) investigate the issue of localized knowledge spillovers from universities to industry, focusing specifically on the biotechnology industry. They conduct this study by examining a dataset of 751 new company or division formations over a 14-year period from 1976 to 1989 and across 183 functional economic regions. Specifically, the authors test the hypothesis that the entry of firms into biotechnology will be determined by the geographic distribution of research stars. The authors define a research star as a scientist that has discovered more than 40 genetic sequences as reported by *GenBank*.

The authors employ regressions on the stock of biotechnology-using firms at the beginning of 1990 by region, estimated in the Poisson form (appropriate for count variables with numerous zeroes). Their reported results indicate that the number of

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local stars and their collaborators is a strong predictor of the geographic distribution of biotech firms in 1990. Importantly, these results persist when controls are added for the number of top-quality universities in the region and the number of faculty with federal support in the region.

Branstetter also investigates the issue of localized knowledge spillovers. The methodology the author employs involves analysing *patent* citations to academic papers, which is subtly different from most of the work of this type, which uses patent citations to patents or paper citations to papers. Specifically, the author examines patent citations to academic papers authored by scientists affiliated with the campuses and laboratories of the University of California system.

Poisson and negative binomial models are used to estimate the effect of geographic distance on the likelihood that a patent cites a paper written at a particular location. The results suggest that distance does matter, or at least regions matter. While being in the same state has a statistically significant impact on the probability of a citation, linear distance measured in miles does not. The results also suggest that the temporal link between academic science and patented innovation is short. The modal lag in the raw data is only two years, indicating that it is recent science that is a driving force behind patenting.

Agrawal (2000) examines the importance of geographic distance and direct interaction between university inventors and company scientists to the successful transfer and commercialization of patented university inventions. This study is motivated by the hypothesis that geography matters because it increases the transaction costs associated with human interaction. Therefore, the geography effect should disappear once controls for interaction are introduced. The author runs this experiment using a dataset containing 124 license agreements associated with inventions from MIT. These data are augmented by interviews with the associated inventors for information regarding the amount of direct interaction that occurred between the inventor and scientists at the firm that licensed the invention.

Using logistic and Tobit regression models, the author reports results that support the hypothesis that geographic distance, measured in miles between MIT and the licensee, has a negative effect on the commercial success of the licensed invention. This effect becomes statistically insignificant when a control for direct scientific interaction, measured in numbers of hours, is introduced. The interaction explanatory variable does have a positive effect on both the likelihood and degree of commercial success.

In terms of applications for this work, these papers collectively suggest a framework for contemplating both policy and strategy in terms of geography. Simply stated, the work in this literature points to factors that influence location decisions, from both private and public perspectives. To what degree should firms consider the location of universities that are engaged in related research when they are deciding where to locate their own R&D facilities? To what extent should the government consider the location of industry clusters when they are deciding where to allocate university research funding? Knowledge spillovers often have a significant tacit component that remains geographically local, since it requires direct interaction amongst scientists and engineers. As a result, policy decisions regarding the allocation of federal research funds across geographic space may have significant effects on local economies.

Perhaps the most interesting conceptual issue that this literature raises is the variance in ‘absorptive capacities’ at the regional level. As discussed in the first section of this essay, the concept of absorptive capacity is traditionally considered at the firm level. However, the evidence presented in this stream of work directly implies that localization of knowledge spillovers does occur and indirectly implies that the degree of localization varies across regions. Given that knowledge localization is of central

concern to government policy, especially in terms of research funding at both the state and federal level, the notion of regional absorptive capacity should be of significant interest. The work that has been done in this area is preliminary, but sufficient to suggest many fruitful directions for future research.

Channels of Knowledge Transfer

This stream of research explores characteristics of the various channels through which knowledge is transferred from the university to industry. The channels under consideration in all of these studies include some subset of publications, patents, consulting, informal meetings, recruiting, licensing, joint ventures, research contracts, and personal exchange. Four of the five papers considered here examine the relative importance of various channels. Three of these emphasize the relatively small role of patents and licenses relative to other channels. This is, at least in part, in response to the heavy focus on patents as a technology-transfer mechanism due to the accessibility of patent data that lends itself well to quantitative analysis.

Cohen *et al.* (1998) and Cohen *et al.* (2000) both examine the relative importance of the complete set of transfer channels from the perspective of the knowledge *recipient*, firms. Agrawal and Henderson (2000) focus particularly on the comparison between patents and papers, but also examine the relative importance of the complete set of transfer channels from the perspective of the knowledge *creator*, professors. Within the context of licensed patented inventions, Colyvas *et al.* (2000) examine the importance of transfer channels that complement patent licensing across different types of technologies. Finally, Shane (2000) investigates the question of when it is best for a university to license an invention back to the inventor by considering the effectiveness of different transfer channels subject to the nature of the technology and its appropriability. These five papers are briefly described below.

Cohen *et al.* (1998) examine the importance of particular channels of knowledge transfer from the university to industry as perceived by industry. This component of the study primarily draws upon a 1994 survey of 1478 US R&D lab managers in the manufacturing sector. Respondents are requested to evaluate the importance of different information channels on a four-point Likert scale. The channels include patents, publications, meetings or conferences, information channels, hires, licenses, joint ventures, contract research, consulting, and personal exchange.

The authors report the results in a tabular format that lists the percentage of respondents indicating that a given channel is at least 'moderately important'. The results indicate significant variance across channels in the number of industries in which at least 50% of respondents indicate that particular channel is important. For example, while only one industry (drugs) out of 34 rates patents important at least half the time, 11 rate publications important. Also, while some channels are considered important by more industries, the less frequently valued channels are not necessarily subsets of the other. For example, 11 industries value publications while only two value contract research, but one of those two is the steel industry, which does not value publications (by at least half the respondents). These results suggest that some channels, such as publications, conferences, informal conversations, and consulting, are considered more important overall for knowledge transfer and also that different industries value different channels differently.

Cohen *et al.* (2000) investigate the pathways through which university research impacts industrial R&D. This study utilizes the same survey data that was used in Cohen *et al.* (1998), described above. This paper emphasizes the importance of publications, consulting, and open meetings and conferences relative to the licensing of patents and the recruiting of students, which is somewhat contrary to the conventional wisdom. Their data indicate that the largest percentage of respondents rated

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publications, conferences, and consulting as at least 'moderately important' knowledge transfer channels. These percentages are 41, 35, and 32%, respectively. The remaining channels are rated at least moderately important by a significantly smaller fraction of respondents, less than 20%.

The authors note that the channels considered important by the most respondents are, with the exception of consulting, those most commonly associated with open science. The authors also investigate how the scores for the different channels relate to each other. They accomplish this by correlation analysis of scores at the respondent level and factor analyses at the respondent and industry levels. The authors find significant correlation across the scores for all channels, but the strongest correlation (all above 0.58) are across the channels they identify as most important, including publications, conferences and meetings, and informal information exchange.

Agrawal and Henderson examine the importance of patents, relative to other channels, as a mechanism of knowledge transfer from universities to industry. This study is motivated by the authors' belief that the heavy use of patents in empirical studies of university technology transfer is disproportional to and misrepresentative of the total knowledge transfer from universities. They conduct this study on a sample of 225 professors from the Mechanical Engineering, Electrical Engineering, and Computer Science departments at MIT.

They report three sets of results. First, they compare the number of patents with the number of publications produced by these professors over the period 1983–1999 and discover that, although the number of patents did increase significantly, it is still only a small fraction (approximately 10%) of the number of publications. Also, patenting is concentrated amongst only a small percentage of faculty. While more than 50% of the sample publish at least one paper in any given year and only 6% have never published, nearly half of their sample have never patented at all. To supplement this part of their study, the authors interviewed a subset (68) of their sample population who, on average, perceive the patent channel to represent merely 7% of the total knowledge transfer.

Secondly, by analysing patent and paper collaborations as well as patent and paper citations, the authors show that those firms which take advantage of patented innovations are often not those that take advantage of published knowledge, suggesting that different firms tend to use quite different channels to access university knowledge. This implies that a focus on patent citations or on licensing behavior may offer only partial insights as to the ways in which MIT interacts with the private sector. Finally, the authors find little evidence to suggest that patenting distracts professors from publishing: faculties that patent are no less likely than their colleagues to publish, and their publications are no less likely to be widely cited.

Colyvas *et al.* (2000) explore in significant detail how particular university inventions moved into practice. They accomplish this by exploiting a unique and unusual data set comprising 11 case studies of inventions from Columbia and Stanford universities. These cases were assembled from invention report records and interviews with licensing officers and licensee firms. The study is motivated by the belief that the dramatic increase in patenting (and knowledge transfer through that channel), which is commonly attributed to the passage of the 1980 Bayh-Dole Act, was actually caused by other factors, including the maturing of important new areas and techniques of university research such as molecular biology, electronics, and software. The Act merely amplified an increase in university technology transfer that was already occurring.

The authors argue that university inventions vary from case to case and that there are a number of factors that influence which out of the set of transfer channels is most important in any particular case. For example, while direct interaction between inventors and

company scientists is necessary for some early-stage or embryonic inventions, others that are most effectively transferred through patent licensing do not require it. The latter type was most common in the area of biotechnology and pharmaceuticals. In this paper, the authors provide preliminary groundwork for the creation of a complex taxonomy of university inventions and related transfer channels.

Shane investigates the effects of licensing university inventions back to the inventor rather than to non-inventors. In particular, he examines the conditions under which inventors may be better suited than non-inventors to develop and commercialize an invention. This research is motivated by the need to increase our understanding of the variance in appropriability across invention types and the effects of this variance on the ability to advance early-stage university inventions successfully. The author runs this experiment using a dataset of 1397 patents issued to MIT over the period 1980–1996. He utilizes royalty, sponsorship, and invention description data recorded by the MIT Technology Licensing Office to supplement this data.

The results support the author's general hypothesis that inventions that can be effectively patented are more likely to be licensed. Results also support the author's less obvious hypothesis that those that cannot be as effectively patented are more likely to be licensed to the inventor and, when this happens, are more likely not to be terminated and to be commercialized. In other words, non-inventors more effectively commercialize inventions when the inventions are appropriable through patents (implying non-inventors are better managers, on average), but the inventor best develops inventions that are more difficult to appropriate. This result has direct implications for the effectiveness of various knowledge transfer channels, depending on the appropriability of the invention.

In terms of applications of this work, these papers collectively suggest frameworks for contemplating firm strategies associated with leveraging public-sector research. While a reasonably efficient market has been established for trade in patent-protected intellectual property through university technology licensing offices, transfer through the other channels described is much less formal and arguably much less efficient. As a result, firms may benefit significantly by investing in the types of relationships that are not necessary in the presence of an efficient market. Such relationships may involve engaging in collaborative research projects, hiring professors as consultants, sponsoring university lab projects, and participating in research consortia, amongst others.

As mentioned earlier, this literature provides compelling evidence that non-patent channels of knowledge transfer are economically important. Thus, there is a need for further research that specifically examines the nature of those transfer channels less studied. In addition, many of the questions addressed in the three research streams described above must be re-examined from the perspective of these channels. This will require a variety of research techniques, since non-patent channels do not leave a convenient paper trail that lends itself to systematic, empirical analysis. Also, even patent-related topics may require re-examination with alternative methodologies so that this channel may be directly compared with the others with similar types of data. In cases where patent-channel knowledge transfer is shown to be similar to other channels, it may be reasonable to generalize from patent data in order to offer empirical insights into non-patent channel topics.

Future Research and Conclusions

It is clear from surveying the literature on this topic that much has been learned about the process of knowledge transfer from university to industry. However, much work remains. In this section, new research questions are offered for each of the four categories described above. These are, of course, not

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intended to represent any form of an exhaustive set, but rather provide a flavor for the types of research that seem most fruitful given past and current efforts. To this end, it is important to point out that the author of this essay purposefully included many examples of very recent papers, some of which have not yet been published, in order to provide a snapshot of the current activity in this field, so that this paper may prove a useful framework for further work to build on.

The studies to date on *firm characteristics* have inspired a focus on factors that influence the firm's absorptive capacity. All of these studies have focused on a single industry, in most cases biotechnology, pharmaceuticals, or semiconductors. The field will greatly benefit from future work that explores the degree to which methods for building absorptive capacity differ *across* industries, and also the ways in which these methods differ. Also, while there have been significant efforts to investigate the mechanics of R&D investment for generating connectedness, further study is needed to understand the other methods for building connectedness, such as university links, research consortia, and industrial partnerships. Finally, variations in connectedness across different political and cultural environments remain to be explored.

Much of the work in the area of *university characteristics* has focused on determining the effects of the Bayh-Dole Act. While this is certainly an interesting and important topic, there are many others that have been largely ignored. For example, we know very little about the amount and type of technology transfer that occurs outside the formal route of the technology transfer office, but many scholars have suggested that there is reason to believe this could be quite significant. Also, the field would very much benefit from more detailed studies that investigate the variance in licensing agreement terms across technologies as well as across universities. While the equity versus cash-only dichotomy is critical, there are also great differences in other areas of licensing contracts, such as the 'use it or lose it' clause that defines development milestones. Finally, given the importance of inventor involvement suggested by several studies, it seems clear that studies to understand better the factors that influence the degree to which professors become involved with the commercialization of their inventions would make a valuable contribution.

In recent years, it seems as though research on *geography in terms of localized knowledge spillovers* has attracted the most amount of public attention. This is most likely to be due to the direct policy implications of this work. Further research in this area will certainly include studies of the 'Internet effect' and the degree to which this weakens the geography effect due to reductions in transaction costs associated with some forms of communication. In addition, given the trend towards greater globalization, studies of border effects on spatial relationships and knowledge spillovers will be in great demand. Finally, although the current literature has collectively presented a very strong case in support of significant localization effects associated with knowledge spillovers, there remain exceptions. That is, there are notable examples in particular industries and particular geographies, where knowledge spillovers appear to defy the otherwise ubiquitous forces of localization. These exceptions demand further investigation.

Issues concerning *knowledge transfer channels* may at one time be both the most and least well studied. The existence of patent and publication archival data in conjunction with the associated citation data offers an unparalleled research tool for objective, quantitative analysis in the area of scientific and technological development. However, while patents and papers are certainly important, such heavy use of these data as has occurred in this field comes at the expense of investigations into other forms of communication of scientific progress and has resulted in a severe lack of variety of research questions. To this end, basic research into the mechanics and characteristics of other channels, such as faculty consulting and the

recruiting of graduate students, would make tremendous contributions to this area of inquiry. It is also important to develop a better understanding of complementarities across channels as well as non-channel complementarities, such as has been suggested about venture capital in the case of knowledge transfer in industries populated with young firms. Finally, research on the different uses of different channels across countries, owing to variations in intellectual property rules, university policies, and culture, amongst other factors, would offer an interesting and important contribution to this field.

To conclude, we have learned from the work in this field that there are differences in the degree to which firms are capable of effectively utilizing university research to their benefit and that these differences vary systematically with the degree to which firms are connected to the university. However, we have only begun to investigate the various mechanisms by which firms are connected and the relative benefits associated with each mechanism. We have learned that variations in certain university intellectual property policies are related to the degree of production and licensing of patents. However, the field has yet to address the many potential university policy issues that arise from non-patent-related technology transfer, which may be substantially more important from an economic perspective.

We have learned that, despite the open-science culture that is prevalent in the university environment and that results in the regular publication and patenting of ideas that are equally available across all geographic space throughout most of the developed world, the commercialization of university inventions remains somewhat localized to the region of invention. However, much work remains to explain the persistence of 'super' high-technology regions such as Silicon Valley and Route 128, and why all cities with significant research universities do not enjoy substantial hi-tech economies. Finally, we have learned that university knowledge may be transferred to industry through a variety of channels and that the patent-related channel is less important than commonly believed. However, the field has only scratched the surface by identifying that the other channels are indeed perceived to be important by both firms and professors, while virtually no scholarly research has directly investigated the characteristics of the non-patent channels.

Overall, it is the intention of this essay to illustrate that the economic importance coupled with the complex nature of this topic combine to offer a wide range of interesting questions and demand a multiplicity of research methodologies.

Notes

1 Support for this research from the Center for Knowledge-Based Enterprises at Queen's University is gratefully acknowledged.

2 These statistics were generated from the AUTM Licensing Survey: FY 1999. Respondents included 190 US and Canadian universities, teaching hospitals, and research institutes.

3 It is important to note that the firm's market capitalization had reduced to approximately $2.5bn at the time of writing this paper (16 February 2001). This dramatic devaluation is reasonably consistent with other firms in this sector, following the March 2000 market correction.

4 The concept of 'absorptive capacity' is prevalent throughout the knowledge transfer literature. This refers to a firm's ability to recognize, assimilate, and apply new scientific information for its innovation and new product development.

References

Agrawal, A. (2000). Importing scientific inventions: direct interaction, geography, and economic performance. Mimeo, Massachusetts Institute of Technology.

Agrawal, A. and Henderson, R. (2000). Putting patents in context: exploring knowledge transfer from MIT. Mimeo, Massachusetts Institute of Technology.

Association of University Technology Managers, Inc. (1999) *AUTM Licensing Survey, FY 1999: A Survey Summary of Technology Licensing (and*

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Related). Performance for U.S. and Canadian Academic and Nonprofit Institutions, and Patent Management Firms. Northbrook, IL: AUTM

Audretsch, D.B. (2000). Is university entrepreneurship different? Mimeo, Indiana University.

Audrestch, D.B. and Feldman, M.P. (1996). R&D spillovers and the geography of innovation and production. *American Economic Review*, **86**(3), 630–640.

Branstetter, L. (2000). Measuring the link between academic science and industrial innovation: the case of California's research universities. Mimeo, University of California, Davis.

Cockburn, I. and Henderson, R. (1998). Absorptive capacity, coauthoring behavior, and the organization of research in drug discovery. *Journal of Industrial Economics*, **XLVI**(2), 157–182.

Cohen W.M. and Levinthal, D.A. (1989). Innovation and learning: the two faces of R&D. *The Economic Journal*, **99**, 569–596.

Cohen W.M. and Levinthal, D.A. (1990). Absorptive capacity: a new perspective on learning and innovation. *Administrative Science Quarterly*, **35**, 128–152.

Cohen, W.M., Florida, R., Randazzese, L. and Walsh, J. (1998). Industry and the academy: uneasy partners in the cause of technological advance. In Noll, R.G. (ed.), *Challenges to Research Universities*, Ch. 7. Washington, DC: Brookings Institute Press.

Cohen, W., Nelson, R. and Walsh, J. (2000). Links and impacts: survey results on the influence of public research on industrial R&D. Mimeo, Carnegie Mellon University.

Colyvas, J., Crow, M., Gelijns, A., Mazzoleni, R., Nelson, R., Rosenberg, N. and Sampat, B.N. (2000). How do university inventions get into practice? Mimeo, Stanford University.

Di Gregorio, D. and Shane, S. (2000). Why do some universities generate more start-ups than others? Mimeo, University of Maryland.

Feldman, M., Feller, I., Bercovitz, J. and Burton, R. (2000). Equity and the technology transfer strategies of American research universities. Mimeo, Johns Hopkins University.

Griliches, Z. (1979) Issues in assessing the contribution of R&D to productivity growth. *Bell Journal of Economics*, **10**, 92–116.

Henderson, R., Jaffe, A. and Trajtenberg, M. (1998). Universities as a source of commercial technology: a detailed analysis of university patenting, 1956–1998. *Review of Economics and Statistics*, **80**(1), 119–127.

Jaffe, A. (1989). The real effects of academic research. *American Economic Review*, **79**, 957–970.

Jaffe, A., Trajtenberg, M. and Henderson, R. (1993) Geographical localization of knowledge spillovers by patent citations. *Quarterly Journal of Economics*, 577–598.

Jensen, R. and Thursby, M. (1998). Proofs and prototypes for sale: the tale of university licensing, NBER Working Paper 6698.

Lim, K. (2000). The many faces of absorptive capacity: spillovers of copper interconnect technology for semiconductor chips. Mimeo, MIT.

Shane, S. (2000). Selling university technology: patters from MIT. Mimeo, University of Maryland.

Shane, S. and Stuart, T. (2000). Organizational endowments and the performance of university start-ups. Mimeo, University of Maryland.

Thursby, J.G. and Thursby, M.C. (2000). Who is selling the ivory tower? Sources of growth in university licensing. NBER Working Paper 7718.

Ziedonis, A.A. (1999). Inward technology transfer by firms: the case of university technology licenses. Mimeo, University of California, Berkeley.

Zucker, L., Darby, M. and Brewer, M. (1998). Intellectual capital and the birth of U.S. biotechnology enterprises. *American Economic Review*, **88**, 290–306.

Zucker, L.G., Darby, M.R. and Armstrong, J.S. (2000). University science, venture capital, and the performance of U.S. biotechnology firms. Mimeo, University of California, Los Angeles.