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THE NEW ECONOMICS OF INNOVATION, SPILLOVERS AND AGGLOMERATION: A REVIEW OF EMPIRICAL STUDIES

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This paper reviews recent empirical studies of location and innovation. The objective is to highlight the questions addressed, approaches adopted, and further issues that remain. The review is organized around the traditions of measuring geographically mediated spillovers and productivity studies that introduce a geographic dimension. The first part identifies four separate strains in the empirical spillover literature: innovation production functions; the linkages between patent citations, defined as paper trails; the mobility of skilled labor based on the notion that knowledge spillovers are transmitted through people; and, last, knowledge spillovers embodied in traded goods. The second part considers the composition of agglomeration economies, the attributes of knowledge, and the characteristics of firms.

KEY WORDS: Innovation, Geography, Spillovers, Location
JEL Classification: O3, L2

1. INTRODUCTION

There is general consensus that the rate of technical change is important in determining an economy's rate of growth. We have, however, a limited understanding of the sources of technical progress and the reasons why the innovation varies over time and across space. The new growth theories suggest that differences in growth rates may result from increasing returns to knowledge (Romer 1986; Lucas 1988, 1992; Grossman and Helpman 1992). One source of increasing returns may be agglomerations or geographic concentrations of knowledge that provide a means to facilitate information searches, increase search intensity, and, in general, ease task coordination. In addition, knowledge is not easily contained and geography provides one means to define knowledge spillovers. For these reasons,

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location may enhance the generation of innovation and yield higher rates of technological advance and economic growth (Krugman 1991a,b; David and Rosenbloom 1990).

Empirical studies now define location and geography differently from an older tradition that was motivated to identify optimal location for economic activities. New methods of modeling imperfect competition and technological innovation have placed the persistence of agglomeration economies and the existence of increasing returns, especially within a limited spatial context, at the heart of the analysis. Within the new empirical literature there is an appreciation for the locational context and the diversity of the landscape that condition economic activity. The concept of location is now defined as a geographic unit over which interaction and communication is facilitated. Recent empirical studies attempt to capture the geographic landscape over which economic activity is enhanced.[1]

There are two major intellectual traditions for the empirical study of innovation and location. The first tradition is predicated on the concept of geographically mediated spillovers and includes a geographic dimension to the determinants of innovation. Studies in this tradition are based upon the logic of the production function which employs some measure of innovation as the dependent variable against a set of possible explanatory variables — all measured for a common geographic unit. These studies try to quantify the impact of knowledge spillovers on innovation using geography as a platform. The second tradition is motivated to understand differences in economic outcomes such as economic growth or productivity across locations. This work focuses on growth or productivity as the dependent variable and considers factors that condition the effects of location on these outcomes. In this tradition, innovation may enter as a potential intermediate link as, for example, agglomeration economies drive innovation which then drives growth. Most importantly because geographic characteristics

[1]In studying the networks in California's Silicon, Valley Saxenian (1990, pp. 96-97) emphasized that it is the communication between individuals that facilitates the transmission of knowledge across agents, firms and even industries. "It is not simply the concentration of skilled labor, suppliers and information that distinguish the region. A variety of regional institutions — including Stanford University, several trade associations and local business organizations, and a myriad of specialized consulting, market research, public relations and venture capital firms — provide technical, financial, and networking services which the region's enterprises often cannot afford individually. These networks defy sectoral barriers: individuals move easily from semiconductor to disk drive firms or from computer to network makers. They move from established firms to start-ups (or vice versa) and even to market research or consulting firms, and from consulting firms back into start-ups. And they continue to meet at trade shows, industry conferences, and the scores of seminars, talks, and social activities organized by local business organizations and trade associations. In these forums, relationships are easily formed and maintained, technical and market information is exchanged, business contacts are established, and new enterprises are conceived... This decentralized and fluid environment also promotes the diffusion of intangible technological capabilities and understandings."

are exogenous it is possible to disentangle effects.

The purpose of this paper is to provide a review of recent empirical studies of location and innovation. The objective is to highlight the questions that empirical studies have addressed, approaches adopted, and further questions that remain. This inquiry is organized around the two traditions: first, considering studies that attempt to measure geographically mediated spillovers; and, second, related studies with a geographic dimension. The first part of this review identifies four separate strains: empirical studies employing innovation production functions; empirical studies on the linkages between patent citations, defined as paper trails; studies that measure the mobility of skilled labor on innovation based on the notion that knowledge spillovers are transmitted through people; and, last, empirical studies based on the notion that knowledge spillovers are embodied in traded goods. The second part of this review considers the composition of agglomeration economies, the attributes of knowledge, and the characteristics of firms as they relate to location.

2. EMPIRICAL STUDIES OF GEOGRAPHICALLY MEDIATED KNOWLEDGE SPILLOVERS

Griliches (1992) defines knowledge spillovers as "working on similar things and hence benefitting much from each other's research." As an example, Jaffe (1986) found that a significant fraction of the total flow of spillovers that affect a firm's research productivity originates from other firms. This work reveals that firms benefit from the R&D efforts of other firms that are in close technological proximity. Once we believe that knowledge spillovers can easily cross firms then the possibility that spillovers may be geographically mediated becomes credible. An empirical testing of the effect of geographic proximity is a logical extension of this line of inquiry. This review now considers four approaches to the study of knowledge spillovers.

2.A *Geographic Innovation Production Functions*

In the first study to examine geographically mediated knowledge spillovers, Jaffe (1989) modified the knowledge production function approach introduced by Griliches (1979) to account for spatial and product dimensions:

$$I_{si} = IRD^{\beta_1} * UR_{si}^{\beta_2} * \varepsilon_{si} \tag{1}$$

where I is the measure of innovative output, *IRD* is private corporate expenditures on R&D and *UR* is the research expenditures undertaken at universities.[2] This conceptualization changed the observation from the traditional unit of the firm to the geographic level, s, for an industry, I.

The geographic unit Jaffe used was at the state level. In contrast to other types of economic analysis in which the unit of observation is well known and easily identifiable, the most appropriate unit to use on a spatial dimension is not well established. States are used because they are easy to identify, and the data are accessible and more reliable than at more local levels.

Jaffe found that patents occur in those states, s, 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. Feldman (1994b) adapted the knowledge production function framework to data on new market introduction in order to test the model against a more direct measure of innovative output than patent data.[3] Since commercial innovations were closer to the market than patents, Feldman added related industry presence and the receipts for business services as two additional knowledge generating inputs suggested by the case study literature. The basic result held: geographic regions with greater amounts of knowledge-generating inputs produce more innovation. These findings suggest that knowledge spillovers tend to be geographically bounded within the region where new economic knowledge was created. That is, there are geographic limits to the spillovers of new economic knowledge.

While the earliest studies to estimate the knowledge production function used state level data, the robustness of the basic results using sub-state data hold (Anselin et al., 1996). One limitation to the geographic estimation of the knowledge production function is conceptual because there is no understanding of the way in which spillovers occur and are realized at the geographic level. The pre-existing pattern of technology related activities makes it difficult to separate spillovers from the correlation of variables at the geographic level. Economic activity may be co-located but the pattern of causality is difficult to discern.

Jaffe (1989) found an important indirect or inducement effect as university research increases industry R&D which thereby increases patents. This effect is quantitatively larger than the direct effect of a given increase in university research.

[2] Jaffe's formulation also included a measure of the geographic coincidence of university and corporate research to compensate for the use of the state as the unit of analysis.

[3] The United States Small Business Administration's Innovation Data Base consists of new product introductions compiled from the new product announcement sections of over one-hundred technology, engineering and trade journals spanning every industry in manufacturing. An innovation is defined in the database as a process that begins with an invention, proceeds with the development of the invention, and results in introduction of a new product, process or service to the marketplace.

The knowledge production function implies that innovative activity should cluster in regions where knowledge-generating inputs are the greatest and thus where knowledge spillovers are the most prevalent. Audretsch and Feldman (1996), follow Krugman's (1991b) example, and calculate Gini coefficients for the geographic concentration of innovative activity to test this relationship.[4] The results indicate that a key determinant of the extent to which the location of production is geographically concentrated is the relative importance of new economic knowledge in the industry. 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. In this work, skilled labor is included as a mechanism by which knowledge spillovers may be realized as workers move between jobs in an industry taking their accumulated skills and know-how with them.

These studies, in conclusion, provide evidence of the existence of geographically mediated spillovers. These findings do not address either the path that spillovers take or the mechanisms by which spillovers are realized. These have been provided by work reviewed in the next section.

2.B Paper Trails

Persuasive evidence about the existence of knowledge spillovers is found by examining what may be termed the *paper trails* left by patent citations. Krugman (1991a, p. 53) argues that economists should abandon any attempts at measuring knowledge spillovers, because "knowledge flows are invisible, they leave no paper trail by which they may be measured and tracked." But Jaffe, Trajtenberg and Henderson (1991, p. 578) point out that, "knowledge flows do sometimes leave a paper trail" — in particular, in the form of patented inventions and new product introductions. Building on Trajtenberg's (1990) approach of linking an originating or major patent application to the other patents that reference or cite it, this work traces the

[4]The Gini coefficients are weighted by the relative share of economic activity located in each state. Computation of weighted Gini coefficients enables us to control for size differences across states. The Gini coefficients are based on the share of activity in a state and industry relative to the state share of the national activity for the industry. The locational Gini coefficients for production are based on industry value-added. We calculate the amount of value added in an industry and a state divided by national value-added for the industry. This ratio is normalized by the state share of total manufacturing value-added in order to account for the overall distribution of manufacturing activity. An industry which is not geographically concentrated more than is reflected by the overall distribution of manufacturing value-added would have a coefficient of 0. The closer the industry coefficient is to 1, the more geographically concentrated the industry would be. Cases is which data are suppressed are omitted from the analysis. The Gini Coefficients for innovation are based on counts of innovation in a state and industry are calculated in a similar way.

pattern of patent citations to explore both the temporal and geographic span of knowledge spillovers. For example, starting with 1450 patents that originated in 1980, Jaffe, Trajtenberg and Henderson trace the characteristics of approximately 5200 citations that occurred to these originating patents from 1980 to 1989. The relationships between the originating patents and the citing patent are used to identify knowledge spillovers.

To adjust for bias due to the existing geographic distribution of technical activity, a control sample that closely resembles the citing patent in terms of technology and timing was selected. The frequency of the match between the originating patent and the control patent provide a baseline against which the frequency of originating patent-citing patents matches are normalized (Jaffe et al., 1993: p-581-583). This allows a test for the extent to which spillovers are localized relative to what would be expected given the existing distribution of technological activity.[5]

Jaffe, Trajtenberg and Henderson (1993) find evidence of the localization of citations, that is, patents cite other patents that originate in the same city with greater frequency. Citations are five to ten times as likely to come from the same city as the control patents.[6] For every geographic level, and adjusting for different organizational types, such as universities, top corporation and other corporations, citations are statistically significantly more localized than the controls. These results hold for two cross-sections. It is important to point out that the effects, though statistically significant, are fairly small.

This research further uncovers factors that condition localization. For example, citations are more likely to be localized in the first year following the patent. This effect fades with time: citations show less geographic effects as knowledge diffuses. This work also highlights the conditions on spillovers as the frequency and duration of citations depends on the scientific field. For example, Jaffe and Trajtenberg (1996) find that electronics, optics, and nuclear technology enjoy high immediate citation but, due to quick obsolescence, experience a rapid fading of citations over time. The effect of the patent on subsequent citations also depends on the institutions from which they originated. For example, government patents tend to be less "fertile", having fewer citations than university and corporate patents. University patents are more fertile than corporate patents. Additionally, these results are variant to time suggesting that technological opportunity may be changing. For example, citation intensity, the average number of citations that a patent receives, declined in the late 1980s across all institutions and categories.

[5]In a further attempt to capture true spill-overs, this work also excludes self-citations, that is, patents that are owned by the same organization as the originating patent.

[6]For example, 12.6% of the university patents and 21.9% of the top corporate patents were localized from the 1980 cohort.

This methodology has been applied by Almedia and Kogut (1997) to study patenting in the semiconductor industry. The basic results hold - patent citations are highly localized, indicating that there are geographic limits to knowledge spillovers. There has not, to date, been an empirical study that considers how geographic spillovers may be affected by new telecommunications technology. We might expect an "Internet effect" in which new technology may diminish the advantages of location by increasing access to knowledge and speeding its diffusion.[7]

2.C Ideas In People

None of the above studies address the mechanism by which knowledge spillovers are realized. One avenue that has been explored by Zucker and Darby (1996) is that ideas are embodied in individuals who have the skill, knowledge and know-how to engage in technological advance. Zucker and Darby (1996) summarize a series of papers that examine the role of "star scientists" as a source of intellectual capital that drives the transformation of bioscientific knowledge into commercial applications. This work focuses on the human capital of key individuals rather than the average human capital in a local labor market.[8] This work demonstrates that localized intellectual capital is key in the development of the biotech industry and that knowledge generates externalities that tend to be geographically bounded within the region where these scientists reside.

A "star scientist" is defined as a highly productive individual who discovered a major breakthrough. Using this criteria, there are 337 stars who authored 4315 articles related to biotechnology. In addition, there is a group of collaborators who co-authored with the stars yielding a total of 4,196 observations in the U.S.[9] These individuals embody the intellectual capital necessary to commercialize breakthrough discoveries in biotech. These scientists are geographically concentrated in 141 universities, 74 research institutes and 48 firms in a relatively small number of locations in the U.S.

The start-up of New Biotech Entities (NBEs) is localized in regions in which this intellectual capital resides. These scientists embody knowledge of breakthrough techniques that is initially only available at the lab bench

[7]Glaeser (1998) suggests that there is no evidence that the Internet will destroy cities.

[8]Lucas (1988) suggests that the ability to develop and implement new technology depends on the average level of human capital in the local economy. Using national level data, Bartel and Lichtenberg (1987) demonstrate that more local skilled labor force produces greater innovation. Glaeser et al find that higher average levels of human capital are tied to higher rates of growth in cities.

[9]Zucker, Darby and Brewer (1994) find that firm scientists had a higher total number of citations than scientists in universities or in research institutes and hospitals.

of these scientists, making it costly for others to obtain or use. Zucker, Brewer and Armstrong (1994) find localized linkages between the stars and the NBEs. The number of publications in these bench-level working relationships predicted higher subsequent firm productivity in terms of products in development, products on the market and employment growth in the firm. Firms with access to leading edge scientists preformed better than enterprises lacking such access.

Zucker, Darby and Brewer (1997) find that intellectual capital (in terms of the numbers of stars and their collaborators in a given area) is predictive of NBEs, controlling for presence of universities and federal funds. The Zucker paper empirically demonstrates boundary spanning between universities and NBEs via star scientists at universities who have made scientific breakthroughs. Using panel data on the number of NBE's within a local labor market[10], knowledge spillovers from the star scientists is demonstrated.

Almedia and Kogut (1997) extend this approach of following intellectual capital by considering the inter-firm and inter-mobility of star patent holders in order to trace the transfer of ideas in semiconductors. Their results suggest that inter-firm mobility results in the transfer of ideas as demonstrated by the subsequent assignment of patents and that these knowledge spillovers are geographically confined.

In conclusion, this work demonstrates that localized intellectual capital is key in the development of the new industry and that knowledge generates externalities that tend to be geographically bounded within the region where these scientists reside. In related work, Stephan and Audretsch (1996) examine the scientific advisory boards of NBEs and find that these relationships are not necessarily geographically mediated, indicating that further work is needed to reconcile the conditions and stages of the industry life cycle when location and proximity matter.

Sokoloff (1988), in an investigation of nineteenth patenting activity, finds that the regional concentration of patenting was geographically concentrated but then became more disperse as industrialization occurred.

The work of Zucker and Darby focuses on the human capital of key individuals rather than the average human capital in a local labor market. Lucas (1988) suggests that the ability to develop and implement new technology depends on the average level of human capital in the local economy. Using national level data, Bartel and Lichtenberg (1987) demonstrate that greater skill levels in the labor force produces greater innovation. Glaeser et al (1992) find that higher average levels of human capital are tied

[10]The local labor market is defined using Bureau of Economic Analysis (BEA) units. There are 183 functional units.

to higher rates of growth in cities. It may be that key individuals are important to new company start-ups but are not sufficient to anchor an industry in a location. This is a testable hypothesis that has implications for places that are trying to develop technology intensive industries.

2.D Ideas In Goods

Knowledge spillovers may be embodied in goods in which the innovator is unable to appropriate all the surplus from the trade.[11] There are a series of empirical studies which assume that trade is the prime mechanism by which spillovers are mediated. Coe and Helpman (1995) find that international R&D spillovers mediated by trade are strong and significant. Import-weighted foreign R&D spillovers are significantly correlated with domestic productivity levels. Similarly, Park (1995) considers R&D sources, either public or private, and further disaggregates by sector. Park uses these measure of sectoral allocation of R&D to measure technological proximity and finds evidence of international R&D spillovers.

Keller (1997a) compares the elasticity of domestic productivity with respect to foreign R&D with an elasticity based on counterfactual, randomly created international trade patterns. Using a Monte-Carlo simulation, Keller created a series of randomly generated bilateral trade relationships and creates trade weighted foreign R&D stocks. He concludes that the randomly generated trade patterns give rise to large estimated international R&D spillovers. He concludes that R&D spillovers must be estimated in a model which allows simultaneously for trade-related international technology diffusion. Keller's results cast doubt on the previous studies, however it should be noted that studies in this vein are based on estimations of a knowledge production function with aggregate data for which there is not means to control for heterogeneity between firms, industries and countries. Branstetter (1996) uses firm level data to assess international and intranational spillovers and finds that knowledge spillovers are primarily intranational in scope, indicating that spillovers are confined within a country. There is still much to be done to understand, and quantify, international knowledge spillovers.

To summarize, these four approaches demonstrate the existence of geographically-mediated knowledge spillovers, the persistence and importance of localized knowledge and one path, skilled labor, that provides a mechanism for knowledge spillovers. The next section seeks to integrate what we have learned from empirical studies of firms' production and investment decisions that have added a geographic dimension. The objective is to

[11] Branstetter (1997) provides a comprehensive review of international knowledge spillovers.

establish what we have learned about the factors that condition the relationship of location on innovation.

3. LOCATION, LOCATION, LOCATION

This section organizes the empirical literature that adds a geographic dimension to the study of economic phenomenon such as growth, productivity and investment decisions. These studies suggest that there are several key considerations that condition the effects of location on innovation, and subsequently other economic outcomes. The first of these to be considered here is the composition of agglomeration economies, the second considered are the attributes of knowledge that condition the effect of location on economic activity, and finally, the characteristics of industries will provide some general parameters on the interaction of innovation and location.

3.A Agglomeration Economies

In seeking to understand how location affects economic activity, empirical research has classified agglomeration economies into either localization economies or urbanization economies. This distinction was first noted by Loesch (1954). Localization economies are external to a firm but internal to an industry within a geographic region. In contrast, urbanization economies are noted to be the scale effects associated with city size or density. These definitions imply different concepts of the composition of economic activity within a location and have implications for industrial location and innovation (Henderson, 1983). Each of these are addressed in empirical studies with their subsequent impact on knowledge spillovers and innovation.

Localization economies, or what Glaeser, Kallal, Scheinkman and Shleifer (1993) define as *Marshall-Arrow-Romer* externalities, are knowledge spillovers external to firms, yet internal to an industry within a city. A local industry agglomeration may increase innovation directly by providing industry specific complementary assets and activities that may either lower the cost of supplies to the firm or create greater specialization in both input and output markets. We expect that industries in which complementary assets are important would more likely be concentrated geographically and realize greater innovative productivity.

The empirical evidence on localization economies is mixed. Henderson (1986) finds that localization raises factor productivity for the U.S. and Brazil. In contrast, neither Glaeser et al. (1993) nor Feldman and Audretsch (1996) find that industry localization increases either growth or innovative activity. This may be due to the fact that industries which have a high degree of concentration in a local economy may be mature industries that have large scale production facilitates that dominate certain locations. A high concentration of an industry in a location may measure geographic specialization and not dynamic localization economies.

One reason that industries may concentrate geographically is due to locational factor endowments. Head, Reis and Swenson (1995: page 227), drawing on the international trade literature, provide an alternative hypothesis of endowment driven localization. Under this formulation, industries may be localized due to differential factor endowments among places. For example, sawmills might congregate in a particular state to take advantage of the supply of high quality timber. This reason would be distinct from localization due to knowledge spillovers. The location of Japanese investment in the U.S. provides a quasi-experiment that allows Head, Reis and Swenson (1995) to trace the degree to which Japanese investment reflects either of these sources of localization. The evidence is that Japanese investments are influenced by the location of prior investment in the same industry, suggesting that firms locate near other firms in order to benefit from information externalities and not for factor endowment reasons.

In contrast, urbanization economies are the scale effects associated with the attributes of place. Urbanization economies are external to industries but internal to geographic units such as cities. It is urbanization economies that Lucas (1993) describes when he asserts that the only compelling reason for the existence of cities would be the presence of increasing returns to agglomerations of resources which make these locations more productive. Urbanization economies have been measured by population size and density in the literature. Again, the empirical evidence has been somewhat mixed. Henderson (1986) finds evidence of urban diseconomies or congestion effects on productivity growth. Nakamura (1985) and Moomaw (1988) find evidence that urbanization economies are more important in specific industries such as apparel, food products, and printing, but not in heavy, durable product industries.

Jacob (1969) argues that urbanization economies are realized through the exchange of complementary knowledge across diverse firms and economic agents within geographic regions. In economics this is the concept of cross product increasing returns — one activity increases the marginal product of another activity and the effect is greater with proximity. In a theoretical context, Jacob's agglomerations may reduce search costs and also increase the opportunity of serendipitous events that would provide innovative opportunities.

Empirical studies have supported the idea that location brings together closely related activities to benefit innovation. Jaffe et al. (1993) find evidence that knowledge spillovers are not confined to closely related technologies, as approximately 40 per cent of citations do not come from the same primary patent class as the originating patent. Glaeser et al. (1993)

provide the first empirical test of Jacob externalities using the concentration of the top five industries in a city and find that more diversity in the local economy is associated with higher rates of growth.

One question in empirical work is how we might define diverse yet complementary knowledge that would create economically useful spillovers. Feldman and Audretsch (1996) use survey data from Levin et al. (1987) to discern the disciplines that form a common science base that contributes to the basis for cross-industry increasing returns. This work finds that industries that rely on the same science base tend to cluster geographically and the presence of diverse industries within the same science-base in a city leads to increased innovation.

The concept of agglomeration economies also includes the presence of intermediate suppliers and service providers. A question in empirical work is what types of industries and activities constitute an agglomeration. For example, industrial R&D and university research are inputs in the formulation of the knowledge production function. This is predicated on an understanding that universities are important suppliers of knowledge (Mansfield, 1995). There are many empirical studies that establish the importance of local universities to innovation. For example, Beeson and Montgomery (1992) examine the relationship between universities and labor market conditions. They find that universities raise the average skill level of the surrounding area and that positively affects wage and employment rates. The study focuses on employment growth rates for the time periods 1975-1980 and 1980-1989 and finds that employment growth is related to increases in university R&D funding as well as to the number of nationally rated science and engineering programs at local universities. The results are consistent across the two time periods.[12]

For specific industries, it may be possible to define a set of relevant suppliers. For example, Smith and Florida (1994), in a study of Japanese investment in the automobile industries and auto-related parts suppliers, find that suppliers locate near the automobile assembly plants to form the sort of industrial district agglomeration that Marshall discusses. We expect that an agglomeration of related suppliers would result in increased innovation or productivity. There have been no general tests of this hypothesis using a source such as input/output tables or commodity flows. Justman (1994) uses this type of data to demonstrate that local demand influences industry location decisions and it would be useful to extend this approach.

[12]The results on income, employment rate and net migration are somewhat mixed. Choice of time period does not include the turnaround prompted by innovation in the computer industry known as the Massachusetts Miracle nor does it capture the computer revolution which certainly are two incidents of high innovative activity that anecdotally are associated with increased local earnings, higher employment rates and net in-migration.

In conclusion, the external economies associated with location have been defined in a variety of ways. The main concern is on the composition of activity within a region, either own industry localization, urban scale economies, Jacobs' concept of diversity or the idea of specialized supplier networks. Another way to consider the interaction of location and innovation is based on attributes of knowledge which condition the ways in which different industries might benefit from location. These are considered in the next section.

3.B Attributes of Knowledge

Knowledge has certain characteristics which may condition the effects of location on innovation. Since knowledge is one of the most decisive inputs for innovation, this section considers what empirical work suggests about the tacitness of knowledge, technological opportunity and the appropriability of knowledge for the location of innovation.

Knowledge varies to the degree that it is tacit or articulable. Knowledge with a low degree of tacitness may be easily standardized, codified, and transmitted via journal articles, project reports, prototypes, and other tangible mediums. In contrast, tacit knowledge has a higher degree of uncertainty and the precise meaning is more interpretative and is not easily conveyed in a standardized medium. As a consequence, when knowledge is more tacit in nature, face to face interaction and communication are important and geographic proximity may promote commercial activity (Von Hipple, 1994). That is, the less codified and articulated the knowledge, the greater the degree of centralization in geographic organization.

A problem arises in the measurement of the tacitness of knowledge. Using data on the results of publicly supported R&D projects in the European Community, Feldman and Lichtenberg (1997) construct several indicators of tacitness based on the degree to which projects results in prototypes which might be easily transferred or others result in know-how that are novel and less able to be transmitted. The results indicate that the more tacit, or less codifiable, the knowledge generated by the R&D is expected to be, the greater is the extent of geographic, and administrative, centralization of R&D activities.

Knowledge, rather than being a continuous flow, is affected by new discoveries and breakthroughs that provide different opportunities to realize technological advance and innovation. Caballero and Jaffe (1993) argue that the extent of knowledge spillovers depends on both the rate at which new ideas outdate old ideas, that is the obsolescence of ideas, and on the rate at which knowledge diffuses among users. Their empirical results, based on patent citations, conclude that the stock of existing knowledge that is useful in generating new inventions has been declining. This suggests that current inventors have to spend more on searching out useful knowledge and may imply the utility of a location that would lower these search costs. Industries with high average annual rates of knowledge obsolescence, we may hypothesize, would face the greatest pressures to locate near the sources of new knowledge.

Tests of the effects of technological opportunity on the interaction between location and innovation have mostly been indirect. Some studies have made cross industry comparisons and have found a high degree of spatial clustering in particular industries that face high technological opportunity. For example, Jaffe and Trajtenberg (1996) conclude that both the frequency and the duration of the citation of a patent is highly dependent on the field. Some fields, such as electronics, optics, and nuclear technology are marked by high immediate citation but, due to quick obsolescence, a rapid fading of citations over time. Furthermore, this work reveals that citations are more localized in the first year following a patent but that geographic effects dissipate quickly over time. Unfortunately, this work does not address the interaction of location and technology. Similarly, Audretsch and Feldman (1996) find a direct relationship between the propensity for industries to concentrate geographically and the knowledge intensity of the industry's activity. If we assume that knowledge intensive industries are also face high technological opportunity this suggests that location appears to matter most for economic activities that face high technological opportunity. Similarly, Henderson (1993) finds that both localization and urbanization effects are most important for high tech industries.

The effects of the appropriability of knowledge on either encouraging or discouraging innovation are rather ambiguous (Cohen, 1995: page 229-30). And there have been no direct general tests of the effects of differences in appropriability on location and geographic clustering. There are some interesting conjectures that warrant further investigation. For example, Liebeskind et al. (1995) argue that the rapid pace of innovation in biotechnology is fueled and accelerated by strict property rights regimes. The first firm to claim property rights over innovation will reap economic benefits. Firms therefore enter into patent "races." But this will be complicated as organizations may not have the required knowledge internally. This creates an imperative to balance the need to cooperate in order to share new economic knowledge with the need to compete in order to benefit economically. The result may be the existence of social networks defined as a "collectivity of individuals among whom exchanges take place that are supported only by shared norms of trustworthy behavior" (Liebeskind et al. 1995: page 7). Location may facilitate the social contacts necessary for the development of these networks and may decrease the costs of monitoring untrustworthy behavior. Certainly, if firms could innovate without sharing knowledge then we might expect them to locate in geographic isolation. In that case, the resulting locational patterns of innovative firms would be very different from what we observe.

An interesting insight into the effect of appropriability on innovation may be seen by contrasting the work of Zucker and Darby (1996) with Audretsch and Stephan (1996). Both studies focus on biotech but at slightly different stages of the commercialization process. Zucker and Darby find that firm formation at the time when appropriability is low is more geographically concentrated. In contrast, at the stage of initial public offering (IPO), when firms have acquired patent rights and are revealing information in order to raise funds, Audretsch and Stephan find a greater geographic reach in the organization of scientific advisory boards. The answer may be that close geographic collaboration is useful before the appropriation of commercial rewards. When property rights have been assigned, a company, specifically in this case a biotech entity, can identify key individuals who may have required knowledge or who may add credibility to the endeavor because of their expertise. These issues raise questions of firm characteristics which are addressed in the next section.

3.C Firm Characteristics

Empirical work has considered the effects of location on firm characteristics such as the stage of industry development, firm size and strategy. A fundamental question concerns what types of firms are able to absorb and benefit economically from location.

The expected economic value of new knowledge to a firm is shaped by what is termed as the core competency of the firm. As Cohen and Levinthal (1990) point out, the costs associated with innovation, such as learning new techniques and absorbing new research results, are less if the new knowledge is relevant to the firm's on-going activity and existing expertise. Henderson (1993) compares new industry entrants' and incumbents' ability to exploit significant change in new technology and finds that new entrants are more likely to commercialize radical new innovation. The fact that small firms generate a disproportionate share of innovation support this view. Indeed, some have argued that small firms become a vehicle for the commercialization of new knowledge.

Location may allow small firms to achieve the economies of scope and scale associated with larger operations by co-locating with complementary, external resources. Feldman (1994a) uses the knowledge production function to establish that third-parties, firms or research institutions, such as universities, may provide geographically localized knowledge inputs to benefit small firms. Knowledge spillovers from a large R&D conducting firm or research institution may benefit smaller firms who are receptive to more radical innovation that may be competency destroying for the larger firm. The new innovation would be attributed to the smaller firms however knowledge spillovers from the external environment make the innovation possible. Indeed, the work of Zucker and Darby (1996) concludes that it is the star scientists who transfer knowledge in order to realize economic returns from the human intellectual capital developed at universities.

Beyond the founding of a new company, location may facilitate access to resources that allow firms to grow, develop and innovate. Lerner (1996) finds evidence that small start-up firms benefit from being in a location that is attracting venture capital investment. This work tracks the long run growth patterns of Small Business Innovation Research (SBIR) grant recipients against matched samples of similar firms and finds that employment and sales growth were significantly higher if the award was made to a firm located in a zip code that received private venture capital activity. These results suggest that firms benefit from rich information flows within these locations.

Other work considers the effect of knowledge spillovers on the productivity of within firm R&D. Adams and Jaffe (1996) find that the drug industry R&D exhibits less diminution with distance, and a greater spillover elasticity; yet, geographically distant R&D is almost worthless in the industrial chemicals group.

4. REFLECTIVE CONCLUSIONS

In recent years, economists have returned in earnest to the study of location and innovation and a sizeable empirical literature examines the phenomenon of geographic clustering, specifically the factors or conditions that give rise to them, the existence and span of local externalities, and whether these pertain to certain industries or certain stages of industries' development. The empirical work reviewed here provides insights into the emerging understanding of the effect of location on innovation. Historians Leslie and Kargon (1997) conclude that there are too many unique factors that created Silicon Valley to ever duplicate its success. This view is not very satisfying to an economist. Our objective is to find systematic patterns, and towards that end a substantial literature is beginning to emerge.

Science-based activity is at the heart of new theories of economic development, technological change and industrial evolution (Romer 1986 and 1990, Lucas 1993 and Krugman 1991a and 1991b). Increasingly, it is recognized that the engines of national economic performance are sub-national technology districts that are characterized by strong ties between regional actors (Storper, 1995; Scott, 1993). This work is complemented by the empirical research reviewed here that finds that knowledge spillovers from science-based activities are localized and contribute to higher rates of innovation, increased entrepreneurial activity and increased productivity within geographically bound areas. The spillover of knowledge may be seen in the paper trails as demonstrated by patent citations and knowledge spillovers are embodied in people and in traded good. There is evidence that there are geographic limits to the extent to which knowledge may spillover, however this is not to say that location is important to innovation in all circumstances. There is further evidence that the degree to which location matters to innovation depends upon the type of activity, the stage of the industry life cycle and the composition of activity within a location.

The "black box" of innovation, as opened by Rosenberg (1982, 1994), now encompasses a broad landscape of actors, institutions and relationships that condition innovation. And it is recognized that location may be one of the factors that conditions innovation and technical advance.

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