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R&D Spillovers and Innovative Activity

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The new learning has raised a number of explanations why smaller enterprises may, in fact, tend to have an innovative advantage, at least in certain industries. The purpose of this paper is to identify the degree to which university and corporate R&D spills over to innovative activity at the state level. We find substantial evidence that spillovers are facilitated by the geographic coincidence of universities and research laboratories within the state.

INTRODUCTION

Just as the economy has been besieged by technological change that has left virtually no sector of the economy untouched during the last decade, scientific understanding of the innovative process—that is, the manner by which firms innovate, and the impact such technological change has in turn on enterprises and markets—has also undergone a revolution, which, if somewhat quieter, has been no less fundamental. Well into the 1970s, conventional wisdom about the nature of technological change generally pervaded the economics literature. This had been shaped largely by scholars such as Joseph Schumpeter and John Kenneth Galbraith.

At the heart of this conventional wisdom was the belief that monolithic enterprises exploiting market power were the driving engine of innovative activity. Schumpeter had declared the debate closed, with his proclamation in 1950 (p. 106) that 'What we have got to accept is that [the large-scale establishment] has come to be the most powerful engine of progress'. Galbraith (1956, p. 86) echoed Schumpeter's sentiment: 'There is no more pleasant fiction than that technological change is the product of the matchless ingenuity of the small man forced by competition to employ his wits to better his neighbor. Unhappily, it is a fiction'.

While this conventional wisdom about the singular role played by large enterprises with market power prevailed in the economics literature during the first three decades subsequent to the close of the Second World War, the most recent decade witnessed a number of new studies challenging this conventional wisdom (Acs and Audretsch, 1987, 1988, 1990, 1993). Most importantly, these studies have identified a much wider spectrum of enterprises contributing to innovative activity, and that, in particular, small entrepreneurial firms as well as large established incumbents play an important role in the process of technological change. Taken together, these studies comprise the new learning about innovative activity—both its sources and its consequences.

The new learning has raised a number of explanations why smaller enterprises may, in fact, tend to have an innovative advantage, at least in certain industries. Rothwell (1989) suggests that the factors yielding small firms with the innovative advantage generally emanate from the difference in management structures between large and small firms. For example, Scherer (1991) argues that the bureaucratic organization of large firms is not conducive to undertaking risky R&D. The decision to innovate must survive layers of bureaucratic resistance, where an inertia regarding risk results in a bias

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against undertaking new projects. In the small firm, however, the decision to innovate is made by relatively few people.

Second, innovative activity may flourish most in environments free of bureaucratic constraints (Link and Bozeman, 1991). That is, a number of small-firm ventures have benefited from the exodus of researchers who felt thwarted by the managerial restraints in a larger firm. Third, it has been argued that while the larger firms reward the best researchers by promoting them out of research into management positions, the smaller firms place innovative activity at the center of their competitive strategy (Scherer, 1991).

Finally, research laboratories of universities provide a source of innovation-generating knowledge that is available to private enterprises for commercial exploitation. Jaffe (1989) and Acs *et al.* (1992), for example, found that the knowledge created in university laboratories 'spills over' to contribute to the generation of commercial innovations by private enterprises. Similarly, Link and Rees (1990) surveyed 209 innovating firms to examine the relationship between firm size and university research. They found that, in fact, large firms are more active in university-based research. Small- and medium-sized enterprises, however, apparently are better able to exploit their university-based associations and generate innovations. Link and Rees conclude that, contrary to the conventional wisdom, diseconomies of scale in producing innovations exist in large firms. They attribute these diseconomies of scale to the 'inherent bureaucratization process which inhibits both innovative activity and the speed with which new inventions move through the corporate system towards the market' (Link and Rees, 1990, p. 25).

The purpose of this paper is to identify the degree to which university and corporate R&D spills over to innovative activity at the state level. In the second section, we examine state patterns of innovation. In the third section, we examine the extent of R&D spillovers while in the fourth section the recipient of the spillovers is examined. The fifth section presents conclusions. We find substantial evidence that spillovers are facilitated by the geographic coincidence of universities and research laboratories within the state. Moreover, we find that corporate R&D is a relatively more important source for generating innovation in large firms, while spillovers from university research laboratories are more important in producing innovative activity in small firms.

STATE PATTERNS OF INNOVATION

While previous research notes that innovative inputs are spatially concentrated, Peter Hall (1985, p. 11) concludes that the suspicion that product innovations are highly spatially concentrated remains unconfirmed in the literature. The SBA data[1] supports the long-held notion that product innovations are concentrated in certain locations. Forty-six states plus the District of Columbia were the source of some innovative activity. There is, however, significant concentration of activity as eleven states accounted for 81% of the 4200 innovations. The states that produced the greatest number of innovations were California (974), New York (456), New Jersey (426), Massachusetts (360), Pennsylvania (245), Illinois (231), Ohio (188), Texas (169), Connecticut (132), Michigan (112) and Minnesota (110).

To normalize for differences in state capacity, innovation can be measured on a per capita or per worker basis. Table 1 presents the number of innovations per 100 000 manufacturing employees in 1982, ranked from the most innovative to the least innovative. New Jersey had the highest rate of innovation, followed by Massachusetts and California. These states generated innovations at greater than twice the national rate of 20.34 innovations per 100 000 manufacturing workers. Seven other states—New Hampshire, New York, Minnesota, Connecticut, Arizona, Colorado and Delaware—were also more innovative than the national average.

Table 1 also provides a comparison of states for various measures of innovative activity. Although the alternative measures of innovative activity are highly correlated within states, the relative ranking of states between the categories is very different. Employment-based definitions of innovative industries rank states such as Arizona and Connecticut higher due to the prevalence of high-technology branch plants located there.[2] The patent measure ranks older, industrial states such as Illinois, Michigan and Ohio higher than the innovation measure.[3] This may be because the state industrial mix reflects concentrations of industries that exhibit a higher propensity towards patenting. To the

Table 1. How Do States Compare on Various Measures of Innovative Activity?

State	Innovation per 10000 workers	Rank	Patents per 100000 workers	Rank	High-tech workers (%)	Rank
Arizona	27.70	8	70.20	19	41	1
California	46.94	3	925.50	1	37	4
Colorado	22.46	9	95.13	16	35	5
Connecticut	28.51	7	312.32	9	39	2
Florida	14.60	18	121.49	14	31	10
Georgia	10.10	27	55.01	22	10	42
Illinois	18.16	13	702.29	4	28	14
Indiana	7.49	34	224.64	10	21	26
Iowa	8.16	32	69.63	20	23	22
Kansas	7.77	33	41.55	24	37	3
Kentucky	3.33	42	59.89	21	17	33
Louisiana	2.39	44	46.70	23	29	13
Massachusetts	51.87	2	383.67	8	33	7
Michigan	11.02	25	494.27	7	15	36
Minnesota	28.65	6	179.94	12	27	16
Missouri	8.20	31	121.20	15	20	27
New Jersey	52.33	1	753.87	3	30	11
New York	29.48	5	818.62	2	22	24
Ohio	15.00	17	572.78	6	22	23
Oklahoma	10.15	26	129.80	13	33	6
Pennsylvania	18.28	12	667.34	5	23	20
Rhode Island	18.46	11	26.93	26	16	35
Utah	11.83	22	29.51	25	31	9
Virginia	9.09	29	85.10	18	26	17
Wisconsin	15.61	16	181.66	11	24	19

degree that innovation citations reflect new commercially viable innovations brought to the market, these other measures may misinterpret the success with which states are the sources of innovative activity.

R&D SPILLOVERS

Adam Jaffe (1989) provides the first attempt to model the extent to which university research spills over into the generation of the inventions and innovations of private firms at the state level. While previous research (Griliches, 1979; Jaffe, 1986) considers R&D spillovers across technical areas, this work reflects the first attempt to model geographically mediated spillovers. Jaffe's statistical results provide evidence that not only does patent activity increase in the presence of high corporate expenditures on R&D but, in addition, corporate patent activity responds positively to knowledge spillovers from university research.[4]

Jaffe's model uses a knowledge production-function framework with a two-input modified Cobb–Douglas model:

$$\log P_{is} = \beta_1 \log IND_{.s} + \beta_2 \log UNIV_{is} + \beta_3 \log POP_{.s} + \beta_4 (\log U_{is} * \log C_{.s}) + \varepsilon_{is} \quad (1)$$

The dependent variable is the number of corporate patents per state. The independent variables include total industrial R&D expenditures by state, $IND_{.s}$, university research by technical area by state, $UNIV_{is}$, and a geographic coincidence index, $C_{.s}$, which measures the locational proximity of research activities within the state.[5] The unit of observation is at the level of the state, s, and the 'technological area', or industrial sector, i. State population, $POP_{.s}$, is included to control for size differentials across the geographic units of observation.

Jaffe's (1989) statistical results provide evidence that corporate patent activity responds positively to commercial spillovers from university research. Not only does patent activity increase in the presence of high private corporate expenditures on R&D but also as a result of research expenditures undertaken by universities within the state. The results concerning the role of geographic proximity in spillovers from university research are clouded, however, by the lack of evidence that geographic proximity within the state matters as well. According to Jaffe (1989, p. 968) 'There is only weak evidence that spillovers are facilitated by geographic coincidence of universities and research labs within the state'.

While Jaffe's model is constructed to identify the contribution of university research to generating 'new economically useful knowledge', Zvi Griliches (1990), F. M. Scherer (1983) and Edwin Mansfield (1984) have all warned that measuring the number of patented inventions is not the equivalent of a direct measure of innovative output.

A different and more direct measure of innovative output was introduced in Acs and Audretsch (1987), where the measure of innovative activity is the number of innovations recorded in 1982 by the US Small Business Administration from the leading technology, engineering, and trade journals in each manufacturing industry. A detailed description and analysis of the data can be found in Acs and Audretsch (1988, 1990). Because each innovation was recorded subsequent to its introduction in the market, the resulting database provides a more direct measure of innovative activity than do patent counts. That is, the innovation database includes inventions that were not patented but were ultimately introduced into the market and excludes inventions that were patented but never proved to be economically viable enough to appear in the market. Jaffe's model can be used to compare the influence of university spillovers on innovation with the results that Jaffe reported using the patent measure.

Table 2 compares the mean measures of university research expenditures and corporate patents for all 29 states used by Jaffe with the mean number of innovations per state. While Jaffe's variables are based on an eight-year sample (1972–7, 1979 and 1981), the innovation measure is based on the single year 1982. University research and industrial R&D expenditures are presented in millions of 1972 dollars.

While Jaffe was able to pool the eight years of data together across each state observation in estimating the production function for patented inventions, this is not possible using the innovation measure, due to data constraints. Thus, it is important to first establish that Jaffe's results do not vary greatly when estimated for a single year than when estimated over the longer time period. All data sources and a detailed description of the data and measures can be found in Jaffe (1989).

The parameter estimates of Equation (1) using patents as dependent variable are:

$$\log(P_{is}) = 0.668\log(IND_{.s}) + 0.241\log(UNIV_{is}) + 0.059\log(POP_{.s}) + 0.020\log(UNIV_{is} * \log C_{.s}) \quad (2)$$

This model appears to be a reasonable approximation of the results found in Table 4B of Jaffe's 1989 paper. Using the patent measure for a single year yields results virtually identical to those based on the pooled estimation reported in Jaffe's article. That is, both private corporate expenditures on R&D as well as expenditures by universities on research are found to exert a positive and significant influence on patent activity. The industry coefficient of 0.668 is remarkably close to the coefficient of 0.713 estimated by Jaffe using the pooled sample. From these results, the single estimation year does not greatly alter the results obtained by Jaffe using several years to measure the extent of patent activity.

Table 2. Summary Statistics for Regression Sample

	Mean	St. dev.	Min.	Max.
University research	98.8	144.0	12.0	710.4
Industrial R&D	582.9	823.5	3.8	4328.9
Geographic index	0.63	0.35	0.03	1.00
Population	9.5	16.0	0.0	75.0
Corporate patents	879.4	975.7	39.0	3230.0
Innovations	130.1	206.4	4.0	974.0

Notes:
All dollar figures are millions of 1972 dollars. The data for university research expenditures and corporate patents are from Jaffe (1989).

The estimated parameters for Eqn (1) using innovations as the dependent variable are:

$$\log(INN_{is}) = 0.428\log(IND_{.s}) + 0.431\log(UNIV_{is}) - 0.072\log(POP_{.s}) + 0.173\log(UNIV_{is} * \log C_{.s}) \quad (3)$$

There are two important differences that emerge when the innovation measure is used instead of the patent measure. First, the elasticity of the $\log(UNIV_{is})$ almost doubles from 0.241, when the patent measure is used, to 0.431, when the innovation measure is used. The impact of university spillovers is apparently greater on innovations than on patented inventions. Second, the impact of the geographic coincidence variable is much greater on innovative activity than on patents. This suggests that geographic location may be more important than Jaffe's work concluded. Table 3 provides a summary and comparison of the results.

Substitution of the direct measure of innovative activity for the patent measure in the knowledge production function generally strengthens Jaffe's arguments and reinforces his findings. Use of the innovation data provides even greater support that, as Jaffe predicted, spillovers are facilitated by the geographic location of university research and industries R&D activities within the state.

Using either measure of innovative activity, industry R&D and university research have a strong and statistically significant effect. Differences between the two measures may reflect their different stages in the innovation process. Industry R&D expenditures has a larger coefficient and statistically stronger effect on patents than on innovations. Patents are closer to the initial invention stage of the innovation process and, as such, may be more directly related to the work of the R&D lab. University research, in contrast, has a greater effect on the number of commercially viable innovations from a state. This result is somewhat surprising since university research is typically associated with enhancing technological opportunities rather than generating innovations (Nelson, 1986). The question arises if commercially viable innovations may benefit from spillovers of other types of activities which are omitted from this simple model.[6]

Table 3. OLS Regression Results Using Jaffe's Patent Measure and the Innovation Measure by State and Technological Area (*t*-statistics in parentheses)

	(1) Patents	(2) Innovations
$\text{Log}(IND_{.s})$	0.668^b	0.428^b
	(8.919)	(4.653)
$\text{Log}(UNIV_{is})$	0.241^b	0.431^b
	(3.650)	(6.024)
$\text{Log}(UNIV_{is} * \log C_{.s})$	0.020	0.173^a
	(0.244)	(1.914)
$\text{Log}(POP_{.s})$	0.059	−0.072
	(1.297)	(−1.287)
n	145	125
R^2	0.959	0.902

[a] Statistically significant at 90% level of confidence for a two-tailed test.
[b] Statistically significant at 95% level of confidence for a two-tailed test.

FIRM SIZE

Table 4 ranks the states according to innovative activity and shows the distribution of innovations across large and small firms, along with the corresponding industry R&D expenditures and expenditures on research by universities. The states where the innovative activity of large firms exceeded that of small firms the most were Minnesota, Michigan, Connecticut and Arizona. In contrast, in Rhode Island, Florida, Delaware and Colorado, small firms were considerably more innovative than their larger counterparts.

The unit of observation for the dependent variable to be estimated is the number of innovations (alternatively by large firms, and by small firms) made in a specific technological area and within a particular state. Given that observations are available for five technological areas over 29 states, the entire sample size is 145 observations. Not only were there no innovations registered for certain technological areas within particular states but the number of observations with a zero value is even greater for large-firm innovations and small-firm innovations. Thus, the model is estimated using the Tobit method of estimation, and the results are shown in Table 5.[7]

The first equation estimates the innovative activity of large firms and the second equation the innovative activity of small ones. Regardless of firm size, the knowledge production function for innovative output holds in that additional inputs in knowledge-generating R&D, both by private corpora-

Table 4. Innovative Output in Large and Small Firms and R&D Inputs by State[a]

State	Total innovations	Large-firm innovations	Small-firm innovations	Industry R&D expenditures	University research
CALIF	974	315	659	3883	710.4
NY	456	180	276	1859	371.0
NJ	426	162	264	1361	70.8
MASS	360	148	212	954	245.3
PA	245	104	141	1293	139.2
ILL	231	100	131	894	254.9
OHIO	188	76	112	926	76.2
CONN	132	77	55	650	54.7
MICH	112	61	51	1815	103.2
MINN	110	64	46	399	55.7
WISC	86	33	53	224	65.0
FLA	66	21	45	375	70.1
GA	53	20	33	78	57.8
IND	49	20	29	398	51.3
COLO	42	13	29	167	77.2
ARIZ	41	23	18	201	37.4
VA	38	19	19	207	45.9
NC	38	16	22	193	64.6
RI	24	4	20	32	14.9
OKLA	20	12	8	93	19.9
IOWA	20	12	8	135	46.4
KANS	15	3	12	66	26.6
UTAH	11	2	9	72	32.5
NEB	9	1	8	9	20.4
KY	9	6	3	72	17.5
LA	5	0	5	65	33.4
ARK	5	5	0	9	12.0
ALA	5	0	5	54	28.3
MISS	4	1	3	420	61.4

[a] Industry R&D and university research expenditures are in millions of 1972 dollars and are taken from Jaffe (1989).

tions and by universities, lead to increases in innovative output. The relative importance of industry R&D and university research as inputs in generating innovative output varies between large and small firms. That is, for large firms not only is the elasticity of innovative activity with respect to industry R&D expenditures more than two times greater than the elasticity with respect to expenditures on research by universities, but it is nearly twice as large as the elasticity of small-firm innovative activity with respect to industry R&D. In contrast, for small firms the elasticity of innovative output with respect to expenditures on research by universities is about one-fifth greater than the elasticity with respect to industry R&D. Also, the elasticity of innovative activity with respect to university research is about 50% greater for small enterprises than for large corporations.

The hypothesis that the coefficients of the log of industry R&D are equal for large and small firms is

Table 5. Tobit Regressions of Innovative Activity by State and Technological Area (*t*-statistics in parentheses)

	(1) Large firms	(2) Small firms
$\text{Log}(IND_{.s})$	0.950	0.550
	(7.133)[b]	(4.184)[b]
$\text{Log}(UNIV_{is})$	0.446	0.661
	(4.569)[b]	(5.848)[b]
$\text{Log}(UNIV_{is} * \log C_{.s})$	0.033	0.111
	(0.687)	(1.965)[b]
$\text{Log}(POP_{.s})$	−0.554	−0.314
	(−6.558)[b]	(−3.914)[b]
n	145	145
Log (likelihood)	−202.19	−225.86

[a] Statistically significant at 90% level of confidence for a two-tailed test.
[b] Statistically significant at 95% level of confidence for a two-tailed test.

rejected at the 95% level of confidence. Similarly, the hypothesis that the coefficients of the log of university research are equal for large and small firms is rejected at the 95% level of confidence. Thus, there is substantial evidence that, just as private corporate R&D plays a relatively more important role than do spillovers from university laboratories in generating innovative activity in large companies, R&D spillovers from universities play a more decisive role in the innovative activity of small firms than do spillovers from private industrial R&D.

The geographic proximity between the university and corporate laboratories within a state serves as a catalyst to innovative activity for firms of all sizes. The impact, however, is apparently greater on small firms than on large firms. The elasticity of innovative activity with respect to the geographic coincidence index is nearly four times greater for small firms than for their larger counterparts.

CONCLUSIONS

The findings in this paper provide at least some insight into the puzzle posed by the recent studies identifying a vigorous amount of innovative activity emanating from small firms in certain industries. Substitution of the direct measure of innovative activity for the patent measure in the knowledge-production function generally strengthens Jaffe's (1989) arguments and reinforces his findings. Use of the innovation data provides even greater support than was found by Jaffe that spillovers are facilitated by the geographic coincidence of universities and research labs within the state. How are these small, and frequently new, firms able to generate innovative output while undertaking generally negligible amounts of investment into knowledge-generating inputs, such as R&D? At least one answer, implied by the findings in this paper, is through exploiting knowledge created by expenditures on research in universities and on R&D in large corporations.

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NOTES

1. For a discussion of the SBA data of the state level, see Feldman (1992).
2. Estimates of employment in high-technology industry are for the year 1977 from Amy Glasmeier (1985). This measure has a correlation coefficient of 0.4474 with innovations and 0.3201 with patents.
3. Patent counts are from Jaffe (1989) and represent the average annual corporate patenting activity for a state for the years 1972–7, 1979 and 1981. Jaffe provides data for only 29 states and rankings here reflect the relative position out of the 29 listed cases.
4. In addressing the question 'Patents as indicators of what?' Griliches (1990) concludes that 'Ideally, we might hope that patent statistics would provide a measure of the [innovative] output ... The reality, however, is very far from it. The dream of getting hold of an output indicator of inventive activity is one of the strong motivating forces for economic research in this area.'
5. To overcome the conceptual problem of measuring geographic proximity, Jaffe constructs an index of geographic coincidence of university and industrial research labs. His hypothesis is that research will yield more innovative activity if university and industrial labs are geographically concentrated. For example, more patents would be expected in Illinois where industrial and research labs are located in different SMSAs than industrial labs. Jaffe's geographic coincidence index is only marginally statistically significant, but the correction is important.
6. Commercially viable innovations are the result of several different, but complementary, types of knowledge: technical knowledge coupled with knowledge of the market. Technical knowledge, partly codified and formal, and partly informal and tacit, provides the discovery and development of a new invention. In order to generate a profit, technical knowledge must be coupled with the complementary knowledge of the market. New product innovations introduced to the market must consider consumer demand for the product as well as the process of introducing the new product to the market. While university research and industrial R&D are important components of the invention process which result in the granting of a patent, these resources are only one component of the process of introducing commercially viable innovations. Jaffe's formulation does not consider spillovers from other complementary activities—for example, familiarity with technology as well as producer services, which facilitate the process of introducing a new product innovation.
7. The intercept has been suppressed in estimation.

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