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The Geographic Sources of Innovation: Technological Infrastructure and Product Innovation in the United States

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Since the sixteenth century, and perhaps before, the fortunes of regions and nations have depended on new ideas and new products that energized these places and facilitated their economic growth. If innovation is one of the keys to prosperity, then precisely how this happens—how a region breaks with convention and introduces new products—is a question of some significance. Not surprisingly, a variety of scholars have tried to find the keys to innovation, to unlock the doors of the innovation process, and to render what is inside less mysterious and more accessible to less fortunate regions and states (Kline and Rosenberg 1987; Landes 1969; Malecki 1991; Mokyr 1990; Rosenberg 1972; 1982). In his classic work on innovation and capitalism, Joseph Schumpeter (1954) argues powerfully that economic growth requires innovation—the generation of higher quality products at lower unit costs than had previously been obtainable.

What then do we know about this key variable for economic growth? The literature on innovation, as one might expect, is daunting; it ranges from heroic accounts of inventors and innovators to the more prosaic accent on the factors of land, labor, and capital. A full appreciation of innovation, of course, requires both of these approaches, and various others in between; but in this paper we have space to deal with only a portion of the problem—the geographic dimensions of innovation and their structural conditions in one place, the United States, and at one time, the early 1980s.

Geographers and economists have often noted the congruent clustering of economic activity and innovation. While much about this congruence remains unclear, we know that the clustering or agglomeration of economic activity creates scale economies, facilitates face-to-face interaction, and shortens interaction distances. The interaction of all of these factors lends itself to innovation in economic processes and products. In contemporary developed or mature economies, product innovation is also linked with the composition of firms and activities in these clusters. Especially important in this regard is the technological infrastructure within these clusters. Building upon recent reconceptualizations in economic geography and economics, we suggest that innovation in the late twentieth century is unusually dependent on an area's underlying technological infrastructure. Having burst beyond the confines of the organizational boundaries of an individual firm, innovation is increasingly dependent on a geographically defined infrastructure that is capable of mobilizing technical resources, knowledge, and other inputs essential to the innovation process. This infrastructure consists of sources of knowledge: networks of firms that provide expertise and technical knowledge; concentrations of research and development (R&D) that enhance opportunities for innovation by providing knowledge of new scientific discoveries and applications; and business services with expertise in product positioning and the intricacies of new product commercialization. Once in place, these geographic concentrations of infrastructure enhance the capacity for innovation as their respective regions develop and specialize in particular technologies and industrial sectors. Geography, in other words, serves as the vessel in which entrepreneurs, venture capitalists, and other agents of innovation, organize an

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infrastructure that brings together the crucial resources and inputs for the innovation process.

The empirical model of the geography of innovation presented here tests the hypothesis that innovation is concentrated in places that possess a well-developed technological infrastructure. The latter is defined in terms of the agglomerations of four indicators: 1) firms in related industries; 2) university R&D; 3) industrial R&D; and 4) business-service firms. Our analysis confirms and extends this hypothesis. We demonstrate that not only do innovations cluster geographically in areas that contain concentrations of specialized resources indicative of technological infrastructure, but also that these spatial concentrations of specialized resources mutually, and positively, reinforce a region's capacity to innovate.

Innovation in Geographic Theory

Recent research on the geographic, organizational, and economic dimensions of innovation divides into three streams. The first of these deals with the location of R&D inputs and technology-based industries. Malecki's (1981; 1985; 1986; 1990) documentation of the location of R&D activities has been followed up by research on the spatial distribution of high-technology industry and employment. Markusen, Hall, and Glasmeier (1986) observe, for example, that high-technology industries are associated with higher wage rates and higher levels of unionization. Some scholars note that these clusterings of innovative capacity are less the result of planning and of conscious strategy than of chance, serendipity, or "historical accidents" (Arthur 1990b; Scott and Storper 1990). It is difficult, however, to explain exactly why some regions are able to capture the consequent benefits of serendipity, while other regions are not and their fortunes languish. A number of scholars have noted the increasing importance of innovation to the economic restructuring of advanced capitalist economies (Florida and Kenney 1990; Harvey 1989; Storper and Walker 1989). And there is a growing literature on national innovation systems (Nelson 1993). However, given what is known about the innovation process, it is worth considering sub-national or regional systems of innovation.

A second stream of research attempts to do this, providing richly detailed case studies of the origins and development of "regional innovation complexes" (Stohr 1986). Case studies of Route 128 (Dorfman 1983), Silicon Valley (Saxenian 1985), and Orange County (Scott 1988), among others, suggest that innovation is a complex geographic process with multiple spatial determinants. The focus on individual case studies, while richly informative, does not yield the kind of general findings which would permit a broad conceptualization of the geographic dimensions of innovation. The case study literature encourages scholars to shift focus from the firm-level to a consideration of innovation as a social process reliant on external, geographically based sources of knowledge (Dosi 1988).

A third stream of literature considers the role of geographic agglomeration in technological innovation and economic development (Oakey 1985; Thomas 1985). Storper and Walker's (1989) theory of "geographic industrialization" captures the spatial nature of the process of technological change and industrial development. Other studies of the role of agglomeration economies focus upon the concentrations of key resources and organizational networks (DeBresson and Amesse 1992). Florida and Kenney (1988), for example, report that innovation is a product of an underlying social structure of innovation which is geographically based. Jaffe (1989) and Acs, Audretsch, and Feldman (1992) note the productivity effects associated with the proximity of industrial and academic R&D. According to this line of thinking, the regional specialization of industrial activity is an important facet of advanced industrial economies (Krugman 1991a; 1991b; David and Rosenbloom 1990). Locational clusters of economic activity and innovation are, in turn, the product of historical processes or "path-dependence" (Arthur 1988; 1990a). As regions develop, certain capacities are "locked-in" as resources are tailored to the innovative activity of specific technologies or industries. Historical processes reinforce the regional specialization of innovative capabilities. Innovation thus benefits from the congruent clustering of related institutions and the synergies created by embedded networks of individuals and institutions—relationships not adequately incorporated into existing models.

Drawing upon recent advances in geographic theory, particularly the concept of "geographic industrialization" (Storper and Walker 1989), we suggest that geography indeed plays a most fundamental role in the innovation process. Innovations are less the product of individual firms than of the assembled resources, knowledge, and other inputs and capabilities that agglomerate in specific places. Innovating firms and organizations harness the institutions and the resources that constitute the technological infrastructures of specific places. This infrastructural perspective on innovation differs sharply with the prevailing "location scanning" perspective. The latter suggests that individual firms freely scan the environment and select particular locations in accordance with the functional requirements of firms. The former suggests instead that innovation depends on a technological infrastructure of various resources and institutions—the indigenous manufacturing capabilities of networks of firms, the R&D efforts and capabilities of private enterprises and universities, the concentrations of specialized commercialization support services—that develop over time. In time, as it were, specific places develop differential technological capabilities and capacities for innovation. Geography thus plays a fundamental role in the innovation process; it constitutes the spatial locus wherein the various elements of technological infrastructure are organized.

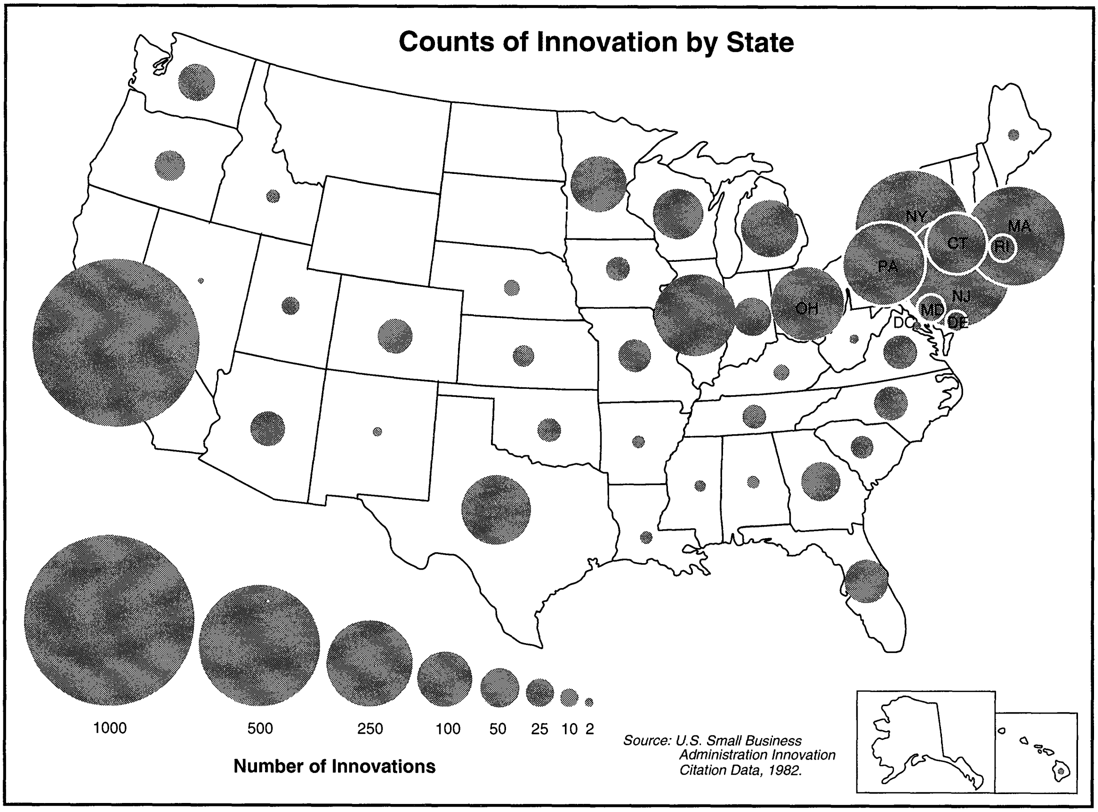
Furthermore, given this general perspective on innovation processes, we do not believe that serendipitous events "spark" economic development: the spark of innovation and the ability of an area to capture the benefits of serendipity are rather the products of a well-rounded technological infrastructure. The regional capacity to sustain innovation is thus embodied in institutions and resources that reflect significant investments over time. In this sense, an area's underlying technological infrastructure enhances the potential for innovation and shapes the locational choices of individual firms. Simply put, locational advantage and innovative capacity stem from, and are embodied in, the technological infrastructure of a place.

The Geographic Distribution of Innovation in the United States in 1982

We begin our analysis with an overview of the geographic distribution of new product innovations in the United States in 1982. Our source of data on commercial product innovation is the 1982 census of innovation citations from trade journals and business publications conducted by the Small Business Administration (SBA). Unlike patent data which certify new inventions, the SBA innovation census reports on the market introduction of new product innovations.[1] The SBA innovation census lists 4,476 product innovations; of these, 4,200 innovations contain information on the location of the establishment that introduced the innovation.

As Figure 1 shows, the geographic distribution of product innovations is highly concentrated among states. Eleven states account for 81 percent of the 4,200 innovations (Table 1). When the absolute distribution of innovations is converted to a rate of innovations per 100,000 manufacturing employees, geographical concentration persists (Figure 2). The rates of product innovation in New Jersey, Massachusetts, and California are double the national rate; and seven other states—New Hampshire, New York, Minnesota, Connecticut, Arizona, Colorado, and Delaware—exceed the national average.

Table 2 sheds additional light on the relationship between innovation and other commonly used measures of innovative activity. Simple correlations between the 1982 SBA innovation data and patent counts, R&D expenditure, and high-technology employment by state[2] suggest a close association. While R&D is considered an input to innovation, patents and high-technology employment are often used as proxies of innovative output. The geographic distribution of patents and high-technology underscore the patterns of concentration revealed in the SBA data. As Figure 3 demonstrates, patents are geographically concentrated in California and on the east coast in Massachusetts, New York, and New Jersey. Patents, however, exhibit more geographic dispersal than product innovations. Griliches (1990), Mansfield (1984), and Scherer (1983) all warn that the



Source: U.S. Small Business Administration Innovation Citation Data, 1982.

Figure 1. Number of innovations by state in 1982.

number of patented inventions is not directly equivalent to a measure of innovative output as many patented inventions never become commercially viable products while many successful products are never patented. There is a higher incidence of patenting in the states of Ohio, Pennsylvania, Illinois, and Michigan—the traditional manufacturing belt. This finding may reflect industry differentials in the propensity to patent. For example, Scherer (1983) finds a higher incidence of patenting in traditional industries such as industrial and residential equipment; stone, clay, and glass products; and household appliances. In addition, firms may opt not to patent in rapidly changing technological fields such as advanced electronics because the technical detail required in patent applications release proprietary design details which can be easily exploited by competitors (Mansfield 1984).

The geographic concentration of product innovation is even more pronounced among particular industries. Table 3 shows considerable specialization of innovative activity at the state level. California, for example, specializes in electronics-related innovation. Indeed, it is the most innovative state in five electronics-related sectors: computers, measuring instruments, communications equipment, electronic equipment, and electronic industrial machinery. California's advantage reflects, in large measure, the broad infrastructure for electronics-related innovation that has grown up in California's Silicon Valley over the past three decades (Saxenian 1985). Similarly, New Jersey, with its world-class pharmaceutical and chemical complexes, leads in innovations related to drugs and medicine (Feldman and Schreuder 1993). New York State, meanwhile, is a center for innovations in photographic equipment—a

Table 1. Distribution of Innovation by State.

State	Innovations	Innovations per 100,000 Manufacturing Workers
New Jersey	426	52.33
Massachusetts	360	51.87
California	974	46.94
New Hampshire	33	30.84
New York	456	29.48
Minnesota	110	28.65
Connecticut	132	28.51
Arizona	41	27.70
Colorado	42	22.46
Delaware	15	21.13
National	4200	20.34
Rhode Island	24	18.46
Pennsylvania	245	18.28
Illinois	231	18.16
Texas	169	16.14
Wisconsin	86	15.61
Washington	48	15.38
Ohio	188	15.00
Florida	66	14.60
Oregon	32	14.48

Source: Numbers of innovations are from the SBA innovation data. Numbers of manufacturing workers are from the *1982 Census of Manufacturers* (U.S. Bureau of the Census 1986).

fact which is not altogether surprising given the opto-electronics complex around Rochester—comprised of companies such as Kodak, Xerox, and Bausch and Lomb, among others (Sternberg 1991). Innovation in metal fabrication and industrial machinery are concentrated in the heavy manufacturing states of the industrial Midwest. Ohio, long a center for steel production and metal-working for heavy manufacturing and consumer durable goods, is the leader in innovations in metal fabrication. Pennsylvania, with a similarly long history of heavy manufacturing in steel, electronic-power equipment, and other sectors, accounts for the lion's share of innovation in the field of general industrial machinery. And lastly, Illinois with its massive industrial complexes around Chicago (Markusen and McCurdy 1989) and elsewhere accounts for the largest share of innovation in the domain of special industrial machinery.

Table 2. Correlation Analysis of Alternative Measures of Innovation.

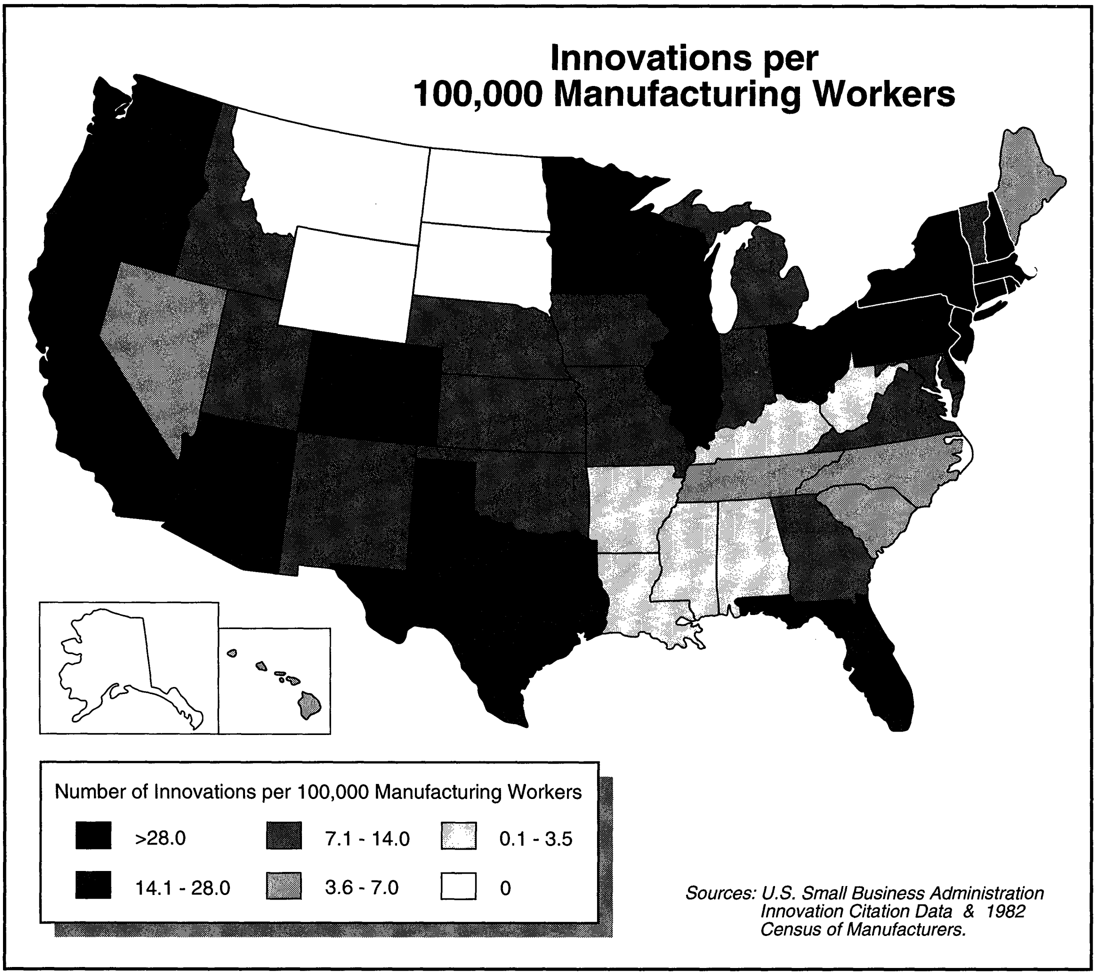
	Innovation	Patents	R&D	Employment
Innovation	1.0000			
Patents	.9344	1.0000		
R&D	.8551	.8804	1.0000	
Employment	.9737	.9888	.7013	1.0000

Sources: Patent counts by state are from Jaffe (1989). High-technology employment data are from the U.S. Office of Technology Assessment (1984). R&D expenditures are from the National Science Foundation as reported by Jaffe (1989).

The locational specialization of innovation is further highlighted in the location quotients reported in Table 3.[3] The average location quotient of 239.5 for the thirteen most innovative industries offers a clear indication of a significant specialization in innovative activity by state. Generally speaking, then, the product innovation data convey considerable regional specialization in innovative activity in states that have developed specialized capacities for innovation in particular technologies and industrial activities.

A Geographic Model of Innovation

The geographic distribution of innovation is, we believe, a function of an area's underlying technological infrastructure. As noted above, this technological infrastructure consists of: concentrations of industrial and university R&D that enhance new product ideas and inventions by providing sources of technological opportunity; agglomerations of manufacturing firms in related industries that provide additional sources of expertise and tacit knowledge, particularly the capacity to translate new ideas into actual commercial products; and networks of business-service providers that support the overall product innovation process by supplying knowledge and information on technological trends and product markets. The congruent clustering of these several inputs creates scale economies, facilitates knowledge-sharing and cross-fertilization of ideas, and promotes face-to-face interactions of the sort that enhance effective technology transfer. The geographic proximity of these inputs promotes information transfer and spill-overs that lower the costs and reduce the risks associated with innovation. Furthermore, the clustering of these regional "stocks" of innovative capabili-



Sources: U.S. Small Business Administration Innovation Citation Data & 1982 Census of Manufacturers.

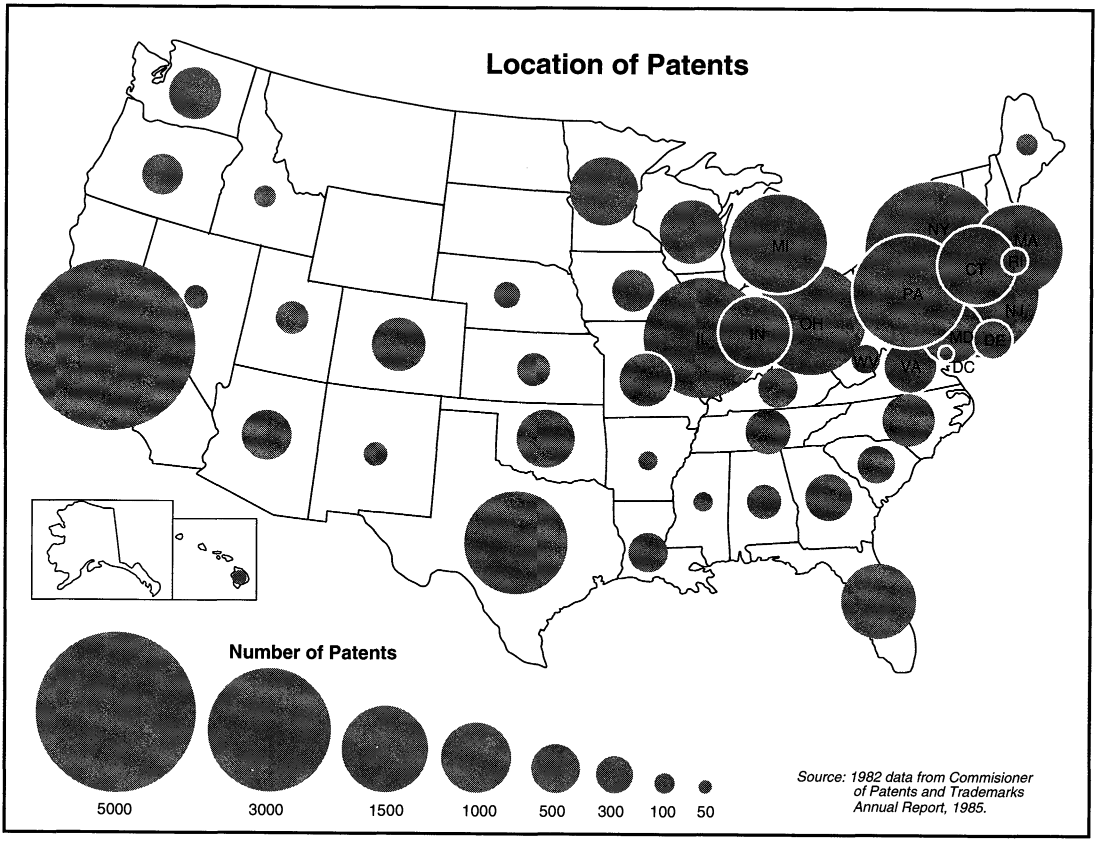
Figure 2. Innovations per 100,000 manufacturing workers in 1982.

ties and resources are embodied in human and institutional forms and interrelations that reflect a cumulative history of investments made in specific places over long periods of time (Sweeney 1987; Tassey 1991; Storper and Walker 1989).

Product Innovations: The Dependent Variable

The dependent variable in this model, namely the commercial product-innovation citations compiled by SBA in 1982, is based on the only data currently available on the geographic locations of commercial innovation. These data represent an advance on previous research that measures innovation with the proxies of patents (Jaffe 1989), high-technology firms and employment (Markusen, Hall, and Glasmeier 1986), R&D expenditures (Malecki 1983), or R&D personnel.

Although the SBA data offer a more direct measure of product innovations, our source has its limitations and potential biases. First, the SBA innovation citations are compiled from a wide variety of industry announcements and trade publications, and these may be biased toward unusual or special-interest products. Second, the SBA data are compiled by states.



Location of Patents

Source: 1982 data from Commisioner of Patents and Trademarks Annual Report, 1985.

Figure 3. Number of patents by state in 1982.

Using the state as the unit of analysis inevitably obscures spatial processes that occur within a state or across state boundaries. While we would prefer to use sub-state units of analysis and then aggregate in accordance with functional linkages and dependencies (Czmanski and Ablas 1979), such data are simply unavailable. Since the SBA data are the best that we have, we attempt, alternatively, to minimize potential sources of aggregation bias by introducing an index of geographic concentration as a control variable. Third, the SBA data are only available for one year, 1982. While cross-sectional data such as these preclude consideration of subsequent technological and industrial restructuring, the SBA's selection of 1982 has some compensating virtues. The early 1980s is a particularly useful time to explore the geography of innovation, since these years are generally regarded as ones of considerable innovation (U.S. Office of Technology Assessment 1984). With the emergence of new high-technology industries such as personal computers, computer work-stations, software and biotechnology, innovation occurred in entrepreneurial start-up companies as well as in the larger, more established firms such as IBM and DuPont. In this regard, 1982 provides a particularly useful vantage point on the geography of innovation. The SBA data, moreover, distinguish between the location of the establishment responsible for the major development of an innovation and the location of the corporate headquarters or parent company. We, of course, use the establishment location in our analysis.

The dependent variable in our model, innovative output (INN_{is}), is the number of innova-

Table 3. State Competitive Advantage in Innovative Industries.

Industry	N	Leading State	n	Location Quotient
Computers	954	California	356	167.8
Measuring Instruments	668	California	134	126.4
Communications Equipment	376	California	116	132.2
Electronic Equipment	261	California	128	211.3
Medical Instruments and Supplies	228	New Jersey	57	248.2
General Industrial Machinery	164	Pennsylvania	25	261.5
Drugs	133	New Jersey	52	381.3
Special Industrial Machinery	116	Illinois	11	171.4
Misc. Fabricated Metal Products	105	Ohio	18	384.0
Electronic Industrial Machinery	74	California	17	94.4
Photographic Equipment	61	New York	18	260.0
Plastic and Synthetic Materials	51	Texas	10	491.7
Cleaning Preparations	50	New York	10	183.3

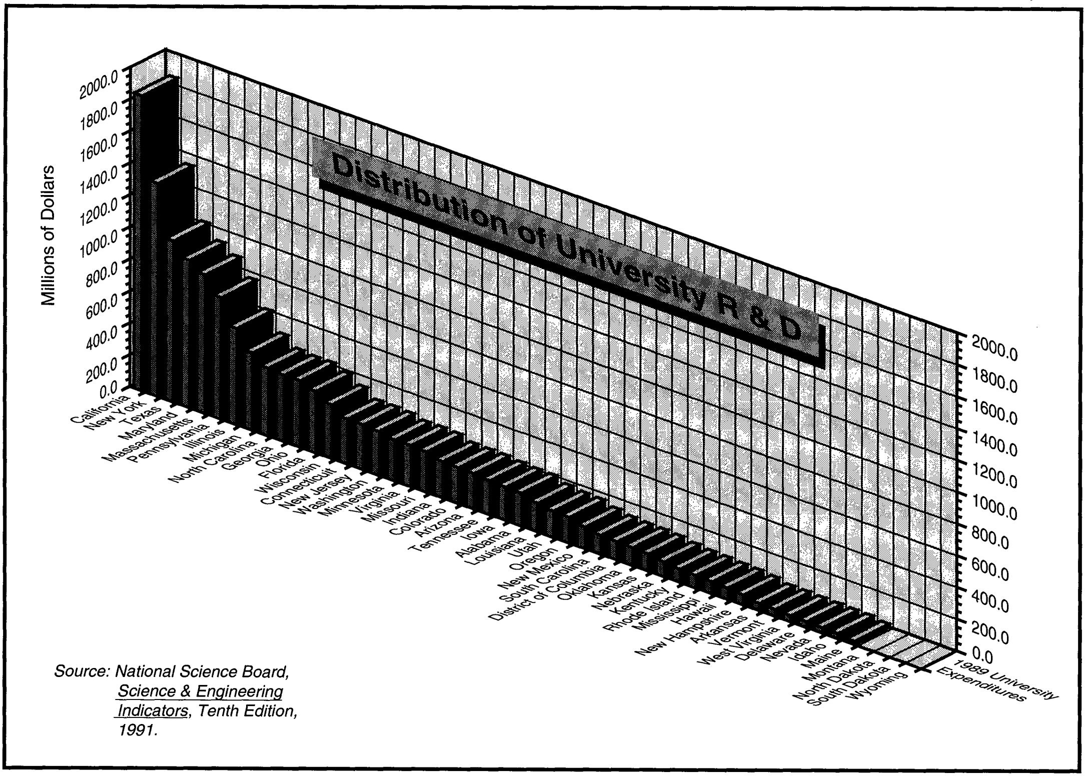
N indicates the total number of innovations for an industry; and n indicates the number of innovations for a state.

tions for an industry i in a state s in 1982. When these data are stratified by state and by industry, a large number of zero cells result. In order to proceed with the estimation, we confine our analysis to the thirteen most innovative three-digit Standard Industrial Classification (SIC) code industries. Each of these industries accounts for 50 or more innovations, and the thirteen industries as a whole account for 80 percent of total innovations in our sample (Table 3). The remaining 82 industries with one to 50 innovations account for just 20 percent of all innovations in 1982.

Technological Infrastructure: The Independent Variables

The four independent variables in the model are indicators of technological infrastructure. They are: (1) firms in related manufacturing industries, (2) industry R&D, (3) university R&D, and (4) business services. These are supplemented by a series of control variables. Because innovation is a process, it is characterized by a time lapse between the first stages of invention and the final stages of commercialization. The length of this lag is difficult to specify, however. A recent study estimates that the lag between an academic research finding and the commercial introduction of a new product averages seven years, with a standard deviation of two years (Mansfield 1991). We thus assume that innovations introduced into the market in 1982 would benefit from the stock of infrastructural resources that had been in existence for the preceding decade. Accordingly, we measure the stocks of the four innovative inputs as the average annual expenditures for each in the ten years prior to the 1982 introduction of innovations into the commercial market.

University research provides basic knowledge that may be critical for the innovation process. Nelson (1986) and Mansfield (1991) note that university R&D enhances the stock of basic knowledge, generates increased technological opportunities across a wide range of industrial fields, and increases the potential productivity of private industrial R&D. Overall then, university R&D has a positive effect on commercial innovation and generates a significant social rate of return—in excess of 25 percent according to one recent study (Mansfield 1991). Figure 4 presents the distribution of university-research expenditures. While the concentration of university R&D in a few major clusters, for example Boston-Cambridge and the San Francisco Bay area, is well known, other states, notably New York, Texas, and Maryland also have high expenditures on university research. The presence of university research simply may not be sufficient by itself to guarantee innovation and technology-based spin-offs (Feldman 1994b). There is some evidence that the co-location of university and industrial R&D at the state level tends to exert positive impacts on the generation of patents



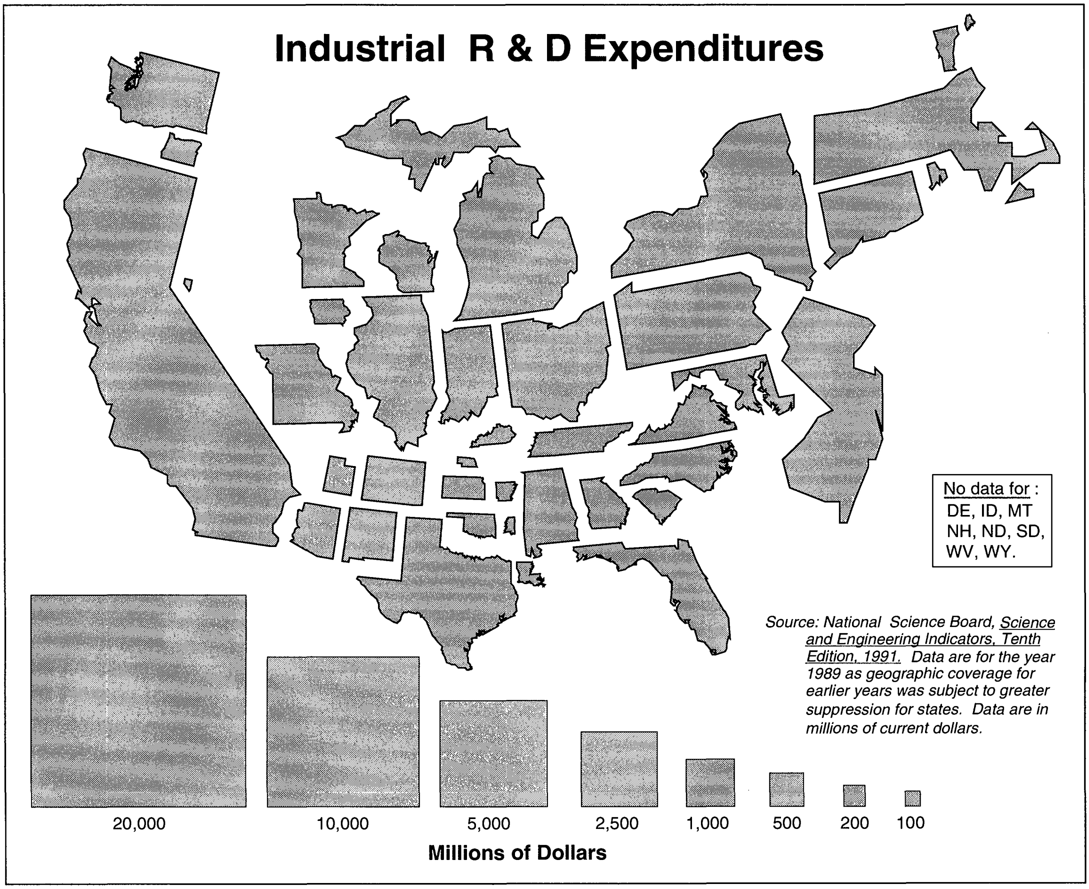
Source: National Science Board, Science & Engineering Indicators, Tenth Edition, 1991.

Figure 4. Distribution of university R&D expenditures in 1989.

and innovations (Jaffe 1989; Acs, Audretsch, and Feldman 1992). But the evidence is not unequivocal; Markusen, Hall, and Glasmeier (1986) report that university-research expenditures may have a negative effect on the location of high-technology industry.[4]

Because of the vast differences in the scope and commercial applicability of university research, our measure of university R&D ($UNIV_{ls}$) is based on funding at the level of academic department. Using data from the National Science Foundation's (NSF) *Survey of Science Resources,* we assign academic departments to relevant industries at the level of the two-digit SIC code. Innovations in industry SIC 283, Drugs, for example, are linked to research in the academic departments of medicine, biology, chemistry, and chemical engineering (Feldman 1994a).

Industrial R&D laboratories also serve as sources of scientific and technical knowledge required for new product development. With the notable exceptions of firms such as ATT and IBM that conduct basic research in laboratories, industrial R&D laboratories tend to specialize in market-oriented R&D, and more specifically, in the translation of scientific and technical information into new innovations. Geographers, in particular, have highlighted the regional concentration of industrial R&D and its important role in the innovation process and in the formation of regional innovation complexes (Stohr 1986; Tassey 1991). Malecki's (1983) study of the geographic distribution of R&D noted the regional specialization of R&D activity, in general, and the marked concentrations on the East and West Coasts, in particular. Figure 5 demonstrates the continuation of this pattern with a proportional representation of state industrial R&D expenditures. Here it is important to note that, as we found with university research, the geographic distribution of



Source: National Science Board, Science and Engineering Indicators, Tenth Edition, 1991. Data are for the year 1989 as geographic coverage for earlier years was subject to greater suppression for states. Data are in millions of current dollars.

Figure 5. Industrial R&D expenditures in 1989.

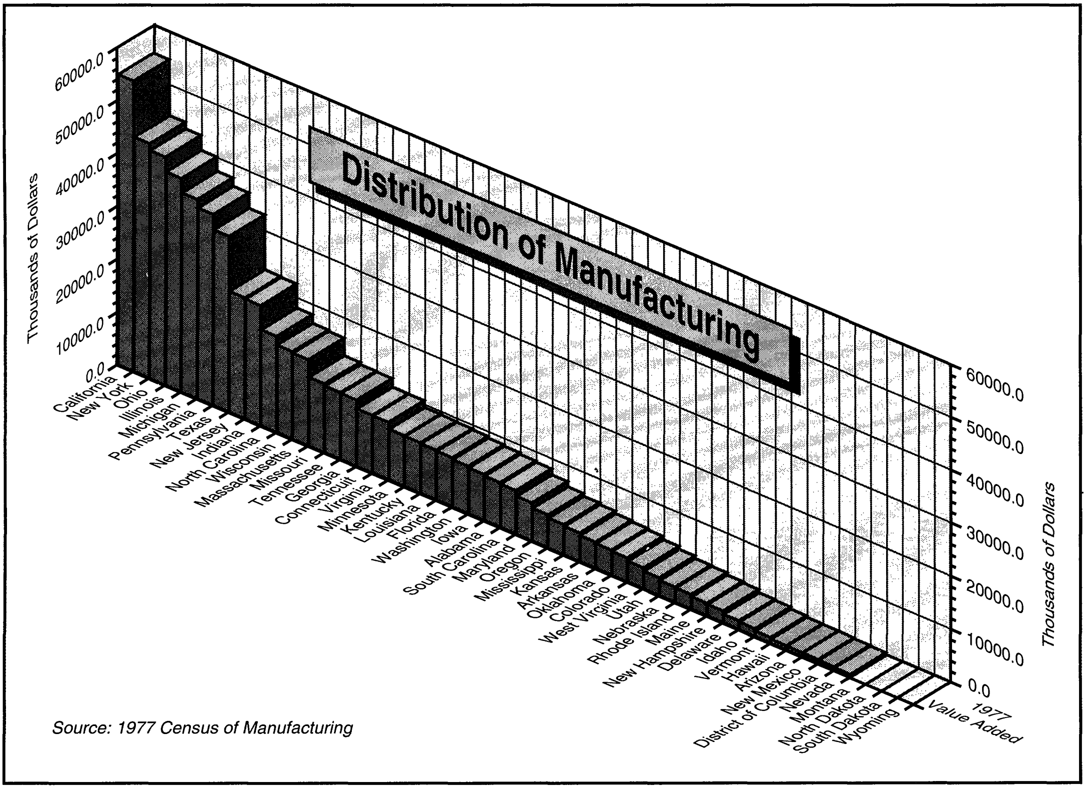
a single component of the technological infrastructure does not mirror precisely the geographic distribution of innovations. The location of industrial R&D more closely resembles the location of patents. This incongruence is not surprising from our point of view since multiple resources are required to create the technological infrastructure on which innovation depends.

Industrial R&D (IND_{ls}) is measured as the expenditures for in-company industrial R&D as reported to the NSF Science Resources Survey. This report has limitations, however. It does not include the cost of R&D contracted to universities and colleges, nor to nonprofit organizations, research institutions, and other companies. In addition, NSF's confidentiality requirements prevent data disclosure in 21 of the 50 states. But these omissions are not so serious as might first appear. The 21 states for which R&D data are unavailable account for just 325 innovations or 7.7 percent of all innovations. Conversely, we have industrial R&D expenditures for 29 states, and they account for 92 percent of all SBA-reported innovations and 81 percent of university-research expenditures in 1982. Our model, thus, uses the innovation data for the 29 states and 13 industries that together account for the overwhelming number of product innovations in 1982.

Turning next to our third independent variable, we note that geographers and economists have often pointed to the role of proximity in the innovation process. Cities and regions serve as "incubators" of innovations (Thompson 1962). More specifically, in the case of high-technology regions, networks of manufacturing firms are particularly crucial for new ideas and sources of knowledge for innovation (Stohr 1986; Storper and Walker 1989; Sayer and Walker 1993). Concentrations or agglomerations of firms in related industries provide a pool of technical knowledge and expertise and a potential base of suppliers and users of innovations. These networks play an especially important role when technological knowledge is informal or "tacit" in nature, when knowledge and ideas are hard to codify, and when "practical mastery" plays a large role (Storper and Walker 1989). Suppliers and end-users of a technology also provide an important source of additional knowledge and ideas (Von Hippel 1988). Concentrations of these firms foster important synergies in the innovation process, as for example when innovations in semiconductors spill over into electrical, consumer electronics, and computer industries.

The presence of concentrations of firms in related manufacturing industries ($RELPRES_{ls}$) is measured as value-added for the major industry two-digit group that encompasses the three-digit industry under consideration (Figure 6). Returning to our example of the drug industry (SIC 283), we use the value added in the related industrial group of Chemicals and Allied Products—SIC 28.

Business-service providers constitute our fourth and final independent variable. These providers play key roles in regional innovation complexes (Stohr 1986) such as Silicon Valley (Saxenian 1985) and Route 128 (Dorfman 1983). Providers such as commercial-testing laboratories, market-research firms, and patent

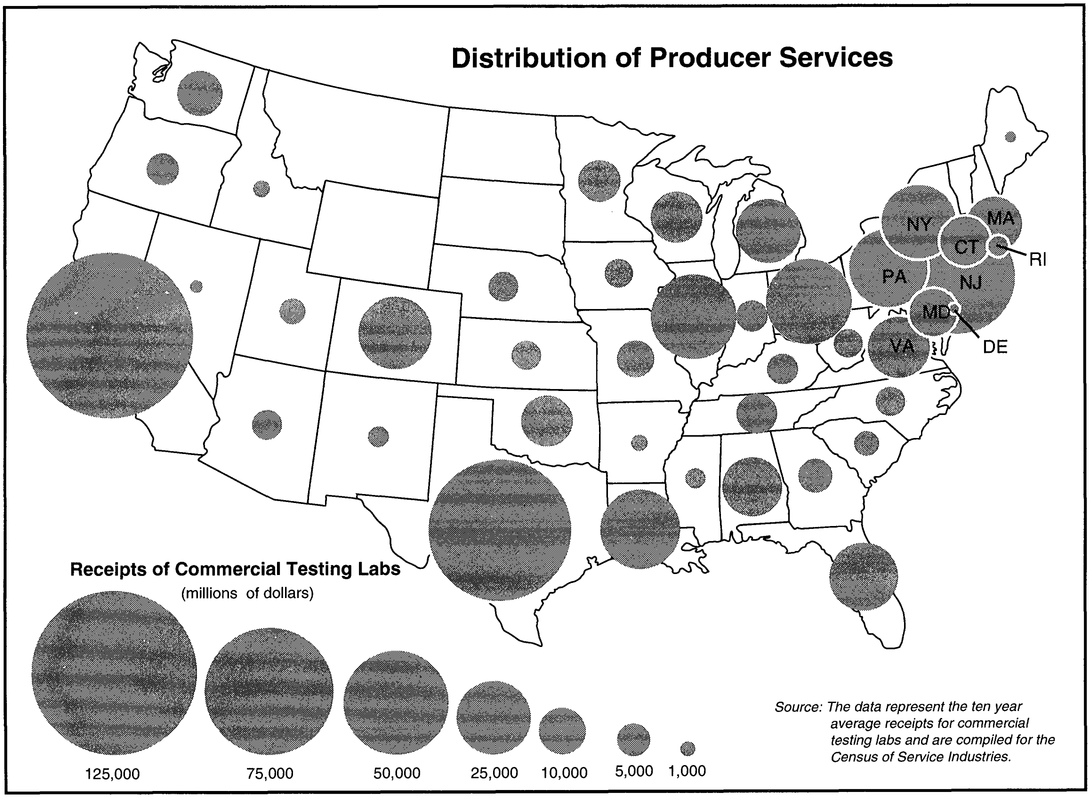


Source: 1977 Census of Manufacturing

Figure 6. Distribution of manufacturing value added in 1977.

attorneys offer important sources of information on technological and product opportunities, marketing and sales trends, regulations and standards, the law, and financing of the sort required to bring innovations to market and to effectively position new product offerings. MacPherson (1991) finds a strong correlation between the usage of external producer services and new products; other research indicates that specialized producer services tend to locate near their clients (Coffey and Polese 1987).

Business services comprise a wide range of activities. Although a variety of firms provide knowledge of the market and the commercialization process, the Census classification system makes it difficult to isolate those services that directly support the innovation process. For example, the census grouping of all legal services under one SIC classification (SIC 8111) makes it impossible to isolate the critical services of patent attorneys for the process of product innovation. Only one SIC category—SIC 7397, Commercial Testing Laboratories—is clearly linked with the introduction of new innovations. In the absence of other data, we use value-added in SIC 7397 as a surrogate indicator for specialized business services (*BSERV*$_{.s}$). The geographic distribution of these services is presented in Figure 7. Once again, we observe geographic concentration in California, New York, New Jersey, Massachusetts, Pennsylvania, and Texas. Of all of our independent variables, the location of specialized business services most closely resembles the location of product innovation. However, these mappings are not perfect, as some states, such as Florida, Louisiana, Connecticut, and Rhode Island have a relatively higher representation of business services when compared to innovation. But that is to be expected since our thesis suggests that it is the interactions and synergies of these elements of the technological infrastructure that provide the key to explaining the geo-



Source: The data represent the ten year average receipts for commercial testing labs and are compiled for the Census of Service Industries.

Figure 7. Distribution of producer services as measured by receipts of commercial testing labs.

graphic distribution of innovation, that is, these elements in space work interactively rather than in isolation.

Implementing a Geographic Model of Innovation: Specification and Estimation

Our geographic model of innovation regards innovation as a function of four classes of innovative inputs: networks of firms in related manufacturing industries, concentrations of university R&D, concentrations of industrial R&D, and concentrations of business-service providers. In formal terms, innovative output (INN_{is}), or the number of innovations for industry i in a geographic area s, is a function of: university research ($UNIV_{ls}$), industrial R&D (IND_{ls}), networks of related firms ($RELPRES_{ls}$), and specialized business services ($BSERV_{ls}$):

$$Log(INN_{is}) = \beta_1 \log(UNIV_{ls}) + \beta_2 \log(IND_{ls}) + \beta_3 Log(RELPRES_{ls}) + \beta_4 \log(BSERV_{.s}) + \beta_5 CONC_{.s} + \beta_6 \log(POP_{.s}) + \beta_7 \log(SALES_{i.}) + \varepsilon_{is} \qquad (1)$$

Because we expect knowledge spill-overs across related technological fields, the subscript $_l$ refers to industries that use similar technology. Two variables are added to control for aggregation bias. State population ($POP_{.s}$) controls for variable state sizes and thus facilitates cross-state comparisons. An index of geographic concentration ($CONC_{.s}$) controls for within-state variation and compensates for the use of states as the unit of observation.[5] This index measures the share of the state's value of manufacturing shipments held by the state's largest SMSA. A third variable, industry sales ($SALES_{i.}$), controls for variable demands for innovations generated within an industry. The model further specifies innovation as a recursive system consisting of four equations and a series of individual equations that isolate the determinants of industrial R&D, university R&D, and business services.

The second equation in the model examines the determinants of the location of industrial R&D. We expect that R&D laboratories will tend to locate either near production facilities or near firm headquarters (Malecki 1985; 1990), that is to say, the locational patterns will reflect the historical development of industrial R&D (Mowery and Rosenberg 1989) and that industrial R&D expenditures would be allocated to regions with strong and related university research programs (Jaffe 1989; Mansfield 1991). The industrial R&D equation accordingly regards that variable as a function of university research, firms in related industries, and corporate headquarters, ($HDQRT_{.s}$)—an indicator of Fortune 500 corporate headquarters.[6] The equation is as follows:

$$\log(IND_{.s}) = \omega_1 \log(UNIV_{.s}) + \omega_2 \log(RELPRES_{.s}) + \omega_3 \log(HDQRT_{.s}) + \omega_4 \log(POP_{.s}) + \varepsilon_{ls} \qquad (2)$$

The third equation in the model examines the determinants of the location of university R&D. Given that firms tend to use research at nearby universities and the strong tendency for the co-location of industrial and university R&D, the third equation explores the interaction between university research, industrial R&D, and firms in related industries. This equation also includes a variable for federally funded research and development centers ($FFRDC_{.s}$)—an indicator of the university's receptiveness to participate in technology transfer with industry. Equation 3 is specified as follows:

$$\log(UNIV_{lS}) = \gamma_1 \log(\Sigma IND_{ls}) + \gamma_2 \log(\Sigma RELPRES_{ls}) + \gamma_3 FFRDC_{.s} + \gamma_4 \log(POP_{.s}) + v_{IS} \qquad (3)$$

The fourth and final equation in the system examines the determinants of the location of specialized business services. The presence of such services is expected to reflect the client base on which these services depend, for example, industrial R&D laboratories (Coffey and Polese 1987). We also expect that specialized producer services, such as commercial testing laboratories, are a function of the overall base of business services, hence our inclusion of a variable ($TOTALBSERV_{.s}$) that represents the stock of receipts for general management and consulting services (SIC code 7392). Equation 4 is thus specified as follows:

$$\log(BSERV_{.s}) = \alpha_1 \log(IND_{.s}) + \alpha_2 \log(TOTALBSERV_{.s}) + \alpha_3 \log(POP_{.s}) + \xi_{.s} \qquad (4)$$

The four equations form a recursive system for testing the effects of technological infrastructure on commercial product innovation and for isolating the determinants of the components of that infrastructure. The system is recursive in the sense that there is no direct feedback from the second, third, and fourth equations to the first equation. And because of the time lag in translating successful innovative output into a new round of expenditures on innovative inputs, the system is not simultaneous in the usual sense. Summary statistics for the system appear in Table 4.

Before presenting the results, however, we need to attend to three statistical issues: the censored nature of the dependent variable, the likelihood of disturbances, and the prospect of multicollinearity in the independent variables. In the first instance, the dependent variable is censored in the sense that the number of innovations by state and industry will either be zero or some positive integer. Because the estimation of a production function such as equation (1) relies on a log–log transformation, observations with a value of zero present a problem. In order to estimate the innovation equation, it is necessary to transform the dependent variable, INN_{is}, and thus eliminate zero values. The new dependent variable, $\mathrm{Log}[10(1+INN_{is})]$, eliminates zero values yet preserves the relative ranking of innovative observations.

A second statistical issue is the likelihood of disturbance. Owing to spatial autocorrelation, the structure of the error terms is often a problem with regional cross-sectional data. A random shock affecting economic activity in one state may, for example affect economic activity in adjacent states when the several states exhibit economic linkage. In this case, disturbance terms in contiguous or related states will be related and the parameter estimates will not be efficient. The results of Durbin-Watson tests for autocorrelation on various orderings of the observations are inconclusive, however; hence we make no corrections for spatial autocorrelation. A second concern is the possibility of heteroscedasticity of the error term. The Breusch-Pagan test for heteroscedasticity in the error term reveals none in the innovation equation specification.

The third statistical issue is the presence of multicollinearity in the independent variables. This is particularly a problem with cross-sectional geographic data since these data may be affected by some common trend or underlying

Table 4. Summary Statistics.

Variable	Mean	St. Dev.	Min	Max
Innovations (INN_{is})[a]	7.72	24.49	0.00	365.00
University Research (UNIV$_{ls}$)[b]	32.52	59.41	0.30	380.60
Industry R&D ($IND_{.s}$)[b]	582.90	818.51	9.00	3883.00
Related Industry Presence ($RELPRES_{ls}$)[b]	903.06	1062.60	4.04	4404.00
Business Services ($BSERV_{.s}$)[b]	13.88	17.02	0.50	89.52
Geographic Concentration Index ($CONC_{.s}$)[b]	0.41	0.23	1.10	0.94
Industry Sales ($SALES_{i.}$)[b]	9.82	3.48	3.73	16.24
Sales of Fortune 500 Firms ($HDQRT_{.s}$)[b]	30,281.00	55,249.00	100.00	271,700.00
FFRDC ($FFRDC_{.s}$)[b]	0.59	1.00	0.00	4.00
General Business Services ($TOTALBSERV_{.s}$)[b]	443.21	545.71	40.71	2440.00
$\sum IND_{ls}$c	84.49	120.35	0.49	603.90
$\sum RELPRES_{ls}$c	1732.10	1901.10	59.17	8381.00
State Population ($POP_{.s}$)[d]	5919.07	4905.33	955.00	22,350.00

[a] Measured as integer counts of innovations.

[b] University research expenditures, industrial R&D expenditures, related-industry value added, receipts from specialized business services and total industry sales are in millions of 1972 dollars.

[c] The summation operator on industrial R&D expenditures (IND_{ls}) and value added and $RELPRES_{ls}$ indicates a total for industries relevant to an academic department (Feldman 1994a).

[d] Population is measured in thousands.

Table 5. Correlation Matrix for Independent Variables.

	$IND_{.s}$	$UNIV_{ls}$	$RELPRES_{ls}$	$BSERV_{.s}$
$IND_{.s}$	1.00			
$UNIV_{ls}$	0.68	1.00		
$RELPRES_{ls}$	0.63	0.39	1.00	
$BSERV_{.s}$	0.73	0.56	0.53	1.00

Note: Reported correlations are for the log values of each of the variables.

state characteristics. The correlation matrix of the innovative inputs indicates some evidence of multicollinearity (see Table 5), and this interdependence may result in higher variances in the parameter estimates and lesser statistical significance in the coefficients.

Given these concerns, the four equations are estimated using Three-Stage Least-Squares (3SLS) Regression. We also use instrumental variables to correct for correlation across the equations. In the model, these instruments include all of the exogenous variables that appear on the right-hand side of the equations. The first stage of estimation uses the contemporaneous values of the variables and then adjusts for the covariance matrix of the residuals. The interrelationships between the variables and the equations indicate that the efficiency of the parameter estimates increase with this type of estimation.[7]

Geographic Sources of Innovation: The Empirical Results

Table 6. Model Results.

Dependent Variable: Log[10(INN_{is} + 1)]		
Log($IND_{.s}$)	0.241^{a}	(0.054)
Log($UNIV_{is}$)	0.155^{a}	(0.043)
Log($RELPRES_{ls}$)	0.144^{a}	(0.045)
Log($BSERV_{.s}$)	0.272^{a}	(0.055)
Log($POP_{.s}$)	0.054^{b}	(0.030)
Log($SALES_{i.}$)	-0.236^{a}	(0.113)
$CONC_{.s}$	1.021^{a}	(0.189)
Dependent Variable: Log($IND_{.s}$)		
Log($UNIV_{.s}$)	0.566^{a}	(0.074)
Log($RELPRES_{.s}$)	0.466^{a}	(0.089)
Log($HDQRT_{.s}$)	0.180^{a}	(0.040)
Log($POP_{.s}$)	0.0486^{b}	(0.026)
Dependent Variable: Log($UNIV_{ls}$)		
Log(ΣIND_{ls})	0.256^{a}	(0.039)
Log($\Sigma RELPRES_{ls}$)	0.338^{a}	(0.047)
$FFRDC_{.s}$	0.539^{a}	(0.054)
Log($POP_{.s}$)	-0.118^{a}	(0.031)
Dependent Variable: Log($BSERV_{.s}$)		
Log($IND_{.s}$)	0.109^{a}	(0.040)
Log($TOTALBSERV_{.s}$)	0.707^{a}	(0.057)
Log($POP_{.s}$)	-0.295^{a}	(0.215)

Note: The instruments used include all of the exogenous variables appearing on the right-hand side of the equations in the model. Standard errors are in parentheses. The number of observations is equal to 377.
[a]significance of at least .95.
[b]significance at .90.

Table 6 presents the results of the estimation of the innovation model. Generally speaking, the model performed well. The coefficients for all four components of the technological infrastructure—industrial R&D, university research, related industries, and business services—are positive and statistically significant. Our findings are also robust, judging from runs of a number of permutations of the model. The first run measures all variables on a per-capita basis, and the basic results (signs and significance) remain the same. The second run tests the robustness of the results for states with more than one large manufacturing center. Once again, the basic results are unchanged. Simply put, the empirical results suggest that innovative activity within states is indeed related to the factors that comprise their underlying technological infrastructure.

Consider first the innovation equation. The coefficient estimates for all of the independent variables are positive and significant. The size of the industrial R&D coefficient suggests that it plays a key role in the innovation process. The coefficient of university R&D is similarly positive and significant. The latter confirms the results of Jaffe (1989) and Acs, Audretsch, and Feldman (1992) as it demurs from the findings of Markusen, Hall, and Glasmeier (1986) who find that university R&D is negatively related to high-technology industry and employment. The coefficient for the presence of related manufacturing industries is likewise positive and significant, that is, concentrations of and synergies among firms in related industries tend to foster innovation. Furthermore, the size of the coefficient for business services indicates that the presence of these services has a particularly positive effect on the innovation process, perhaps because these services are critical in the concluding marketing phase of the commercialization process.

Turning now to the model's sub-equations, the coefficients for the industrial R&D equation are all positive and statistically significant. Industrial R&D is related to university R&D expenditures, concentrations of firms in related manufacturing industries, and the presence of corporate headquarters. The magnitude of the coefficient of university R&D expenditures, as expected, suggests an especially strong relationship between university and industrial R&D. This result affirms that university R&D increases technological opportunities available in a state or region and provides incentives to invest in private industrial R&D to exploit the stock of basic scientific knowledge (Nelson 1986). The coefficient for the presence of related industries suggests a fairly strong relationship between industrial R&D and the broader industrial base. This is not surprising since industrial R&D tends to feed off, as well as support, clusters of manufacturing activity.

The empirical findings for the university R&D sub-equation indicate a close association between it and industrial R&D and related industries. The relationship between university R&D and the presence of corporate headquarters, however, is somewhat weaker, though still significant. The coefficient for federally funded research centers is positive and statistically significant. In sum, the association between university R&D expenditures and both industrial expenditures on R&D and industrial activity and industrial R&D in related fields reaffirms Mansfield's (1991) finding that private firms utilize research findings generated from nearby universities. On the whole, it appears that university R&D has a greater effect on industry R&D than vice-versa. Indeed, the impact of university R&D on industrial R&D has twice the magnitude of the impact of industrial R&D on university R&D. University R&D may therefore play a critical role in the innovation process by attracting industrial R&D and by leveraging industrial activities. However, the relatively smaller effect of industrial R&D on the university R&D may be explained by the fact that a large proportion of total university R&D, almost two-thirds, is provided by the federal government and as such it may be less responsive to state industrial priorities and concerns (National Science Board 1989).

The findings of the business services sub-equation indicate that the presence of specialized business services is positively related to industrial R&D and to the overall business-services sector. In other words, specialized business services, in this case commercial testing laboratories, are co-located with their principal clientele, the R&D laboratories. In addition, concentrations of specialized producer services are related to a large overall business service sector.

Taken together, these findings provide the beginnings of an explanation for the dynamics of an area's technological infrastructure. The factors that comprise the region's technological infrastructure work together to create an overall capacity that is conducive to innovation. Each of the components must be in place for innovation to occur; however it is the interaction and synergy among these components that accounts for a higher propensity to innovate in particular places. Above all, our findings indicate the mutual reinforcement of the four major components of technological infrastructure: industrial R&D, university R&D, firms in related industries, and business services. The synergies among these four components yield a technological infrastructure with a high propensity for product innovation. The innovative capacity of an area—in this case, states—hinges on this underlying technological infrastructure. Thus, our empirical results confirm that agglomeration, and geography more broadly, play significant and important roles in the organization and mobilization of knowledge in behalf of commercial product innovation.

Some Thoughts on the Geography of Product Innovation: Today and Tomorrow, Here and Abroad

We have explored the geography of innovation, suggesting that it is unusually dependent on an area's technological infrastructure. We have oriented our analysis around an empirical model of the innovation process which introduces a new, and previously unavailable, measure of innovative output at the state level. Our model presumes that innovation is a function of an area's underlying technological infrastructure, which, in turn, consists of: university R&D, industrial R&D, agglomerations of related industry, and specialized business services. The model is formulated as a recursive system in order to improve our understanding of the interrelationships between the four innovative inputs noted above.

The findings of the model confirm the hypothesis that innovation is a function of an area's technical infrastructure. Innovation is related to the geographic concentrations of industrial R&D, university R&D, related industries, and business services. Our results imply significant synergy and mutual reinforcement among the factors that comprise the technological infrastructure.

Our findings further suggest that there is considerable geographic specialization in the technological infrastructures of various places. The capacity to innovate is very much the historical legacy of specialized concentrations of R&D, industrial activity, and support services that build up in particular places over time. In other words, different places are the sources of particular types of innovation. California—with its clusters of high-technology electronic producers, suppliers, business service providers, and venture capitalists in places like Silicon Valley and elsewhere—specializes in innovations related to electronics. New Jersey, with its massive chemical and pharmaceutical complexes, is the center for innovations in drugs, medicines, and medical equipment. Innovations related to photographic equipment and opto-electronics are concentrated in New York, most notably in the Rochester-area's opto-electronics complex composed of Xerox, Kodak, Bausch and Lomb, and related suppliers. The industrial Midwest, with its history of manufacturing infrastructure in steel, automotive, appliance, and consumer durable production, is the primary source of innovations in metal fabrication and industrial machinery. Yet while each of these complexes specializes in a specific type of innovations, they all depend upon a set of underlying factors that comprise a technological infrastructure for generating new ideas and bringing them to the market.

Our findings thus suggest that not only does geography play a central role in the innovation process, but further that innovation is itself a geographic process. Geography, in an integral sense, organizes and advances innovation. The capacity to innovate is the product of complexes of enterprises and R&D; networks of institutions and institutional resources; concentrations of human talent, knowledge, and skill; and a legacy of sustained investment in an area's technological capability. Our findings, therefore, reinforce Storper and Walker's concept of geographic industrialization (1989) while adding to it the related notion that the sources of innovation that propel the contemporary processes of industrialization are themselves geographic in nature. Our results also redirect attention to the ways in which particular places have acquired a comparative advantage for innovation and economic development. If we are correct, locational advantage would seem to reflect cumulative investments in human and technological capability in specific places, more so than the conventional natural advantages of land, labor, and capital. In the modern economy, locational advantage in the capacity to innovate is ever more dependent on the agglomeration of specialized skills, knowledge, institutions, and resources that make up an underlying technological infrastructure.

At a broader level, our findings provide a deeper understanding of innovation as a geographic as well as an economic process. For students of capitalist development from Adam Smith to Karl Marx and Joseph Schumpeter, innovation has been regarded as a primary source—if not "the" primary source—of economic growth and development. For such theorists, innovation is the product of individual capitalist firms, entrepreneurs, and organizations which function to organize and harness the various technological and organizational inputs required for innovation, profit, and growth. But, as we have seen, the capacity for innovation extends far beyond the boundaries of the individual firm. In the United States today, innovation is no longer the province of the inventor, the risk-taking entrepreneur, the insightful venture capitalist, or the large resource-rich corporation. Innovation instead has its sources in a broader social and spatial structure—a landscape of agglomerated and synergistic social and economic institutions welded into a technological infrastructure for innovation. It is in this fundamental sense that geography organizes the innovation process and helps sustain the spatially uneven growth and progress of advanced technological economies.

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Notes

1. While precise data on the economic significance of each innovation are not available, the SBA provided ratings of their economic significance; less than 1 percent represented the first type of product in a category, 14 percent represented a significant improvement over existing technology, and 85 percent represented a modest improvement to an existing product. Information on the revenue generated by each innovation is not available.
2. R&D expenditures are from the National Science Foundation as reported by Jaffe (1989). Patent counts by state are also from Jaffe (1989) and represent the average annual number of patents received in 29 states over an eight-year period. High-technology employment data are from the U.S. Office of Technology Assessment (1984) for the year 1982.
3. Innovation quotients are calculated as the percentage of industry innovations in a state divided by the percentage of national innovations in that industry. The quotient is then multiplied by 100. An innovation quotient of 100 indicates that the innovations in a particular industry are equally distributed in the state and national economies.
4. The result may be attributable to the measurement of university research as federal funding for a single year. Federal funds, on average, account for only 65 percent of total university research expenditures, albeit with sizable variations between institutions. Furthermore, a one-year flow of funds may not capture the stock of university research that defines innovative capacity in an area.
5. In the estimation of the innovation equation, we did not use the log of the geographic concentration variable because there is no strong *a priori* functional specification and because the estimation of the innovation equation with a log transformation of this variable yields similar results.
6. No simultaneity between an area's innovative success and industrial R&D allocation is estimated because of the time lag in introducing an innovation to the market. Industrial R&D typically precedes market introduction by four to five years and thus a firm's response to successful innovative outputs will reflect that time delay.
7. The system of equations is estimated using Seemingly Unrelated Regression which essentially amounts to the first two stages of three-stage least squares. A comparison of the parameter estimates indicates a gain of efficiency with three-stage least-squares regression owing to the presence of cross-equation correlation.

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Feldman, Maryann P., and Florida, Richard. 1994. The Geographic Sources of Innovation: Technological Infrastructure and Product Innovation in the United States. *Annals of the Association of American Geographers* 84(2):210–229. *Abstract.*

The fate of regions and of nations increasingly depends upon ideas and innovations to facilitate growth. In recent years, geographers have made fundamental contributions to our understanding of the innovation process by exploring the diffusion of innovation, the location of R&D, and the geography of high-technology industry. This paper examines the geographic sources of innovation, focusing specifically on the relationship between product innovation and the underlying "technological infrastructure" of particular places. This infrastructure is comprised of agglomerations of firms in related manufacturing industries, geographic concentrations of industrial R&D, concentrations of university R&D, and business-service firms. Once in place, these geographic concentrations of infrastructure enhance the capacity for innovation, as regions come to specialize in particular technologies and industrial sectors. Geography organizes this infrastructure by bringing together the crucial resources and inputs for the innovation process in particular places. Using a direct measure of commercial product innovation, an empirical model of the geography is presented. The model tests the hypothesis that innovation is concentrated in places that possess a well-developed technological infrastructure. The analysis confirms this hypothesis; innovations cluster geographically in areas that contain geographic concentrations of specialized resources indicative of technological infrastructure. The spatial concentration of these resources, furthermore, reinforces their capacity to innovate. **Key Words:** industry R&D, innovation, knowledge-base, regional capacity, technological infrastructure, university R&D.