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LOCATION AND TECHNOLOGICAL CHANGE IN THE AMERICAN GLASS INDUSTRY DURING THE LATE NINETEENTH AND EARLY TWENTIETH CENTURIES

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ABSTRACT

Scholars have attempted to explain geographic clustering in inventive activity by arguing that it is connected with clustering in production or new investment. They have offered three possible reasons for this link: because invention occurs as a result of learning by doing; because new investment encourages experimentation with novel techniques; and because there are local information flows that make inventors more fertile in areas where producers are concentrated. In this article we test these theories by studying geographic patterns of production and invention in the glass industry during the late nineteenth and early twentieth centuries. We find that the patterns deviate significantly from what the theories would predict, and offer the alternative hypothesis that inventive activity proceeded most intensively in areas where markets for technology had developed most fully—that is, where there were localized networks of institutions that mobilized information about technological opportunities and mediated relations among inventors, suppliers of capital, and those who would commercially develop or exploit new technologies.

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Economic growth depends over the long run on inventions that make it possible to produce more and better goods with society's limited resources. For this reason, scholars as well as policy makers have long sought to understand the conditions that influence the level of inventive activity in an economy. Because rates of invention have been significantly higher in some locations than in others, one approach has been to try to identify the sources of such geographic variation. Perhaps the best known attempt is the argument that technological discovery occurs as part of the process of learning by doing, and that therefore geographic clustering in invention is a function of geographic clustering in production, which in turn may result from comparative advantage or from location-specific externalities.[1] A related theory hypothesizes that regions where an industry is experiencing new investment or rapid growth in production tend to generate higher rates of invention, the reason being that there is greater

[1]The geographic clustering of invention can be tracked using the *Annual Reports of the Commissioner of Patents*. There are, of course, many discussions in the learning-by-doing literature that are relevant to the study of variation in rates of invention across locations, beginning with the seminal articles by Alchian, "Progress Curves," and Arrow, "Economic Implications of Learning By Doing." For several very different treatments of learning-by-doing that see it operating beyond the level of the firm, see Gilfillan, *Sociology of Invention*; Landes, *Revolution in Time*; and Young, "Learning By Doing." On why there is geographic clustering in production, see Leamer, *International Comparative Advantage*; Krugman, *Geography and Trade*; and Marshall, *Principles*, pp. 267-277.

opportunity or pressure in such areas to experiment with new techniques.[2] A third perspective, one that has recently attracted attention from "new growth theorists," argues that information flows are conducive to invention—that is, inventors working on a related set of problems in close spatial proximity to each other will be more productive than those who are geographically isolated because of the greater likelihood that they will share information (whether inadvertently or deliberately).[3]

All of these explanations for the clustering of invention have one important element in common. They treat the geographic pattern of inventive activity in an industry as a function of the location of production—either total or new—in that specific industry. Unfortunately, most studies that have explored geographic patterns in invention have focused on overall patenting rates. There has been little systematic examination on the industry level of the extent to which patterns of inventive activity did in fact replicate those of production.[4] In this article, we study in detail a single industry—glass—over the late nineteenth and early twentieth centuries in order to evaluate these competing, if not mutually exclusive, views of the sources of geographic

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[2]For example, see Schmookler, *Invention and Economic Growth*, ch. 6

[3]For examples of, or evidence for, this argument, see Jaffe, Trajtenberg, and Henderson, "Geographic Localization of Knowledge Spillovers;" Krugman, *Geography and Trade*; and Landes, *Revolution in Time*.

[4]For examples, see Pred, *Circulation of Information*; Higgs, "American Inventiveness"; Sokoloff, "Inventive Activity"; and Lamoreaux and Sokoloff, "Long-Term Change." An important exception is Schmookler, *Invention and Economic Growth*, chs. 6-7, but Schmookler was concerned to show covariation between patenting and investment by industry, both over time and cross-sectionally, rather than investigate the degree to which geographic patterns of patenting and investment corresponded.

clustering in invention. The glass industry is a particularly interesting case to explore because production was concentrated in just a few areas of the country, yet the industry experienced both geographical restructuring and major technological advance during this period. We begin by tracing the history of the industry, including the changes over time in its spatial distribution of production, labor force, and patents, and then turn to the relationship between the geographic concentration of glass production and that of inventive activity in that industry. We find that, although there was clustering in both production and patenting (our measure of invention), the geographic patterns were quite different. Some production centers were also centers of invention, but others were not. Conversely, some areas with high rates of inventive activity had very little production. Moreover, regions with new plants had no apparent advantage in invention. We conclude from these results that the geographic concentration of production (whether total or new) was neither a necessary nor a sufficient condition for the clustering of inventive activity in the industry. Our alternative hypothesis, which derives from our own earlier work on overall patenting, postulates that inventive activity proceeded most intensively in areas where trade in technological information had developed most fully.[5] The ability to sell patented inventions encouraged, and in turn was stimulated by, an increasing tendency among patentees to specialize in invention and extract the returns from their efforts by selling their devices to others, rather than by directly exploiting them themselves. Although well developed markets for patented technology sometimes emerged in specialized production centers, they developed most densely in regions of the country (Southern New England is the prime example) where patenting activity

[5]Lamoreaux and Sokoloff, "Long-Term Change."

had long been concentrated. In such areas they encouraged inventive activity across a wide range of industries, regardless of the extent of local production.

History of the Industry

The availability of fuel supplies has always strongly affected the locational decisions of firms in the glass industry. During the early part of the nineteenth century, when trees provided the industry with its main source of energy, most glass producers set up shop in or near the abundant forests of Massachusetts, New York, New Jersey, Maryland, and Pennsylvania. Even at that time, however, a few manufacturers in the Pittsburgh area used coal in the melting process, and when wood supplies in the Northeast began to decline, this segment of the industry gained ground, both absolutely and relatively. By mid-century cheap coal offered firms in the Pittsburgh region a significant cost advantage, and the district became the center of glass production in the United States.[6]

During the 1880s the realization that natural gas had burning properties that were superior to coal, and the nearly contemporaneous discovery of new natural gas resources in the Middle West, stimulated a second westward migration of the industry. Although Pennsylvania retained its position of leadership, thanks in part to its own resources of natural gas, production in gas-poor regions like New England declined. As Table 1 indicates, the number of establishments in Ohio's gas belt mushroomed from 19 in 1879 to 59 in 1889, and the total value of glass produced in the state rose from $1.5 to $5.6 million. The number of establishments in Indiana, which also

[6]Davis, *American Glass Industry*, pp. 41-43, 71-74.

TABLE 1

GEOGRAPHIC DISTRIBUTION OF ESTABLISHMENTS AND VALUE OF OUTPUT IN THE GLASS INDUSTRY

State	1879		1889		1899		1909		1919		1929	
	No. of Establishments	Value of Output ($000)	No. of Establishments	Value of Output ($000)	No. of Establishments	Value of Output ($000)	No. of Establishments	Value of Output ($000)	No. of Establishments	Value of Output ($000)	No. of Establishments	Value of Output ($000)
California									7	3,761	16	9,680
Illinois	6	901	13	2,372	6	2,834	11	5,047	14	18,245	13	22,938
Indiana	4	791	21	2,995	110	14,758	44	11,593	35	30,107	26	34,490
Kansas							23	2,087				
Maryland	7	587	11	1,257	7	558	7	1,038	8	4,032	7	5,040
Massachusetts	10	854	6	431	5	418						
Missouri	6	920	5	1,215	3	766	4	1,993				
New Jersey	22	2,810	34	5,218	26	5,094	23	6,961	21	13,695	10	16,284
New York	29	2,421	30	2,723	27	2,757	24	4,509	19	12,996	17	17,857
Ohio	19	1,549	59	5,649	28	4,547	45	14,358	44	35,241	25	39,309
Oklahoma									16	4,751	10	5,029
Pennsylvania	77	8,721	99	17,179	119	22,011	112	32,818	102	80,480	70	81,050
West Virginia	4	749	7	945	16	1,872	51	7,779	77	42,730	48	48,385
All Others	10	852	9	1,065	8	925	19	3,962	28	15,848	21	23,758

Note: In some cases where the number of establishments and value of output for a state are left blank, figures for the state are included in the category All Others. The Census did not report figures separately where there were only one or two firms in a state.

Sources: U.S. Census Office, *Twelfth Census: Manufacturers*, Part III, pp. 952-4; U.S. Bureau of the Census, *Thirteenth Census*, *Manufactures* Vol. X, p. 876; and *Fifteenth Census: Manufactures,* Vol. II, p. 869.

boasted large gas reserves, similarly jumped, rising from 4 to 21 over the same period, while the value of output increased from $0.8 to $3.0 million.

Over the next couple of decades production continued to migrate in response to the ebb and flow of new gas supplies. Ohio's gas resources were quickly exhausted, and the industry there declined during the 1890s. Indiana gained temporarily at Ohio's expense, though its supplies too were short-lived. The discovery of additional reserves in Kansas, Oklahoma, and West Virginia during the early twentieth century stimulated investment in those states as well. Except for the case of West Virginia, however, these subsequent migrations were never as dramatic as the shift to Ohio and Indiana that occurred during the last two decades of the nineteenth century. Manufacturers learned to substitute producer gas made from coal for natural gas in the melting process, and this change reduced the locational pull of gas reserves.[7] Indeed, the trend during the early twentieth century was for the industry to reconcentrate itself in western Pennsylvania and neighboring West Virginia, where there were abundant coal resources. By the 1920s over 40 percent of the industry's production was located in just a small number of counties in these two states.

The switch to natural gas not only triggered shifts in the location of production but also paved the way for revolutionary innovations in glass manufacturing technology. As might be expected, these changes occurred first in the heating process. Until the late 1880s, manufacturers had used batch methods of production, melting glass in individual pots arranged within furnaces

[7]Manufacturers also began to use petroleum as a fuel during the early twentieth century. U.S. Department of Commerce, *The Glass Industry*, pp. 12-13, 55, 187-8; Davis, *American Glass Industry*, p. 175; U.S. Census Office, *Twelfth Census: Manufactures*, Part III, pp. 958, 966; *National Glass Budget*, 10 Sept. 1927, p. 25.

and devoting about half their production time to cooling the melted glass, removing it from pots, and reheating their furnaces. European manufacturers had been experimenting with gas-fueled tank furnaces that melted glass continuously, and the switch to natural gas spurred the importation of this technology to the United States. The first successful installation of a continuous tank furnace occurred at a window glass factory in Jeannette, Pennsylvania, in 1888. During the next decade tank furnaces spread rapidly through that branch of the industry and, by 1900, accounted for more than half the nation's capacity to make window glass. The bottle branch of the industry experienced a similar shift in favor of tank furnaces at about the same time.[8]

The new volume of production made possible by continuous tank furnaces in turn stimulated manufacturers to automate other phases of the production process. Until the 1890s, for example, glass bottles and jars were fashioned completely by hand in "shops" of highly skilled workers. During that decade several different inventors brought out machines that automated the blowing part of the process, but these devices still required the services of skilled gatherers to feed the molten glass into molds. Then, in 1903, Michael J. Owens of Toledo, Ohio, developed a fully automated bottle machine that pulled glass directly from the tank, virtually eliminating the use of skilled labor. Owens and his backers initially decided to license their technology rather than produce bottles themselves, and by 1910 more than 60 of the machines were in use. In 1908, however, the Owens Bottle Machine Company began to make its own bottles and acquired

[8]Davis, *American Glass Industry*, pp. 125-6, 175; U.S. Census Office, *Twelfth Census: Manufacturers*, Part III, pp. 966, 989-90; U.S. Department of Commerce, *The Glass Industry*, pp. 11-12, 61-2; U.S. Bureau of Labor Statistics, *Productivity of Labor*, pp. 3-4.

several of the concerns to which it had licensed its technology, with the result that by 1917 the firm controlled 77 of the 191 machines in operation. The more restrictive licensing policy that the Owens Company pursued once it began to make its own bottles stimulated other inventors to improve existing blowing machines by developing automatic feeding mechanisms, and by the 1920s a number of alternative fully automatic machines were on the market. In 1918 only about 500,000 gross of bottles were produced on these other machines, as opposed to about 10 million on the Owens machines, but by 1925 the gob feeders, as they were called, were catching up, accounting for about 8.5 million gross bottles compared to the Owens machines' 12.5 million. By that year, these two categories of machines together accounted for 90 percent of the bottles made in the United States.[9]

A similar technological revolution transformed the window glass industry during the early twentieth century. Before 1900 window glass was entirely the product of skilled craftsmen, who blew the molten metal into large cylinders which they then opened and flattened. At about the same time that Owens was introducing his bottle machine, J. H. Lubbers, working with the backing of the American Window Glass Company, was developing a machine capable of replicating the gathering and blowing operations performed by skilled window-glass workers. Lubbers's cylindrical machines quickly spread through the industry. They, and the other comparable window-glass machines that soon came on the market, accounted for as much as

[9] Davis, *American Glass Industry*, pp. 81-2, 141-2, 205-11, 213-14; Scoville, *Revolution in Glassmaking*, pp. 145, 154-62, , 182-9; U.S. Department of Commerce, *The Glass Industry*, pp. 14-15, 63-4, 212-14; U.S. Bureau of Labor Statistics, *Productivity of Labor*, pp. 4-5, 28-45; *National Glass Budget*, 7 May 1927, p. 8; 30 July 1827, pp. 3, 5-7, 21, 24, 26; and 2 June 1828, p. 20.

two-thirds of the industry's product by 1920. Meanwhile, however, inventors were hard at work developing an alternative way to manufacture window glass—sheet drawing—that would triumph in the 1920s and account for about 80 percent of domestic output by 1930. One of the two sheet drawing machines that would achieve commercial importance during that decade was invented by Irving W. Colburn. When Colburn's Blackford, Pennsylvania, company failed, Owens convinced the Toledo Glass Company to purchase the patents and provide the capital needed to make the invention workable. The other main contender in the sheet-drawing field was a machine developed by Emile Fourcault of Belgium.[10]

Although this discussion has focused on the revolutionary changes that occurred in forming methods during the early twentieth century, other aspects of glass manufacture experienced similar improvement. For example, glass which had previously been annealed in kilns now moved slowly through long, tunnel-like furnaces called lehrs, reducing significantly the time required for cooling. Manufacturers also developed automatic techniques for combining

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[10]The drive to mechanize window-glass production was also stimulated by the role labor organizations played in supporting manufacturers' attempts to restrain competition. For example, at a time when skilled labor was scarce, the American Window Glass Company signed a contract with the glass workers' union that would assure it (and not its competitors) a supply of labor. The price of this agreement was a block of the company's stock, par value $500,000, put in trust for the union. Davis, *American Glass Industry*, pp. 175-93; Scoville, *Revolution in Glassmaking*, pp. 189-94; Fairfield, *Fire & Sand*, pp. 71-83; U.S. Department of Commerce, *The Glass Industry*, pp. 20-2, 65; U.S. Bureau of Labor Statistics, *Productivity of Labor*, pp. 6, 145-58; *National Glass Budget*, 21 May 1927, p. 21; 25 Feb. 1928, pp. 3, 6; and 14 July 1928, pp. 21, 23, 25.

the various glass-making ingredients in the proper ratios and for grinding, polishing, and otherwise finishing their final products.[11]

Geographic Patterns of Production and Invention

The combination of rapid changes in technology and in the location of manufacturing, along with the generally high level of geographic concentration in the industry, makes glass an excellent case for studying the relationship between the location of invention and that of production. In order to track geographic patterns in patenting, we drew a sample of 1082 patents from the *Annual Reports of the Commissioner of Patents* for 1870, 1871, 1880, 1881, 1890, 1891, 1899, 1901, 1909, 1911, 1918, and 1919. The data include inventions pertaining to the main branches of glass production (we call this subset "industrial glass patents"), as well as a number of design patents and many inventions related to optical devices (for example, lenses, telescopes, and eyeglasses). For each patent, we recorded the names and addresses of the patentees and their assignees and then linked these observations with additional information, such as other inventive activity by the patentees and information about the geographic areas in which the patentees resided.

As the regional shares of glass production, labor force, and patents recorded in Table 2 indicate, there were substantial and persistent regional disparities in inventiveness over our period. The most striking outlier was Southern New England (Connecticut, Massachusetts, and

[11]Davis, *American Glass Industry*, pp. 122, 180, 252-5; U.S., Census Office, *Twelfth Census: Manufactures*, Part III, pp. 962-3; U.S. Department of Commerce, *The Glass Industry*, pp. 65-66; *National Glass Budget*, 7 May 1927, pp. 3, 7, 11; 5 May 1928, pp. 3, 7; and 9 June 1928, pp. 3, 23.

TABLE 2

SHARES OF GLASS PRODUCTION, LABOR FORCE, AND PATENTS

	1870 -71	1880 -81	1890 -91	1899 -1901	1909 -11	1918 -19
Southern New England						
% of Production	13.5	5.1	2.2	1.4	1.2	0.7
% of Labor Force	14.5	4.9	1.8	1.2	1.3	0.8
% of All Glass Patents	14.8	16.3	10.3	1.7	3.0	7.3
% of Industrial Patents	19.5	16.8	9.9	1.0	2.6	5.2
New York						
% of Production	13.0	17.8	11.3	9.7	8.6	7.2
% of Labor Force	15.3	16.1	9.6	8.0	8.2	7.2
% of All Glass Patents	9.1	19.5	7.1	6.0	7.7	11.7
% of Industrial Patents	9.8	14.7	5.9	5.5	7.8	10.3
New Jersey/Delaware						
% of Production	14.9	12.2	11.5	8.2	7.3	5.4
% of Labor Force	17.5	14.1	11.9	9.6	8.1	7.9
% of All Glass Patents	0.0	2.4	4.8	3.4	3.0	2.9
% of Industrial Patents	0.0	3.2	4.9	4.0	3.1	3.0
Pennsylvania						
% of Production	43.8	37.5	37.8	35.6	33.8	29.4
% of Labor Force	39.8	38.5	39.2	35.3	32.7	27.5
% of All Glass Patents	55.7	28.5	31.8	26.8	27.8	32.1
% of Industrial Patents	43.9	32.6	32.4	29.0	27.5	36.1
West Virginia						
% of Production	1.0	3.2	2.0	2.9	7.3	14.9
% of Labor Force	0.9	3.7	2.8	3.4	7.8	13.9
% of All Glass Patents	9.1	0.0	2.4	7.7	2.6	5.1
% of Industrial Patents	7.3	0.0	3.0	8.5	2.1	5.6
Ohio						
% of Production	3.3	6.6	12.7	7.3	14.0	13.0
% of Labor Force	2.9	6.6	13.6	8.2	13.5	13.6
% of All Glass Patents	0.0	8.7	15.9	11.1	11.7	13.9
% of Industrial Patents	0.0	10.5	18.6	11.0	14.0	15.9
Indiana						
% of Production	4.1	3.3	6.4	22.6	10.9	11.1
% of Labor Force	2.8	3.3	6.2	22.5	12.0	11.2
% of All Glass Patents	0.0	0.0	1.6	12.3	4.8	3.7
% of Industrial Patents	0.0	0.0	2.0	14.0	5.2	3.0
Other Midwest						
% of Production	2.3	9.0	10.4	8.8	10.0	9.1

% of Labor Force	1.8	7.2	9.9	8.4	9.5	7.4
% of All Glass Patents	3.4	6.5	12.7	10.2	16.1	7.3
% of Industrial Patents	7.3	3.2	14.7	5.0	18.1	6.9
Other U.S.						
% of Production	4.0	5.3	5.7	3.5	6.9	9.2
% of Labor Force	4.4	5.6	5.0	3.4	6.9	10.5
% of All Glass Patents	0.0	6.5	4.0	2.6	7.8	8.0
% of Industrial Patents	0.0	5.3	2.0	2.0	7.3	7.7
Foreign						
% of All Glass Patents	8.0	11.4	9.5	18.3	13.5	8.0
% of Industrial Patents	12.2	13.7	9.8	20.0	12.4	6.4

Notes and Sources: "Southern New England" includes Massachusetts, Rhode Island, and Connecticut, and the "Other Midwest" includes Illinois, Michigan, Wisconsin, Minnesota, and Missouri. The shares of production and labor force were computed from the totals reported in the respective censuses of manufactures for plate glass, window glass, glassware, bottle glass, glass jars, and various other products such as green glass, stained glass, ornamental glass, and cut glass. See U.S. Census Office, *The General Statistics of Manufactures*; U.S. Census Office, *Manufactures at the Tenth Census*; U.S. Census Office, *Manufacturing at the Eleventh Census: 1890*. U.S. Census Office, *Twelfth Census: Manufactures*; U.S. Bureau of the Census, *Thirteenth Census: Manufactures*; and U.S. Bureau of the Census, *Fifteenth Census: Manufactures*. By 1909-11 and 1918-19 there were no longer enough glass firms in Massachusetts for the Census to report the magnitudes for that state separately. The figures in the table are interpolated using 1890 proportions. The shares of all glass patents and of industrial glass patents were computed from the sample of glass patents described in the text. The category "industrial glass patents" omits design patents and patents for optical devices such as telescopes and eyeglasses.

Rhode Island), which maintained patent shares in excess of its shares of industry production and employment throughout the period. At the opposite extreme were the states of New Jersey and Delaware, with patent shares consistently below their shares of production and employment. Pennsylvania was an intermediate case. Far and away the largest center of glass production in the United States, it registered shares of patenting that exceeded its shares of production in 1870-71 and 1918-19, but dipped below production in between.

As the polar cases of Southern New England and New Jersey/Delaware vividly illustrate, the evidence in the table undercuts any attempt to posit a close linkage between rates of invention and the size of the industry. In 1870-71 each of these two groups of states accounted for roughly 15 percent of the national totals of output and workers in the glass industry, and in each the industry subsequently experienced a secular decline (Southern New England's was particularly pronounced). Yet though New England was home to a great deal of inventive activity in glass, the two Middle Atlantic states were definite technological laggards. Southern New England was responsible for nearly 15 percent of U.S. patents in 1870-71; New Jersey/Delaware accounted for none. In 1919, the former region produced 7.3 percent of the country's glass patents, even though its share of the industry had shrunk to less than 1 percent of total gross output and labor. That same year New Jersey/Delaware accounted for almost ten times the number of glass workers, but received less than half the number of patents. These are not the only cases of sharp and persistent divergences between shares of patents and shares of output and labor. Among the major glass-producing states, Ohio (slightly above average in inventiveness) and Indiana (well below average) provide additional good examples. Moreover, though the numerical estimates vary, the general qualitative result is not sensitive to whether the measure of invention is based on all glass patents or restricted to industrial ones.

Nor was invention disproportionately located in areas where production was expanding most rapidly. Indiana and West Virginia realized major increases in their shares of output and labor force without corresponding advances in inventiveness. Between 1890-91 and 1901, the Hoosier state's share of glass output rose from 6.4 to 22.6 percent, yet its share of patents grew only from 1.6 to 12.3 percent. Similarly, West Virginia raised its share of the industry from 2.9 percent in 1901 to 7.3 and 14.9 percent respectively in 1911 and 1919. In these latter years, however, only 2.1 and 5.6 percent of U.S. patents in glass technology went to residents of that state. Only in Ohio and the group of states combined into the category Other Midwest (Illinois, Michigan, Missouri, Minnesota, and Wisconsin) do we find some support for the idea that increases in inventiveness accompanied surges of production. As Ohio's share of the industry increased after 1870-71, its share of patents grew more than proportionally, especially during the initial phase of what proved to be a major move into the state. Similarly, after the production of glass increased substantially in the Other Midwest from 2.3 of the nation's output in 1870-71 to 9.0 percent in 1880-81, patenting per worker rose well above the national average. In this last case, however, patenting activity was concentrated in big cities like Chicago and St. Louis, which were not important centers of glass production.

Finally, the evidence in the table is also not consistent with the hypothesis that externalities associated with the concentration of production, such as improved information flows that raised the productivity of local inventors, were responsible for the pattern of geographic variation in inventive activity. Such a theory would lead us to expect that the localization of production would generate an even more localized pattern of invention, but as Table 2 shows, the only production center with disproportionate patenting was Ohio, and even in that case, the share of patenting exceeded that of production by only a modest amount. The evidence for Pennsylvania is particularly telling. Because it was the largest production center, one would have expected to find the effect of externalities there if anywhere. For most of the period, however, Pennsylvania's share of glass output and labor exceeded its share of glass patents.

Of course, one common criticism of the use of patent data is that it lumps together all inventions regardless of their worth. It is at least theoretically possible that the numerical preponderance of relatively unimportant patents is skewing our results—that is, that the relative inventiveness of New England resulted from large numbers of insignificant patents that inventors out of touch with what was going on in the industry continued to churn out, or that the apparent backwardness of Indiana misses the significance of key inventions originating in machine shops in that production center. Other evidence, however, confirms the lack of correspondence revealed by the patent data between invention and both production and new investment. In the case of window glass, for example, the firms that moved out to the recently opened gas reserves of Indiana in the 1890s were certainly not the most technologically advanced in the industry. Indeed, as Table 3 shows, as late as 1905 factories in Indiana were less likely to employ continuous-tank technology than those located in the more established glass-producing regions. Only 41 percent of the factories in Indiana had continuous tanks, as opposed to 87 percent in Pennsylvania.

More generally, the geographic concentration of firms in the window glass branch of the industry seems not to have resulted from the locational decisions of the most technologically

TABLE 3

GEOGRAPHICAL DISTRIBUTION OF WINDOW GLASS FIRMS AND ENTRANTS BY TECHNOLOGY

	Hand Methods: Pots	Hand Methods: Continuous Tanks	Machine Methods: Cylindrical	Machine Methods: Sheet-Drawing	Unknown	Percent of Firms Using Hand Methods	Percent of Entrants Using Hand Methods	Percent of Year Total of Entrants
1905								
West Virginia	7	5				100		
Pennsylvania	4	24	1			97		
Ohio		7				100		
Indiana	16	11				100		
Other	9	12				100		
Total	36	59	1			99		
1910								
West Virginia		18 (11)				100	100	32
Pennsylvania		20 (11)	2 (1)		2 (1)	83	85	38
Ohio		11 (6)				100	100	18
Indiana		3				100		0
Other	3	10 (4)				100	100	12
Total	3	62 (32)	2 (1)		2 (1)	94	94	100
1915								
West Virginia		17 (7)	6 (2)			74	78	38
Pennsylvania		11 (3)	7 (1)			61	75	17
Ohio		7 (4)	2			78	100	17
Indiana		2				100		0
Other	1 (1)	8 (4)	2 (2)			82	71	29
Total	1 (1)	45 (18)	17 (5)			73	79	100
1920								
West Virginia		22 (7)	6 (2)	3 (2)		71	64	32

Pennsylvania	11 (1)	8 (1)			57	50	6
Ohio	12 (9)	2			86	100	26
Indiana	3 (1)				100	100	3
Other	17 (11)	2			89	100	32
Total	65 (29)	18 (3)	3 (2)		76	85	100
1925							
West Virginia	18 (1)	5 (1)	4 (2)		67	25	25
Pennsylvania	3 (1)	5 (3)	1		33	25	25
Ohio	4	3	1		50		0
Indiana	1		1		50		0
Other	5 (2)	8 (2)	3 (3)	2 (1)	28	25	50
Total	31 (4)	21 (6)	10 (5)	2 (1)	48	25	100

Note: The number of entrants is in parentheses.

Sources: Data are from industry directories published by the Commoner Publishing Co. (variously titled *Directory of the Glass Trade* and *American Glass Trade Directory*) for 1905, 1910, 1915, 1920, and 1925; and by the *National Glass Budget* (called *Glass Factory Directory*) for 1915, 1920, and 1925.

advanced producers, but rather from those of producers using obsolete technologies. Table 3 reports the geographic distribution over time of both window-glass firms and entrants, broken down by type of technology in use. In 1905, West Virginia accounted for less than 13 percent of the firms in that branch of the industry, but after two decades in which the state experienced substantial new entry, it encompassed fully 42 percent of the firms—more than any other state. West Virginia's new position of dominance, however, was largely attributable to an increase in the number of enterprises using older technologies. In 1925, the state had 58 percent of the firms still engaged in hand production. Other states in the glass belt (Pennsylvania, Ohio, and Indiana) accounted for another 25 percent, and the rest of the country 16 percent. By contrast, West Virginia accounted for only 29 percent of the firms using machine technologies, the other glass-belt states 32 percent, and the rest of the country 35 percent. Firms using the newer technologies were thus more geographically dispersed than those using older methods.[12]

[12]The relatively high levels of geographic concentration that characterized the hand parts of the window glass industry cannot be explained by local concentrations of skilled labor. Otherwise, one would have expected the geographic distribution of firms in 1925 to have looked more like the distribution in 1905. Instead, hand production of window glass largely disappeared from Indiana, and the large numbers of skilled workers who resided there had to migrate elsewhere (mainly to West Virginia) in search of work. For the same reason, the pattern cannot be explained by the presence of local stocks of unused but long-lived machinery and equipment. Indeed, only 31 percent of entrants to the industry (23 percent of entrants in West Virginia) appeared in a location where an earlier firm using the same technology had disappeared. What is most striking when one examines the pattern of entrances and exits from the industry is the high survival rates of hand firms in West Virginia relative to the rest of the country. For example, 70 percent of the West Virginia firms using continuous tank/hand methods of production survived at least five years, compared to 33 percent in Pennsylvania, 23 percent in Ohio, 25 percent in Indiana, and

Despite the preponderance of window glass firms in West Virginia, and the geographic dispersal of the most advanced producers, nearly all of the key inventions in window glass production originated in Pennsylvania. As already mentioned, American Window Glass, whose capacity was almost exclusively concentrated in that state, financed the development of the first cylindrical blowing machine. As in the case of many other consolidations formed during the period, the pricing policies of this combine stimulated the entry of a host of new firms. Some of these firms, of course, employed obsolete technologies, but others engaged in the machine production of window glass, using independently developed cylindrical blowers that were similar in operation to those employed by American Window Glass. All of these machines (except the Frink which was the product of an Ohio inventor) were invented at independent Pennsylvania firms—the Duchamp at the Smethport Window Glass Company, the Healy at Consolidated Window Glass of Bradford, and the PPG at the Pittsburgh Plate Glass Company. Similarly, the next major innovation in window glass, Irving Colburn's sheet drawing machine, was largely developed in Pennsylvania. It was only after repeated setbacks exhausted his backers' money and patience that Colburn, very close to success, turned to Michael Owens in Toledo for help.[13]

Another striking example of the weakness of the geographic link between production and inventiveness is provided by the bottle branch of the industry, in particular by the development

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30 percent in the rest of the country. It is likely that lower fuel costs in West Virginia help to explain these differential survival rates.

[13]Fairfield, *Fire & Sand*, pp. 71-76.

and spread of alternatives to the Owens automatic machine.[14] Because the development of these alternatives involved modifications to semiautomatic machines already in use, one might hypothesize that manufacturers in production centers who had experience with such machines would be well placed to come up with improvements. At first glance, the evidence appears to bear this expectation out. Most of the firms that developed the new machinery were located in major glass-producing areas. For example, the Miller Glass Engineering Company was located in Swissvale, Pennsylvania; the O'Neill Machine Company in Toledo, Ohio; and the Lynch Glass Machinery Company in Anderson, Indiana.[15]

An important exception to this generalization, however, was the Hartford-Fairmont Company, the firm that came up with the first mechanism to challenge in an important way the superiority of the Owens inventions. The case of Hartford-Fairmont suggests that location in the glass belt, and experience in the glass industry, was not a necessary condition for successful innovation—that general technological know-how could serve as an effective substitute. Hartford-Fairmont was located in Southern New England, "several hundred miles from its nearest market." It grew out of a consulting business started by two engineers, William H. Honiss and Hiram A. Lorenz, in Hartford, Connecticut. The engineers had no experience in the glass industry but, renowned for their general technical expertise, were approached by executives

[14]Unfortunately, we cannot provide the same kind of breakdown of firms and entrants by technology for bottle glass producers that we could for window glass. Industry directories did not distinguish bottle producers from other manufacturers of pressed and blown glassware until 1915.

[15]*National Glass Budget*, 2 December 1922, p. 1, and 30 June 1928, p. 26; *Glass Factory Directory* (1925), pp. 75, 79, 85.

of the Beech-Nut Packing Company of Canajoharie, New York, with a problem. Beech-Nut was having difficulty maintaining the vacuum seals it used in its packing operations. Honiss and Lorenz determined that the source of the trouble was imperfections in the glass jars the firm was using and designed new machines to obviate the problem. In 1904 they joined with Beech-Nut to form the Monongah Glass Company in Fairmont, West Virginia, to manufacture the jars, and in 1912 together organized another firm, the Hartford-Fairmont Company, to design and produce glass machinery.[16]

Evidence from industry directories and from trade-journal accounts of important inventions thus confirms our findings based on patent data. The learning-by-doing associated with production or the rapid expansion of investment did not automatically lead to increases in inventive activity. Nor did the clustering of production in geographically restricted areas necessarily generate externalities conducive to technological change. Some production centers had high levels of inventive activity, but others did not. The most intriguing case, moreover, is Southern New England. By the twentieth century the region had lost most of its productive capacity in the industry, yet inventors there continued to contribute improvements to glass manufacturing technology, including such obviously important inventions as the Hartford-Fairmont automatic bottle machine.

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[16]*National Glass Budget*, 30 July 1927, pp. 3, 5-7, 21, 24, 26. Colburn, by the way, was himself originally a New England inventor who set off in search of something profitable to do after earnings fell off at his Fitchburg, Massachusetts, electrical manufacturing business. He had no experience in the glass industry, but was stimulated by Owens's work on the bottle machine to attempt to automate window glass production. Fairfield, *Fire & Sand*, pp. 58-61.

The Importance of the Market for Invention

If production does not account for the location of inventive activity, what does? We can also rule out the possibility that the geographic concentration of patenting resulted from a reluctance to migrate by people with knowledge and experience in glass production. Histories of the industry indicate that wandering habits had long characterized both entrepreneurs and workers, the former migrating in search of fuel supplies, the latter in search of employment, and our own findings confirm this observation. In order to trace systematically the movement of people involved in the industry, we created a data set consisting of the names of individuals, the firms with which they were associated, the locations of these firms, and the dates of the associations. We collected this information from glass-industry directories at five-year intervals from 1905 to 1930 and from scattered issues of trade journals.[17] The full data set contains over 4,300 names.

Nearly two thirds of these individuals appeared in the data set only once—that is, they were listed as an officer or manager of a glass factory in only one of the directory volumes

[17]We were able to obtain directories issued by the Commoner Publishing Company (variously titled *Directory of the Glass Trade* and *American Glass Trade Directory*) for 1905, 1910, 1915, 1920, 1925, and 1930, and directories issued by the *National Glass Budget* (called *Glass Factory Directory*) for 1915, 1920, 1925, and 1930. With minor exceptions the listings in the two publications were the same. We also recorded all mentions of names in the trade journal *National Glass Budget* for the years 1903-5, 1909-11, 1915-17, 1921-3, and 1927-29, and in the *Commoner and Glass Worker* for the years 1903 and 1907. Some of the names were taken from full-length articles on different aspects of the glass industry, but more came from short mentions in columns devoted to the doings of people in the industry. The choice of years was largely determined by the availability of copies of the journals.

surveyed, or they were mentioned in only a single article in a trade journal. Although one might expect that many of the names mentioned in passing in trade journal articles would not show up in our sources again, there should be higher rates of persistence for the officers and managers of glass firms listed in the industry directories. Nevertheless, fully 52 percent of the entries from the directories appeared in our data base only once. The high number of single appearances is itself an index of mobility, though not, of course, of geographic mobility within the industry. More to the point, fully 45 percent of the remaining individuals in our total sample moved at least once during our period, and a fifth of those who moved relocated more than once.

Not only did a high proportion of the people with more than one entry move, but they often moved long distances. Table 4 provides information, broken down by time period, on the propensity of those who moved to leave their localities and states. As might be expected in an industry that was settling down after an episode of geographic restructuring, the total number of moves declined over time, as did the proportion involving migration to other states. Nonetheless, the most striking pattern in the table is the consistently high proportion of moves that occurred across states, amounting to 59 percent of the moves in the pre-1915 period and 55 percent in the post-1915 period.[18] Much of this movement, of course, involved shifts of people among the four

[18]Some caution should be exercised in interpreting these results for, as a result of our collection procedures, some categories may be over or under represented. For example, the number of moves that occurred within the same locality may be an underestimate, because trade journals may not have found such occurrences newsworthy enough to report. On the other hand, the same figure may be an overestimate, because we interpreted all changes in the names of firms with which an individual was associated as moves, even though in some cases companies may merely have experienced reorganizations or changes in ownership.

TABLE 4

EXTENT OF MOVES OF PEOPLE ASSOCIATED WITH THE GLASS INDUSTRY

	Before 1915	In or After 1915	All Moves
Total individuals with moves	437	336	724
Total with moves with locational information	382	312	677
No. whose furthest move was within locality	32 (8.4%)	66 (21.2%)	93 (13.7%)
No. whose furthest move was within state	126 (33.0%)	76 (24.4%)	195 (28.8%)
No. who moved out of state but within glass belt	170 (44.5%)	118 (37.8%)	284 (41.9%)
No. who moved out of glass belt	54 (14.1%)	52 (16.7%)	105 (15.5%)

Notes: The columns "Before 1915" and "In or After 1915" do not sum to the column "All Moves" for two reasons. First, information on the date of a move may be missing. Second, an individual with multiple moves might be included in both periods. We count as a move any change in location, as well as any change in the name of the firm with which the individual was associated.

Sources: See text.

main glass-producing states of Pennsylvania, West Virginia, Ohio, and Indiana, but these four states also exported substantial personnel. As the table shows, nearly a sixth of the total migrants relocated in states out of this region, with the proportion actually increasingly slightly over time.

The composition of the migrants is also revealing. Table 5 reports for each occupational group the proportion of individuals with multiple entries in our data base who moved. One large group of movers (32 percent of the total) consisted of officers or proprietors of glass manufacturing companies, but people in these categories accounted for an even greater proportion (72 percent) of nonmovers. On the other hand, people who served as managers and superintendents of factories, and therefore had a comprehensive knowledge of the production process, were disproportionately represented among the migrants. This group constituted 18 percent of the population of migrants, but only 14 percent of the population of nonmovers. These numbers should be interpreted with caution, because we can not tell whether the vagaries of trade journal reporting caused movers in either of these groups to be overrepresented in the data set.[19] Fortunately, if we look only at the entries that derive from industry directories, we can get a truer sense both of the proportion of managers in the total population relative to officers and proprietors and of the relative propensities of these two groups to move. Limiting the focus in this way, we see that managers and other technologically knowledgeable employees appear to have been even more likely to move compared to owners. In combination, moreover, with the

[19]The problem is even more acute in the case of skilled workers. The movements of these workers were followed especially closely by the *Commoner and Glass Worker*. Because we surveyed relatively few years of this periodical, these workers are underrepresented in our sample, but nonmovers from this group are probably even more underrepresented because their activities rarely made it into the pages of these journals.

TABLE 5

OCCUPATIONS OF MOVERS AND STAYERS IN THE GLASS INDUSTRY

PANEL A--ENTIRE SAMPLE

Occupation	Single Entry	More Than One Entry But Did Not Move	Moved	Ratio of Percentages of Movers to Stayers
Unknown	75 (3%)	5 (1%)	114 (16%)	16.00
Officer or Proprietor	1121 (41%)	631 (72%)	232 (32%)	0.44
Director or Stockholder	574 (21%)	62 (7%)	43 (6%)	0.86
Manager or Superintendent	368 (14%)	124 (14%)	131 (18%)	1.29
Technical Expert	215 (8%)	40 (5%)	28 (4%)	0.80
White Collar Employee	53 (2%)	13 (1%)	7 (1%)	1.00
Foreman or Boss	14 (1%)	0 (0%)	11 (2%)	----
Blue Collar Employee	286 (11%)	3 (0%)	153 (21%)	----

PANEL B--DIRECTORY ENTRIES ONLY

Occupation	Single Entry	More Than One Entry But Did Not Move	Moved	Ratio of Percentages of Movers to Stayers
Officer or Proprietor	897 (76%)	614 (82%)	198 (70%)	0.85
Manager or Superintendent	235 (20%)	117 (16%)	71 (25%)	1.56
Technical Expert	12 (1%)	5 (1%)	10 (4%)	4.00
White Collar Employee	35 (3%)	12 (2%)	1 (0%)	0.00

Notes: Occupations are those reported for individuals at the time they first entered our data base. The occupations in Panel B were the only ones typically reported in industry directories. "Technical Expert" includes people reported as engineers or chemists. In Panel A, that category also includes inventors who did not have any other occupational designation.

Sources: See text.

fact that managers were just as likely as other migrants to move out of state (56 percent moved beyond their state's boundaries), these results make it difficult to argue that the geographic clustering of inventive activity resulted from the reluctance of technologically knowledgeable people to move.

An alternative hypothesis for the observed pattern of geographic concentration in patenting is that inventive activity would tend to cluster disproportionately in places where trade in technology was most fully developed. The logic of this view is that lower costs to marketing inventions or to selling off patent rights would encourage inventive activity, both because individuals with greater potential to invent would tend to gravitate toward such sites, and because inventors located in these areas would be better able to realize returns from inventive activity and so would commit more resources to it. To the extent that the geographic incidence of these markets diverged from that of production, one would expect the distribution of patents to diverge from that of output or labor. Thus high rates of patenting in glass might occur in regions where there was little glass production if local information flows and supports for trade in technology encouraged inventive activity more generally, including cross-over invention from other industries. Conversely, local concentrations of glass manufacturing might not generate much inventive activity in the industry if inexpensive resources had caused producers to locate in sparsely populated areas where inventors had limited access to information and financial support and, more generally, less opportunity to extract returns from their inventions.

In previous work on inventive activity in the economy as a whole, we analyzed the relationship between patenting and the emergence of markets for technology.[20] We showed that trade in patents began to expand rapidly during the second third of the nineteenth century, as new channels for the spread of technological information developed and as growing cadres of patent agents took on the role of intermediaries. We also showed that inventors responded to the resulting greater opportunities to extract returns from their ideas by increasingly specializing in inventive activity and leaving commercial development to others. As technology became more complex and the costs of both invention and development rose over time, patenting came increasingly to be carried out, if not dominated, by highly specialized inventors who assigned away (sold off) the rights to most of their patents.

For the purposes of this analysis, perhaps the most important result of our earlier work was the finding that the market for technology did not develop uniformly across the nation. During the late-nineteenth century, sales of patents were disproportionately concentrated in regions of the country where patenting rates had long been high—the East North Central, the Middle Atlantic, and especially Southern New England—as well as in large cities. It seems that the initially high rates of patenting in these areas enhanced the attractiveness of investment in intermediaries and other institutions that promoted trade in technology, and the consequent greater ability to market patents in turn stimulated yet more invention. As a result, regions that were first to emerge as centers of patenting activity tended to maintain their advantage over time.

[20] Lamoreaux and Sokoloff, "Long-Term Change."

It was primarily in these regions, moreover, that creative individuals responded to the new opportunities for trade in technology by increasing their degree of specialization in invention. Before the Civil War, it was common for inventors to commercialize their discoveries themselves and/or extract returns from their patents by selling off geographically partitioned rights to others who would exploit them in the designated areas. Although these practices continued after the War, as the century progressed it became increasingly common in high patenting areas for inventors to sell off rights to their inventions at or before the time the patent was actually issued. Initially this type of assignment often included the patentee, and was likely a means by which inventors raised capital from local businessmen to support their inventive activity and commercialize their ideas. By the end of the century, however, inventors often relinquished all stake in their patents—assigning complete rights to another party, who was now typically a company. Although this trend might seem to suggest that inventors were becoming employees of firms and simply assigning their patents to their employers, the evidence suggests instead that patentees who assigned to companies were at this time still generally independent inventors.[21] Moreover, consistent with our argument that the evolution of trade in technology stimulated both specialization at invention and high levels of inventive activity, patentees who assigned to companies tended to be the most specialized and productive inventors of all.

If the market for technology evolved more fully in certain regions of the country than in others, and if inventors in regions with such well developed markets were both more numerous and prolific than those elsewhere, then these relationships might explain the geographic pattern

[21]For an extended discussion of this point, see Lamoreaux and Sokoloff, "Inventors, Firms, and the Market."

of patents in the glass industry. Certainly, as Table 6 shows, the market for glass patents evolved along lines that were similar to patents in general. Over time, for example, the proportion of patents assigned at issue increased dramatically, as did the proportion assigned to companies. Another parallel, albeit one that did not materialize until the period 1909-1919, was that patentees who assigned their inventions tended to be more productive than those who did not in terms of the total number of patents filed over their careers. In the case of glass, however, patentees who maintained an ownership stake in their patents after issue continued to be more productive than those who assigned away all their rights to companies. Although there may be a problem here with the small number of cases, it so also possible that the difference is attributable to the relatively uncomplex and inexpensive nature of much glass manufacturing technology (especially when compared to the sectors of the economy that were dominating patenting activity nationally). The relatively small size of firms in both glass manufacture and glass-machinery production meant that it was still comparatively feasible for patentees to participate in the commercial development of their inventions.[22]

Table 7 reports a probit equation which explores, over the sample of industrial glass patents, the geographic relationship between inventive activity and the market for patents in the glass industry. The dependent variable is whether or not a patent was assigned at issue; the independent variables are a series of geographic dummies representing the residence of the patentee, the total number of glass patents awarded to the patentee, and whether or not the patent

[22]In earlier work we found that rates of assignment at issue and of assignment to companies were highest, and that proportions of inventors who maintained stakes in their patents lowest, in the most technologically advanced sectors of the economy. See "Long-Term Change"; and "Patents and the Market for Technology."

TABLE 6

ASSIGNMENTS AND CAREER PATENTING BY GLASS PATENTEES

	1870-81	1890-1901	1909-19
% of Patents Assigned	19.9 (191)	33.3 (309)	51.4 (453)
% of Assignments Made to Companies	31.6 (38)	43.7 (103)	81.1 (233)
% of Patents Where Stake Retained	86.6 (191)	74.8 (309)	54.8 (453)
Ave. No. of Career Patents for All Patentees	2.01 (191)	3.25 (309)	2.86 (453)
Ave. No. for Patents Not Assigned	2.06 (153)	3.33 (206)	2.41 (220)
Ave. No. for Patents Assigned to Companies	1.50 (12)	2.76 (45)	3.39 (189)
Ave. No. for Assigned Patents Where Stake Retained	1.95 (20)	3.73 (45)	3.65 (43)

Notes and Sources: These statistics are computed over all glass patents in our data base awarded to patentees residing in the United States. The numbers in parentheses represent the number of observations over which each statistic was calculated. We constructed the data base by recording all glass patents listed in the *Annual Report of the Commissioner of Patents* for 1870, 1871, 1880, 1881, 1890, 1891, 1899, 1901, 1909, 1911, 1918, and 1919. The number of patents awarded to each individual patentee across the twelve cross-sections is treated as the total number of career patents for that individual. A patentee was considered to have retained a stake in his or her invention if it was not assigned at issue or if an assignment was made to a group that included the patentee, someone with the same last name as the patentee, or a company with the same name as the patentee. The last statistic was calculated only for patentees who assigned two or more of the patents in the data base.

TABLE 7

PROBIT ANALYSIS OF WHETHER OR NOT GLASS PATENT WAS ASSIGNED

Independent Variables	Coefficients and Standard Errors	
Intercept	1.05***	(0.16)
Residence in Southern New England	0.41*	(0.24)
Residence in the Middle Atlantic, except Pennsylvania and West Virginia	0.45**	(0.19)
Residence in Ohio	0.67***	(0.18)
Residence in Indiana	0.12	(0.27)
Residence in Rest of Midwest	0.33*	(0.20)
Residence in Rest of U.S.	-0.04	(0.23)
Residence in Pittsburgh	0.60***	(0.16)
Residence in an Urban Area	-0.25**	(0.10)
Patent Issued after 1895	0.64***	(0.11)
Log of Total Glass Patents of Patentee	0.15***	(0.06)

Note: *** denotes significance at the .01 level, ** the .05 level, and * the .10 level. The cases are individual patents, with the analysis restricted to industrial glass patents issued to residents of the United States. The dependent variable is whether or not the patent was assigned at issue. The omitted geographical dummy is residence in Pennsylvania or West Virginia. The Pittsburgh dummy includes the counties immediately adjacent to the city. Residence in an urban area means residence in a county with a city of at least 25,000 people. The total glass patents received by the patentee were summed only over the years included in our data base: 1870, 1871, 1880, 1881, 1890, 1891, 1901, 1911, 1918, and 1919.

Source: See text.

was awarded after 1895. As the table shows, the likelihood that patents would be assigned at issue varied systematically with location. Inventions from those regions where shares of glass patents exceeded shares of industry production or labor force—Southern New England, Ohio, and the Other Midwest—were significantly (although marginally so in the first and last cases) more likely to be assigned than those from other areas.[23] Moreover, although patents from urban areas in general were no more likely to be assigned than patents from other parts of the same regions, those from the vicinity of Pittsburgh stand out for the high proportion assigned relative to patents from elsewhere in Pennsylvania and from West Virginia. Finally, the probit results also indicate that the probability a patent would be assigned at issue was positively and significantly related to the number of career glass patents received by the patentee—that is, as our hypothesis would lead us to predict, it was the most specialized and productive patentees who participated most intensely in the market.

From our work on economy-wide patenting, we would expect to find that those regions with disproportionate patenting activity and high rates of assignment or trade in technology would also be regions where patentees had higher than average numbers of career patents. The logic here is that the greater ease of selling off patent rights in such areas would lead individuals to be more specialized at invention than was the case elsewhere. The regressions reported in Table 8, estimated over the industrial glass patents in our sample, were designed to explore this issue. The dependent variable in each equation is the log of the total number of glass patents

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[23]One should not attach too much importance to the significance of the Middle Atlantic dummy. The result was driven by a relatively small number of patents issued in New Jersey, most of which were assigned.

TABLE 8

REGRESSIONS WITH PRODUCTIVITY AT PATENTING AS THE DEPENDENT VARIABLE

Independent Variables	Equation 1	Equation 2	Equation 3
Intercept	0.33***	0.30***	0.56***
	(0.07)	(0.10)	(0.08)
Period	0.25***	0.19***	
	(0.07)	(0.07)	
Assigned	0.18***	0.17***	
	(0.06)	(0.06)	
Urban	0.15**	0.20***	
	(0.06)	(0.07)	
Southern New England		-0.05	-0.02
		(0.15)	(0.14)
Middle Atlantic		-0.47***	-0.41***
		(0.12)	(0.12)
Ohio		0.22**	0.30***
		(0.11)	(0.11)
Indiana		0.42**	0.45***
		(0.17)	(0.17)
Other Midwest		0.24*	0.33***
		(0.12)	(0.12)
Pittsburgh		0.08	0.18*
		(0.10)	(0.10)
Other U.S.		0.09	0.08
		(0.14)	(0.15)
Adjusted R^2	0.03	0.10	0.07

Notes: *** denotes significance at the 0.01 level, ** at the 0.05 level, and * at the .10 level. The cases are individual patents, with the analysis restricted to industrial glass patents issued to residents of the United States. The dependent variable is the log of the total number of glass patents in our sample issued to the inventor who received the patent. The independent variables are all dummies. "Period" takes on a value of 1 if the patent was issued after 1895; "Assigned" if the patent was assigned at the time of issue; "Urban" if the patentee resided in a county with a city of at least 25,000 people. The Pittsburgh dummy includes the counties immediately adjacent to the city. The other geographical variables are self-explanatory, except that the Middle Atlantic excludes the states of Pennsylvania and West Virginia, which constitute the omitted geographical dummy.

Source: See text.

issued to individual patentees in the years for which we collected data; the independent variables include dummies for the region of residence of the patentee, whether the residence was in an urban center or in the vicinity of Pittsburgh, and whether the patent was assigned at issue. In general, the results are consistent with our hypothesis. Patentees who assigned their patents at issue, as well as those residing in urban areas, received significantly more patents over their careers. Moreover, the findings for patentees from Ohio and the Other Midwest tend to confirm our expectations that the relative numbers of patents per worker (Table 2), the probability of a patent being assigned at issue, and the number of career glass patents per patentee were positively associated with each other across regions.

The results in the table do, however, pose some puzzles: in particular, why Southern New England had high rates of patenting per worker and a high probability that patents would be assigned, yet did not have higher career patents per patentee; and why Indiana had low patenting per worker, a low probability of assignment, and yet higher career patents per patentee. In the latter case, the explanation may simply be that the few individuals likely to engage in patenting in an area where the institutional environment was inhospitable (and in the case of Indiana the numbers of inventors were indeed quite small) were producers whose businesses both gave them scope for, and were more profitable as a result of, their creative efforts. The case of Southern New England requires more extended consideration. In a region such as this, the presence of a well developed market for technology (as indicated by the high probability that a patent would be assigned at issue) may have had greater implications for the return to inventive activity in general than for the return to invention in a particular industry (in this case, glass). For example, the exodus of glass production from New England may have lowered the advantages to be derived from specializing exclusively in glass patents and encouraged inventors to apply their ideas to a range of different industries. In any event, productive patentees in New England seem to have devoted relatively less of their energies to inventive activity in glass than was true of comparable patentees in the other regions we have studied. As the first equation in Table 9 shows, when the dependent variable is the proportion of patents a glass patentee received for inventions in other industries, the dummy variable for Southern New England is statistically significant and positive. Moreover, as the second equation in the table shows, after one controls for invention in other industries, the behavior of glass patentees in Southern New England conforms to our model—that is, we now observe the expected correlation between high career glass patents per patentee, high patenting rates per worker, and high probabilities of assignment.[24]

The locational pattern of patenting in the glass industry thus appears to be the product of a complex interaction of factors. Concentration of production itself seems to have been neither a necessary nor a sufficient condition for high rates of invention. Although much inventive activity did, of course, take place in locations where production was clustered, patenting in glass was in large measure associated with the same general development that, we have found, stimulated patenting in the economy as a whole—the expansion of trade in technology. What remains to be explained, however, is the reason why markets for glass patents were better developed in some regions of the country than in others. Southern New England's high rates of glass patenting relative to production seem to have resulted from the region's extraordinarily well developed

[24]It should be noted that the coefficients in this equation are not really comparable to the ones in Table 8, because this regression was run on a restricted sample of cases where the patentee received more than one patent.

TABLE 9

DIVERSITY AND PRODUCTIVITY AT PATENTING FOR PATENTEES WITH MULTIPLE PATENTS

Independent Variables	Equation 1 Diversity	Equation 2 Log of Total Glass Patents
Intercept	0.17***	0.67***
	(0.04)	(0.14)
Period	-0.03	0.31***
	(0.03)	(0.10)
Assigned		0.07
		(0.10)
Urban	-0.02	0.71***
	(0.05)	(0.16)
Diversity		-1.02***
		(0.19)
Southern New England	0.30***	0.59***
	(0.06)	(0.23)
Middle Atlantic	-0.06	-0.62***
	(0.05)	(0.17)
Ohio	-0.03	0.17
	(0.04)	(0.15)
Indiana	0.00	0.49**
	(0.07)	(0.24)
Other Midwest	-0.01	0.78***
	(0.05)	(0.17)
Pittsburgh	0.01	0.39***
	(0.04)	(0.14)
Other U.S.	-0.03	0.47**
	(0.06)	(0.21)
Adjusted R^2	0.08	0.26

Notes: *** denotes significance at the 0.01 level, ** at the 0.05 level, and * at the .10 level. The cases are individual patents, with the analysis restricted to industrial glass patents issued to residents of the United States who obtained multiple patents. The dependent variable in Equation 1 is the proportion of patents received by the patentee that were for non-glass inventions. In Equation 2 it is the log of the total number of glass patents in our sample issued to the inventor who received the patent. For definitions of the remainder of the variables, see Tables 7 and 8.

Source: See text.

markets for technology in general—markets that supported inventive activity in a wide range of industries besides glass and helped to sustain distinctive levels and types of human capital in the region. Pittsburgh's status as the major city in a region that had long dominated production in glass may have helped it become both a center of information and a hub of market trade in glass technology. Conversely, the search for cheap fuel that led producers into areas of Indiana that were quite some distance from centers of trade and finance may have limited inventive activity in that state.

Conclusion

This survey of locational and technological change in the glass industry has highlighted two important patterns. The first is the clustering of glass production into recognizable geographical centers, particularly Pennsylvania, West Virginia, Ohio, and Indiana. The second is the divergence between this pattern of concentration and the one that emerges from our analysis of the patent data. Some centers of glass production (Indiana is the most important example) failed throughout our period to make contributions to the advance of technology that were equivalent in magnitude to their proportions of industry output and labor force. Pennsylvania and Ohio had shares of patents that were roughly proportional to their shares of glass output and labor. However, there were other regions where patenting activity in glass exceeded what might be expected given the amount of local production. Southern New England, for example, sustained throughout the period patenting rates per glass worker that were far above the national average, even though production in the region was falling dramatically.

Although some inventive activity in the industry undoubtedly resulted from a process of learning by doing, the lack of correspondence between patterns of patenting and those of production suggests that this process cannot provide a satisfactory account of the overall distribution of inventive activity in glass. Moreover, the same general lack of correspondence, and especially the lack of disproportionate inventive activity in Pennsylvania, the largest production center, leads us to rule out theories that highlight externalities to inventive activity resulting from local concentrations of production. Nor does it seem that regions that experienced rapid growth in output or investment were particularly fertile places for invention. To the contrary, we found that states like Indiana and West Virginia, where new investment was growing very rapidly, attracted a disproportionate number of firms using obsolete technologies.

Although the sources of regional variation in inventive activity are complex, we are at present focusing on the hypothesis that geographic centers of invention in glass technology were contingent upon localized networks of institutions that mobilized available information about technological opportunities and mediated relations among inventors, suppliers of capital, and those who would commercially develop or exploit new technologies. What precisely constituted these networks of institutions is not fully clear, but it is likely that they involved conditions that we commonly associate with markets or market places: formal and informal intermediaries; a concentration of knowledge that facilitated the assessment of inventions and their commercial development; familiarity with contracting issues; and access to financial capital. Where local conditions were propitious, such networks could develop within production centers. For example, Pittsburgh's status as a major industrial and financial hub may have helped western Pennsylvania become a center of inventive activity as well as of production in glass. Such networks could also evolve across industries, as the case of Southern New England suggests. There, it seems, the presence of a sizable population of inventors from early in the nineteenth century on encouraged the development of information flows and institutions conducive to the expansion of trade in technology, which in turn encouraged a greater concentration of creative individuals with the ability to invent in a wide range of industries. As the examples of Southern New England and Pittsburgh suggest, once these localized networks of institutions developed, they tended to persist over time. Moreover, the failure of other regions, especially production centers, to develop similar capabilities suggests that there were formidable obstacles to their replication in new areas.

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