The Role of Independent Invention in U.S. Technological Development, 1880–1930

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Why did independent inventors account for over half of U.S. patents by 1930 and more than three times the number granted to R&D firms? Using new data on patents and historical patent citations, I show that independents supplied high-quality innovations to a geographically broad market for ideas. Those close to large urban centers developed some of the most significant technological advances. Demand for independent inventions remained high during the growth of the corporate economy as firms continued to acquire external innovations that complemented formal R&D. Despite their relative decline, independents remained central to the process of technological development.

"The statement sometimes is made that 'the day of the genius in the garret is done.' Nothing could be further from the truth."
William A. Kinnan, First Assistant Patent Commissioner, *New York Times*, December 18th, 1927

Technological change and organizational development were fundamental to U.S. economic growth during the late nineteenth and early twentieth centuries. Economic activity moved increasingly inside the boundaries of firms and in-house R&D spread widely.[1] Yet despite the growing importance of the modern corporation at this time, new organizational structures were not always necessary for innovation. Figure 1 shows that 53 percent of U.S. patents were granted to independent inventors by 1930. Although the share of

The Journal of Economic History, Vol. 70, No. 1 (March 2010). ISSN 0022-0507.

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I am extremely grateful to the editor, the referees, and Naomi Lamoreaux for helpful comments and suggestions, to James Ryley (President) and David Hawley (Director of R&D) of FreePatentsOnline.com, who supplied 5.1 million XML files used for the 1947–2008 citations, and to Sarah Woolverton from Research Computing Services at Harvard Business School for help with processing these data. Chris Hunter and Tony Scalise from General Electric's Schenectady archive and the staff at the The Niels Bohr Library also helped a lot. Kash Rangan funded this project through Harvard Business School's Division of Research.

[1] Chandler, *Scale and Scope*; and Mowery and Rosenberg, *Paths of Innovation*. More generally, a large literature emphasizes the significance of this period. According to Mokyr, *Lever of Riches* and *Gifts of Athena*, the Second Industrial Revolution shifted the frontier of useful knowledge. Later on, the 1920s experienced a major growth spurt whereby firms adapted to the new innovation and productivity advance was realized. See further, David, "Dynamo and the Computer"; and Jovanovic and Rousseau, "General Purpose Technologies."

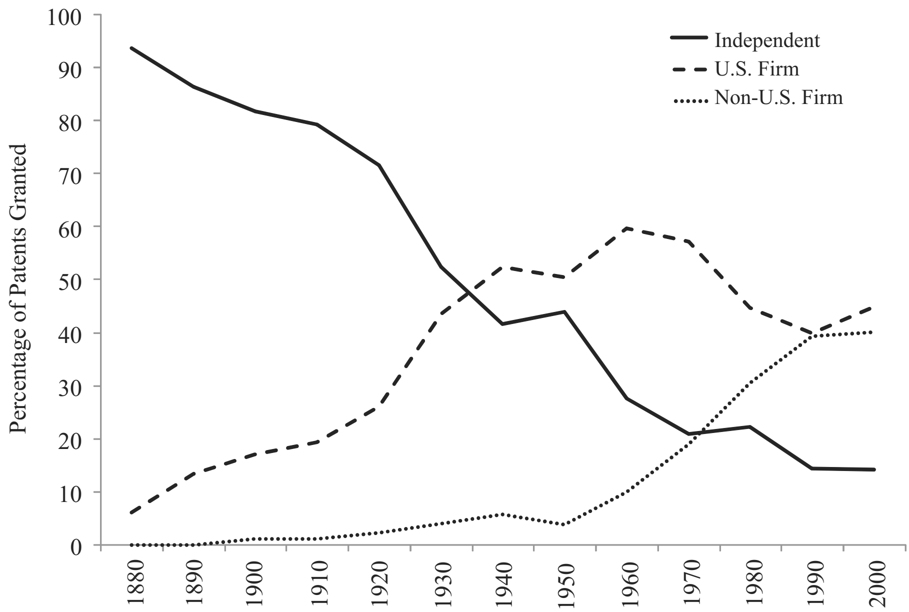

FIGURE 1
INDEPENDENT INVENTOR PATENTS OVER THE LONG RUN

Notes: Percentage of patents in different categories is calculated from my samples and from official figures given in USPTO Gazettes.

independents fell from 1880 onwards, the absolute level remained high. Did independents contribute trivial or nontrivial increments to knowledge capital accumulation? Why did their importance change over time relative to firm-based invention? Answers to these questions can inform our understanding of links between innovation and organizational change during one of the most significant phases in U.S. technological development.

To examine the role played by independent inventors, I use a main data set of 18,048 randomly selected inventions patented by approximately 16,000 inventors at ten-year intervals between 1880 and 1930. I also use a data set of 6,181 R&D-based patents by inventors co-located with an in-house lab who would have been contractually obliged to assign their inventions to their employers.[2] Because these inventions originated from inside the boundaries of firms, they provide a useful comparison group to test for technological differences between corporate and independent inventions. The institutionalization of innovation in R&D labs during the

[2] Fisk, "Fuel of Interest."

early twentieth century represents one of the most significant changes to influence the structure of organized technology formation.[3]

Jacob Schmookler argued that studies of the number of inventions suffer from a "serious but unavoidable defect stemming from an inability to evaluate the merit of inventions."[4] I work to overcome this problem by using a new data set of historical patent citations to identify especially influential technologies. Citations have been used by a number of scholars to adjust patents for quality.[5] The new data include 42.8 million citations to patents granted since 1836 in the population of patents granted between February 1947 (when citations were officially included on patent documents) and September 2008. These citations represent a substantial improvement over the much used NBER patent data file that includes citations starting in patents granted only since 1975.

Using historical citation regressions, I provide baseline estimates showing a citation premium to independent inventor patents relative to patents assigned to firms. One explanation for the prevalence of independents is therefore that the quality of their technological developments was high. Using a matching method to pair up independent inventor patents with patents originating from inside R&D labs with the closest propensity score, I find that independent inventors located near to large cities were responsible for some of the most important technological developments. This finding is consistent with the large literature emphasizing the significance of urban externalities for innovation.[6]

I argue that the high quality of independent innovation can be explained by demand-based incentives. Because independent inventors were disproportionately located in cities, they were close to patent agents and lawyers who facilitated transactions with firms.[7] Corporations, in turn, monitored the market for ideas and devoted considerable resources to acquiring outside patents from inventors across the United States.[8] Whereas inventors working within firms tended to focus their patents more on the areas related to local manufacturing activity, independents responded more to a nationwide market for their ideas. I use Adam Jaffe's technical proximity measure

[3] Mowery and Rosenberg, *Paths of Innovation.*
[4] Schmookler, "Inventors Past and Present," p. 322.
[5] Hall, Jaffe, and Trajtenberg, "Market Value"; and Nicholas, "Innovation."
[6] Kim and Margo, "Historical Perspectives."
[7] Lamoreaux and Sokoloff, "Inventors, Firms" and "Intermediaries."
[8] Nicholas, "Spatial Diversity."

to show that this difference is reflected in the technological profile of independent and firm-based inventions.[9]

If the quality of independent invention was so high, and demand existed for their technological discoveries, what accounts for the changing share of independent versus firm-based inventors illustrated in Figure 1? I show that the decline in independent inventor patent numbers followed a shift in the direction of innovation towards more complex capital intensive areas such as chemicals and electricity, which developed extensively during the Second Industrial Revolution.[10] Yet, as the corporate economy evolved and in-house R&D spread, firms in technologically progressive sectors still maintained extensive links with independents by purchasing the independents' patents to complement corporate research lab activity. A large demand for independent inventions still existed because both types of inventing were combined to develop marketable innovations. Even as the direction of innovation changed, independents remained centrally important to the overall structure of technological development.

HISTORICAL BACKGROUND TO INDEPENDENT INVENTION

The literature on late-nineteenth- and early-twentieth-century innovation has done much to dispel the idea that independent inventors were exclusively a group of garage mechanics and backyard tinkerers with limited capital and equipment making discoveries by trial and error. Thomas Hughes' *American Genesis* shows that independents developed wide ranging capabilities that created large complex interrelated systems of innovation such as electric power and communications networks. Some independent inventors spread their inventions widely and used external capital to fund research investment. Others focused on a single technology space, although they too were frequently engaged in commercialization.

Although Hughes focuses on the activities of 12 main inventors like Elmer Sperry (1860–1930), Lee de Forest (1873–1961), and Edwin Armstrong (1890–1954), a renaissance of thinking on independent inventors has also extended research into areas beyond the leading inventors in their fields. A series of papers have shown how inventors still had the ability to maintain independence from firms in areas such as the Midwest where venture capital finance was available.[11]

[9] Jaffe, "Technological Opportunity."
[10] Mokyr, *Lever of Riches* and *Gifts of Athena.*
[11] Lamoreaux and Sokoloff, "Independent Inventor"; and Lamoreaux, Levenstein, and Sokoloff, "Financing Invention."

Independent inventors in educational institutions frequently consulted for corporations in industries such as pharmaceuticals, electricity, and communications.[12] Wheeler P. Davey (1886–1959), Professor at the Pennsylvania State University, held consulting engagements with General Electric, Dow Chemicals, the Aluminum Company of America, and the New Jersey Zinc Company in areas related to crystal chemistry and X-rays.[13] In a well-known case, in 1920 the Westinghouse Electric and Manufacturing Company purchased Columbia University Professor Edwin Armstrong's radio patents for feedback detection and the superheterodyne circuit for $350,000.[14]

One reason that independent inventors could thrive was the institutional structure of the patenting system. The democratic nature of U.S. patenting encouraged individual inventors and facilitated their response to demand-based incentives.[15] Patent agents and solicitors diffused geographically with urbanization, creating relational self-enforcing agreements between independent inventors and intermediaries.[16] It was also cheaper to patent in the United States. It was 19 times more expensive to carry a patent to full term in Britain in 1875 and still ten times more expensive in 1925.[17] Moreover, U.S. independent inventors who patented in the early twentieth century automatically held intellectual property rights on their inventions for a term of 17 years. By contrast, in Britain the patent term was 14 years until 1919 (when it was extended to 16 years) and nonpayment of renewal fees at specific stages of a patent life meant that less than 5 percent of patents were carried to full term.[18] In Germany, the patent system was even more demanding of inventors on a renewal fee basis.[19]

While we know from previous research that independent inventors existed on a broad scale in the United States and in an institutionally favorable environment for innovation, very little is known about the quality of independent inventions relative to those originating from

[12] MacGarvie and Furman, "Early Academic Science."

[13] Davey had worked as a research scientist at General Electric from 1914 to 1926, but he left to become a full time academic. He maintained his links with industry through an array of consulting engagements. He was considered a pioneer in the field of X-ray diffraction by crystals. Archival material on Davey is available at The Niels Bohr Library at the American Center for Physics, College Park, MD.

[14] Hughes, *American Genesis*, p. 141.

[15] Sokoloff, "Inventive Activity"; Khan and Sokoloff, "Institutions"; and Khan, *Democratization of Invention*.

[16] Lamoreaux and Sokoloff, "Inventors, Firms" and "Intermediaries."

[17] Lerner, "150 Years."

[18] The figures for British patent renewal fees are calculated from statistics in the annual reports of the Comptroller General of Patents.

[19] Streb, Baten, and Yin, "Technological and Geographical."

firms, or how independents functioned within the organizational structure of U.S. technological development. In his 1957 and 1966 studies of independent inventors, Schmookler lamented that he did not have the data to precisely measure the technological significance of independent inventor patents, so he could only surmise that independents were important.[20] Joseph Schumpeter argued that independent inventors were the true harbingers of technological development because the growth of corporate labs with discipline and control methods routinized innovation and undermined creative destruction.[21] His evidence, however, was also impressionistic. In the remainder of this article, I use new data to examine independent invention more systematically.

PATENTS, HISTORICAL CITATIONS, AND R&D LAB INVENTIONS

The 1880–1930 Patent Samples

The primary data sources for this study are 10 percent random samples (by grant number) of U.S. patents taken at ten-year intervals between 1880 and 1930 as described in Table 1.[22] For illustrative purposes, Figure 2 maps the geographic location of independent inventors, which shows they were concentrated in east coast manufacturing areas. I follow the United States Patent and Trademark Office's definition of an independent invention as "a patent for which ownership is either unassigned (i.e., patent rights are held by the inventor) or assigned to an individual at the time of grant."[23] Unassigned patents were much more likely to be created without the resources of a firm.[24] According to Schmookler, patents by individual inventors "can serve as a first approximation to the number of patented inventions made by independents."[25]

Historical patent data reflect economically significant information about technological development. Independent inventors attached great importance to trends in patenting when determining the areas in which they would focus. For example, Elmer Sperry, inventor of the

[20] Schmookler, "Inventors Past and Present"; and *Invention and Economic Growth*.

[21] Schumpeter, *Capitalism, Socialism, and Democracy*.

[22] The data were hand entered from the original patent documents. I start in 1880 because this is the first year when a reasonable share of corporate inventions can be identified. I end in 1930 because this is the approximate crossing point in Figure 1. The USPTO granted 180,477 patents in these years.

[23] USPTO, "Independent Inventor," p. 1.

[24] Merges, "Employee Inventions."

[25] Schmookler, *Invention and Economic Growth*, p. 26.

TABLE 1
DESCRIPTIVE STATISTICS: PATENT SAMPLES, 1880–1930

	1880	1890	1900	1910	1920	1930
Number of patents	1,293	2,532	2,466	3,517	3,716	4,524
Inventors per patent	1.09	1.12	1.11	1.10	1.09	1.12
	(0.34)	(0.36)	(0.34)	(0.32)	(0.31)	(0.37)
Application to grant (days)	170	292	343	536	650	1,029
	(155.69)	(288.34)	(321.01)	(484.64)	(537.59)	(630.90)
Foreign (%)	4.9	7.6	14.5	11.0	10.5	13.1
Independent inventor (%)	93.8	86.6	84.6	76.4	71.6	53.3
Assigned to firm (%)	6.2	13.4	15.4	23.6	28.4	46.8
Publicly traded (%)	1.3	5.6	2.1	11.3	15.0	27.6
Not publicly traded (%)	4.9	7.8	13.3	12.3	13.5	19.1
Firm categories						
Collins and Preston's 100 (%)	—	—	—	2.6	—	—
Chandler's 200 (%)	—	—	—	—	5.3	8.0
Navin's 500 (%)	—	—	—	—	6.0	—
R&D firms (%)	—	—	—	—	5.6	16.6
Citations 1947–2008						
Patents cited (%)	30.2	35.3	42.2	47.8	56.7	68.2
Number of citations	771	2,017	2,429	4,435	6,132	10,917
Citations of cited patents	1.97	2.26	2.33	2.64	2.91	3.54
	(1.82)	(2.30)	(2.07)	(3.52)	(3.00)	(3.44)

Notes: Standard deviations are in parentheses. Independent inventors are defined according to the United States Patent and Trademark Office's definition of "a patent for which ownership is either unassigned (i.e., patent rights are held by the inventor) or assigned to an individual at the time of grant." Patents assigned to publicly traded firms are determined by matches with lists of companies in the *Commercial and Financial Chronicle*, including both the New York and regional stock exchanges. Firm categories are defined as follows: For large enterprises, I used Collins and Preston, "Size Structure," which lists the largest 100 firms by assets size in 1909; Navin's "500 Largest," which lists the largest 500 American industrial corporations in 1917, again ranked by asset size; and Chandler, *Scale and Scope*, which provides asset-based listings of the 200 largest firms in 1917 and 1930. For R&D labs, I matched the assignments up against all firms with industrial research facilities as given in the 1921 and 1931 editions of the National Research Council's survey of industrial R&D laboratories.

navigational gyrocompass, observed patents being issued by the United States Patent and Trademark Office (USPTO) to identify clusters of technologies that other inventors were working on. He improved upon

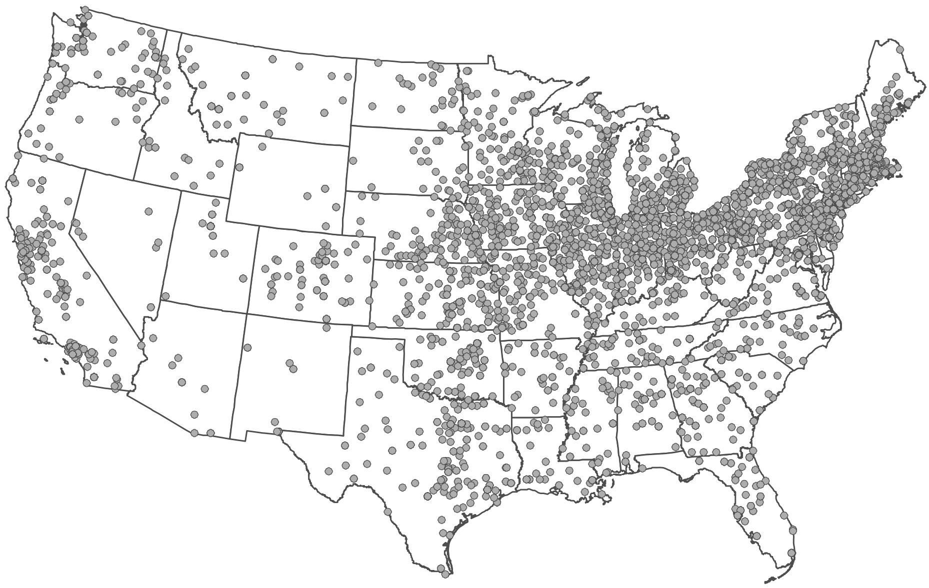

FIGURE 2
THE GEOGRAPHIC LOCATION OF INDEPENDENT INVENTORS, 1880–1930

Notes: Geocoding is based on the residential address of the first named patentee.

their ideas, solved problems that they could not, and exited the field when he perceived opportunities for profit had diminished. The data on technological knowledge that Sperry accessed was publicly available.[26] The USPTO published its *Official Gazette* and *The Scientific American* published its popular weekly lists of patents issued.

Table 1 reveals that the decline of independent invention was only slowly associated with the rising significance of large firms. This can be seen most clearly in comparisons of patents assigned to the largest industrial firms. Norman Collins and Lee Preston's 100 largest firms in 1909 account for under 3 percent of patents in 1910. Thomas Navin's 500 largest firms account for just 6 percent of patents in 1920 and Alfred Chandler's largest 200 firms for 5 to 8 percent of patents between 1920 and 1930. The share of patents assigned to firms with R&D labs listed in the National Research Council's correspondence surveys increases almost threefold during the 1920s to account for around 17 percent of all patents by 1930.[27] Yet, in absolute terms,

[26] Hughes, *American Genesis*, pp. 69–71.

[27] It is important to note that as much as 20 percent of patents assigned to high-technology corporations during the 1920s reflected market-based transactions between firms and external inventors (Nicholas, "Spatial Diversity"). The proportion of patents that originated from R&D labs measured in this way is likely to be upwardly biased.

independents accounted for more than three times the number granted to R&D firms (i.e., 2,409 versus 753 in 1930). Moreover, the growing number of days between application and grant shown in Table 1 may have enabled independents to engage in transactions with firms during the pendency period. Consequently, the level of independent invention shown here is almost certainly downward biased.[28]

Historical Citations, 1947–2008

A key aim of the analysis is to determine the technological significance of independent versus firm-based inventions. I therefore use a new dataset of historical patent citations to quality-adjust the raw patent counts. The new citations contain prior art references from patents granted between February 1947 and September 2008.[29] Following a USPTO Notice issued on December 19th, 1946, examiners were instructed to add citations in the published format of the patent, a practice that was incorporated into the *Manual of Patenting Examining Procedure* (paragraph 1302.12). The citations provide a unique insight into the technological significance of older generations of inventions as they document cumulative innovation in patenting. References in the new format began with patents granted on February 4th, 1947.[30] The addition of the patent citations from 1947 through 1974 fills in a large gap in tracing the precedents for American invention. It almost doubles the share of patents granted between 1880 and 1930 that are subsequently cited from 24 percent to 46 percent.

Table 1 shows that in the 1930 sample over two-thirds of the patents are cited as prior art in more modern patents, and just under one-third in 1880.[31] Table 2 provides examples of some of the most important independent inventions in the data set judged by their citation counts. Some of these innovations were simple modifications of existing technologies such as the safety razor patented by William Bleloch of Johannesburg, but even this patent continued to be cited as prior art by

[28] In 1880 the patent office processed applications relatively quickly, but by 1930 the average pendency period was almost three years. In 1880, 92 percent of patent applications were granted in less than a year compared to just 7 percent in 1930.

[29] References are made by both patent applicants and examiners. These are only separately identified on patents from January 2001.

[30] The first patent document having citations listed in this form is number 2,415,068 issued to James D. Andrew of Essex Fells, New Jersey for a tube spacer in heating apparatus. This patent cites nine patents as prior art.

[31] Truncation in the citations distribution means that later patents are more likely to be cited *ceteris paribus*.

TABLE 2
EXAMPLES OF HIGHLY CITED INDEPENDENT INVENTOR PATENTS FROM THE 1880–1930 PATENT SAMPLES

Patent	Grant Year	First Named Inventor	City, State (Country)	Invention	Citations 1947–2008
225,651	1880	Samuel N. Silver	Auburn, ME	Steam engine	7
439,916	1890	James T. Whittlesey	Lynn, MA	Applying coating to electrical conductors	17
443,764	1890	Joseph B. Hilliard	Glasgow, (Scotland)	Appliance for correcting spinal curvature	17
653,421	1900	William Lorey	Philadelphia, PA	Filter	16
650,860	1900	Thomas J. Mctighe	New York, NY	Electrical connector	13
958,517	1910	John C. Mettler	Evans City, PA	Well casing repairing tool	103
971,583	1910	Benjamin Bell	Philadelphia, PA	Pneumatic spring	29
1,360,720	1920	Edward E. Brown	London (England)	Metal bar construction	29
1,746,525	1930	William A. Darrah	Chicago, IL	Process for measuring light transmission	37
1,768,307	1930	William Edwin Bleloch	Johannesburg (South Africa)	Safety razor	18

Note: All examples are in the top decile of the citation distribution for each year.

modern corporations like The Gillette Company and American Safety Razor Co. In other instances, the invention required a higher level of mechanical ingenuity such as the steam engine patented by Samuel Silver. Independents like William Darrah were active in process innovation, although process patents account for only around 2 percent of the sample overall. Notwithstanding the vast majority of independent inventors in the data set were granted only one patent, in the tail of the distribution are inventors like Thomas Mctighe, who in addition to his highly cited electrical connector invention, was granted over 40 other patents.[32] The most highly cited patent by an independent in the data set is a 1910 invention by John Mettler of Evans City, Pennsylvania for patching leaks in pipe casings. It is cited extensively in subsequent patents related to the construction of oil and gas wells.

[32] For example, Mctighe patented (along with two coinventors, Daniel and Thomas Connolly) the first dial telephone which was exhibited at the Paris Exposition in 1881. See further, Hill, "Early Work."

The R&D Lab Patent Sample

Independent inventors can be defined as unassigned patents using Schmookler's "first approximation," but defining corporate patents as those assigned to firms is likely to create larger measurement errors. Firms often engaged with independents to buy their inventions prior to the patent grant date, and therefore counts of patents assigned to firms may include many that were truly the work of independent inventors.

To address this issue, I use a complementary data set, which identifies firm-based inventors working within a corporate R&D lab.[33] The starting point is the data used in previous work, namely almost 18,000 patented technologies assigned to 69 U.S. firms operating 94 research and development laboratories in 1920s America.[34] For this study, only inventors who were geographically co-located with a lab were retained, the intuition being that these inventors would be employees of the firm given their residential proximity to the labs.[35]

This resulted in a sample of 6,181 patents, from 49 companies including a wide array of firms in different industries such as General Electric, Singer Manufacturing, Du Pont, AT&T, and Eastman Kodak. The patents in the sample received 12,227 citations in patents granted between 1947 and 2008. Table 3 shows some of the most highly cited patents originating from R&D labs such as those from Albert Hull (1880–1966), a famous inventor of the magnetron at General Electric's Schenectady laboratory and Samuel Sheppard, a renowned scientist employed by Eastman Kodak whose patents on light sensitization revolutionized the photographic film industry.

MEASURING PATENT QUALITY

Baseline Regressions

My empirical specifications are designed to compare the quality of independent inventor patents with the quality of patents assigned to firms. For the baseline citation function, which compares citations to independent inventor patents with those assigned to firms, I use a negative binomial specification on cross sections of the patent

[33] Research laboratories first started in the German chemicals industry in the late 1860s spreading to the United States in the following decades.

[34] Nicholas, "Spatial Diversity."

[35] To measure distances between inventors and labs, I calculated the great circle distance (in miles) between the coordinate latitude and longitude pairs. For further details, see Nicholas, "Spatial Diversity."

TABLE 3
EXAMPLES OF HIGHLY CITED PATENTS FROM THE R&D LAB SAMPLE

Patent	Grant Year	First Named Inventor (*Company*)	City, State	Invention	Citations 1947–2008
1,735,986	1929	Frederick Wray (*B.F. Goodrich*)	Akron, OH	Rubber soled shoe	36
1,482,807	1924	Hugh W. Newberg (*Westinghouse E&M*)	Essington, PA	Regulator for rotary pumps/motors	30
1,522,188	1925	Albert W. Hull (*General Electric*)	Schenectady, NY	Electric heating device	30
1,623,499	1927	Samuel E. Sheppard (*Eastman Kodak*)	Rochester, NY	Photographic emulsion	30
1,350,722	1920	Daniel E. Goodenberger (*Firestone*)	Akron, OH	Die for rubber extruding machines	28
1,646,498	1927	John A. Seede (*General Electric*)	Schenectady, NY	Electric heating	28
1,554,614	1925	Robert C. Allen (*Westinghouse E&M*)	Essington, PA	Turbine blading	27
1,627,900	1927	Edward H. Hewitson (*Eastman Kodak*)	Rochester, NY	Process for coating aluminum	26
1,694,264	1928	Albert W. Hull (*General Electric*)	Schenectady, NY	Temperature regulator	25
1,574,944	1926	Samuel E. Sheppard (*Eastman Kodak*)	Rochester, NY	Photographic light sensitive material	24

Notes: All examples are in the top decile of the citation distribution. Self-citations are removed by excluding all citations where the patent assignee on the citing and cited patent matched.

samples. The mean expected value of citations, *HCIT*, to patent *i* is parameterized as follows

$$HCIT_i \sim NB(\mu_i = \lambda_i), \text{ with } \lambda_i = \exp(\alpha INDEP_i + Z_i'\zeta + \varepsilon_i) \qquad (1)$$

where the vector *Z* contains control variables. First, I use a dummy variable to identify foreign inventor patents in the sample since citations to these patents should be lower given attenuation in citations as a function of geographic distance from the United States.[36] Second, I use technology dummies defined by the main patent categories developed by Bronwyn Hall, Adam Jaffe, and Manuel Trajtenberg to control for average differences across sectors in citations.[37] Finally, year dummies absorb average differences in citations for different years.

The key covariate is *INDEP*, which is coded one if patent *i* is an independent inventor patent according to its assignment status and zero for all other patents. The objective is to determine the quality of independent inventor patents relative to the overall pool of patents assigned to firms. Since λ_i is exponential, $[\exp(\alpha) - 1] \times 100$ measures

[36] MacGarvie, "Determinants of International."
[37] Hall, Jaffe, and Trajtenberg, "Patent-Citations," pp. 452–54.

the expected percentage change in historical citations when the dummy variable for independent inventor patents comes on.

Propensity-Score Matching

One potentially confounding problem with the baseline specification and the sample in the baseline regressions is that α may not recover an efficient estimate of the difference in citations between independent inventor patents and patents assigned to firms. Recall that firms often acquired independent inventions prior to the patent grant date and therefore the comparison group in the baseline regression could be contaminated by independent inventions recorded in the patent statistics as those that are assigned to firms. I therefore use the alternate R&D lab patent sample described above, which clearly defines inventions originating from inside the boundaries of a firm.

To compare similar inventions that were created by independents and by R&D firms, I run a probit model of the probability of being "treated" with the dependent variable as the zero-one dummy for being an independent invention as a function of observables. I use the resulting propensity scores to provide a control for each independent inventor patent from the R&D lab patent sample.

The large size of the control sample (N = 6,181) permits key observables to be integrated into the analysis. In other studies, location-based variables have been shown to be important in explaining citations to patents, which may be especially relevant here given that economic activity during the late nineteenth and early twentieth century became increasingly urbanized.[38] Over one-fifth of independent inventors resided within 5 miles of one of the top five cities in the country by population size in 1920 to 1930 or more than one-quarter within the same radius of the top ten cities. Adding in the broader metropolitan areas and the hinterlands, which are covered by the 30 mile radius, the shares increase to around 30 percent and 40 percent for the pooled 1920 and 1930 samples respectively.[39]

To create a geographic location variable, I calculate the distance of inventors from a large city with 100,000 or more inhabitants as listed in the 1921 and 1927 *Biennial Census of Manufactures*, which defines main agglomerations of manufacturing establishments. I set a 5 mile ring

[38] In a Marshallian sense, high-density urban areas offer opportunities for the face-to-face communication of tacit knowledge thereby providing a spur to innovation through intellectual spillovers. For evidence on urban concentration, see Kim, "Urban Development."

[39] Variables measuring the location of inventors relative to large cities are not included in the baseline regressions. They are measured only for inventors in the United States so cannot be included in any regression in Table 4 with the variable identifying foreign inventors.

around these cities to allow for spillovers of knowledge from the city and use a dummy variable to identify inventors within and outside this radius and I then add this variable to the calculation of the propensity score. I also add region-based dummy variables to further match on observables.

PATENT QUALITY REGRESSION RESULTS

Baseline Regression Results

Table 4 reports the coefficients from negative binomial regressions using the specification in equation 1. As a baseline estimate, the coefficient of the independent inventor dummy measures the difference in citations to independent inventor patents relative to patents assigned to firms. The first two columns of results are from regressions on the pooled samples of 1880 to 1930 patents, where differences in citations specific to each year but not varying cross-sectionally are absorbed into the year dummies and average time-invariant differences in citations across sectors are captured by the technology dummies.[40] As expected, the coefficient on the foreign inventor dummy is negative.

The regressions in columns 3 to 8 have the same specification, but are run on three subperiods: 1880 to 1890, 1900 to 1910, and 1920 to 1930 to examine differences in the parameter estimates over time. In columns 9 to 12, I change the comparison group from patents assigned to all firms, to patents assigned to Chandlerian firms and R&D firms based on their allocations into these categories in Table 1. In each set of results the regressions are run on all patents whether cited or not, and again on a sample confined to patents with one or more citations. The goal is to see whether differences in the quality of independent and assigned patents could have been driven by low costs of patenting that led to more patenting of more marginal (zero cited) inventions by firms. One of Schmookler's survey respondents stated that independent inventors "tend to patent only what really works and will bring returns while corporations notoriously indulge in indiscriminate patenting."[41] Alternatively, the cost of patenting was so low in the United States at this time that independents might also have engaged in strategic patenting, so the difference in patenting practices between firms and independents may not have been large.

[40] Patents in 1880 will have lower citation counts than otherwise equivalent patents in 1930. This arises because the information contained in earlier patents gets integrated into later patents over time.

[41] See further, "Inventors Past and Present," p. 322.

TABLE 4
HISTORICAL CITATION REGRESSIONS

	1880–1930		1880–1890		1900–1910	
Comparison Group	Patents Assigned to All Firms		Patents Assigned to All Firms		Patents Assigned to All Firms	
	All Citations	Citations >0	All Citations	Citations >0	All Citations	Citations >0
	(1)	(2)	(3)	(4)	(5)	(6)
Independent inventor	0.0945***	0.0424*	0.1580	0.0741	0.1582**	0.1046*
	[0.0298]	[0.0246]	[0.1288]	[0.1094]	[0.0636]	[0.0534]
Foreign inventor	–0.0439	–0.0107	0.0396	0.0246	–0.0947	–0.0863
	[0.0421]	[0.0351]	[0.1390]	[0.1124]	[0.0739]	[0.0606]
Observations	18,048	9,194	3,825	1,284	5,983	2,722
Technology dummies	YES	YES	YES	YES	YES	YES
Year dummies	YES	YES	YES	YES	YES	YES
	1920–1930		1920–1930		1920–1930	
Comparison Group	Patents Assigned to All Firms		Patents Assigned to Chandlerian Firms		Patents Assigned to R&D Firms	
	All Citations	Citations >0	All Citations	Citations >0	All Citations	Citations >0
	(7)	(8)	(9)	(10)	(11)	(12)
Independent inventor	0.0609*	0.0194	0.0820	0.0170	0.0882*	0.0369
	[0.0339]	[0.0286]	[0.0642]	[0.0515]	[0.0533]	[0.0450]
Foreign inventor	–0.0305	0.0188	–0.0949	–0.0492	–0.1110*	–0.0399
	[0.0538]	[0.0456]	[0.0629]	[0.0537]	[0.0630]	[0.0540]
Observations	8,240	5,188	5,627	3,814	6,030	3,814
Technology dummies	YES	YES	YES	YES	YES	YES
Year dummies	YES	YES	YES	YES	YES	YES

* indicates significance at the 10 percent level.
** indicates significance at the 5 percent level.
*** indicates significance at the 1 percent level.
Notes: Negative binomial regressions are run on the patent samples described in Table 1. Coefficients are reported with robust standard errors. Technology dummies are derived from Hall, Jaffe, and Trajtenberg's main patent classes ("Patents-Citations," pp. 452–54). The dummy "Independent inventor" is coded 1 for independent inventor patents and zero for inventions assigned to firms. "Foreign" is coded 1 for foreign inventor patents and 0 otherwise. When the comparison group is Chandlerian firm patents or R&D firm patents, all patents assigned to firms other than in these categories are dropped.

The coefficient of the independent inventor dummy in the first column of Table 4 measures the effect on historical citation counts to independent inventor patents relative to patents that were already assigned to a firm as of the grant date. It shows that historical citation counts were $[\exp(0.0945) - 1] \times 100 = 9.9$ percent higher for independent inventor patents than for patents within firms. When the regression is restricted to a subset of cited patents, the citations premium is more than halved to 4.3 percent and the effect is statistically significant only at the 10 percent level. Nevertheless, the results provide some prima facie evidence to suggest that independent inventors were developing nontrivial increments to knowledge capital accumulation relative to patents assigned to firms.

Breaking down the results into subperiods indicates some variation over time in the independent inventor citation premium. Using all patents, the coefficients are at their highest in 1880–1890 and 1900–1910 (columns 3 and 5), implying 17 percent more historical citations for independents' patents. Using only patents with one or more citations, the highest coefficient implies that independents received 11 percent more citations in the 1900–1910 period (column 6). The effects are substantially smaller in the other periods. Although a number of the independent inventor coefficients are not statistically significant, all are positive. At a minimum, the results suggest that the quality of independent inventors' patents on average was no worse than the assigned patents and might have been better.

Propensity Matching Results

The comparison group in Table 4 is patents assigned to all firms or patents assigned to firms within the sample data identified as Chandlerian or R&D firms for the time period 1920 to 1930. Table 5 reports the results when estimating differences between historical citations to matched independent inventor patents and control patents from my alternate sample of R&D lab patents. As discussed above, the alternate R&D sample data provide a more homogenous comparison group because they clearly define patents assigned to firm-based inventors.

Table 5 lists the different sets of variables used to estimate the propensity scores, starting with the control variables used in Table 4 and sequentially adding variables for the location of inventors. I use the natural logarithm of citation counts as an outcome variable (where a constant of 1 is added to rescale zero values) so the difference between treatment and control patents in Table 5 is approximately comparable to the coefficient of the independent inventor dummy in the baseline regression. Separate estimates are provided for all citations and nonzero citations.

TABLE 5
MATCHING ESTIMATOR RESULTS

	Variables Used to Calculate Propensity Scores	Independent (treated)	R&D firm (controls)	Difference	*t*-stat
All citations	Year, technology class	0.806	0.701	0.105	0.36
	Year, technology class, proximity to a big city	0.806	0.410	0.396	2.01
	Year, technology class, proximity to a big city, region	0.806	0.786	0.020	0.15
Citations > 0	Year, technology class	0.857	0.788	0.070	0.23
	Year, technology class, proximity to a big city	0.857	0.690	0.168	0.96
	Year, technology class, proximity to a big city, region	0.857	0.781	0.077	0.59

Notes: The outcome variable here is log(1+historical citations) so that the difference between treated and control patents is comparable to the coefficient of the independent inventor dummy in Table 4. Controls are patents with similar characteristics based on the list of variables used to calculate the propensity score. The matching method is nearest neighbor.

The results using the propensity score matching methods are similar to the results in the baseline regressions. The difference between independent and firm-based patents is always positive, but the differences are only statistically significant under one estimation procedure. The magnitudes of the differences between treatment and control patents when controlling for year and technology class are similar to the regression results reported in columns 11 and 12 of Table 4, although none of the estimates is statistically significant. Importantly, the estimate is statistically significant when the propensity score takes into account year, technology class, and proximity to a big city in the sample with all patents included. Although once region is included in the matching process, the size of the difference declines and the difference is no longer statistically significant, even the most pessimistic interpretation of the matching results suggests that patent quality for independent inventions is statistically indistinguishable from inventions emerging from within R&D labs.

A BROAD MARKET FOR IDEAS

Why was the quality of independent invention as high or higher than corporate lab inventions? Both Schmookler and Kenneth Sokoloff would argue that inventors were responding to incentives created by demand.[42] Payoffs, even if only in expectation, can act as a powerful

[42] Schmookler, *Invention and Economic Growth;* and Sokoloff, "Inventive Activity."

spur to independent technological discovery.[43] Demand inducements were particularly strong in cities during the late nineteenth and early twentieth century where networks of patent agents and other intermediaries provided an institutional structure for market-based exchanges.[44] *The Scientific American*, publishing arm of the New York patent agents Munn & Company, frequently printed pieces on independents who profited from their inventions under headlines such as, "FORTUNES IN PATENTS," "PATENTS THAT PAY," and "MANY LITTLE THINGS WHICH HAVE MADE PATENTEES RICH."

While some inventions were traded locally, patent intermediaries also encouraged inventors to advertise their inventions widely, suggesting geographically broad demand-side influences on the market for ideas. William E. Simonds, a patent lawyer in Hartford, Connecticut, provided the following advice:

> "If the inventor can afford it, it is well to have the invention illustrated and described in one or more of the scientific and mechanical publications of the day of which *The Scientific American* and *The American Artisan* of New York, and *The Scientific Press* of San Francisco are notable examples."[45]

The broad geographic scope of patents offered for sale can be seen in national and international periodicals and magazines. In 1920 the Chicago-based *Popular Mechanics Magazine* listed 96 inventions for sale by American independent inventors in 26 different U.S. states, with a further 6 offered for sale by inventors from overseas.[46] *The Chicago Defender* reported on March 30th, 1912 that an African American inventor—Mr. S. A. Baker—had sold his patent for a car heater to a Canadian company for $160,000. In 1928 AT&T, with its central research facility in New York, acquired Los Angeles inventor Howard W. Jewell's technology for encapsulating and protecting underground wires. Joseph C. Theberath of Cleveland, Ohio, had his invention for smoothing the rims of pneumatic tires to prevent puncturing acquired by General Motors, which maintained a principal research facility 178 miles away in Detroit, Michigan.[47]

[43] Astebro, "Independent Invention."

[44] Lamoreaux and Sokoloff, "Intermediaries."

[45] Simonds, *Manual of Patent Law*, p. 213.

[46] These data are based on counts of patents for sale in all editions of the magazine published in 1920.

[47] Nicholas, "Spatial Diversity."

Assuming independent inventors were responding to geographically broad demand-side influences, this should be observable in the technological profile of their patents. If independents are responding to the same national market for ideas throughout the country, the distribution of patents across technology categories for independent inventors should look similar in every city. However, the distribution across technology categories of firms' patents will not look the same in every city because firms in a specific city would focus on patents for their specific industries and the industry distributions in specific cities varied substantially from city to city. Since manufacturing activity was highly regionally specialized at this time, and the technological profile of firms ought to reflect this, we should see even more dissimilarities between the patents of independent inventors and firms at the regional level.[48]

To test for such differences, I use Jaffe's technical proximity metric to define and compare the distribution of inventions patented by independents and firms. In the formula below, based on a New York-Chicago location example, the vector S_{NY} contains the profile of New York independent inventor patents with respect to each of the USPTO's 3-digit patent classes and S_{CH} is a vector containing the profile for independents in Chicago. The elements of each vector are shares of patents in each of the 3-digit classes and the metric ρ is the uncentered correlation between the vectors. A high value implies technical proximity between both groups of patents and vice versa for low values.

$$\rho_{NY,CH} = S_{NY} S'_{CH} / [(S_{NY} S'_{NY})^{1/2} (S_{CH} S'_{CH})^{1/2}] \quad 0 \leq \rho_{NY,CH} \leq 1$$

Calculations of ρ confirm these differences. For independent inventors in New York and Chicago, two major cities in the data set, ρ = 0.76 whereas ρ = 0.41 for patents assigned to firms. Examination of the underlying distributions shows that Chicago firms had a greater concentration of patents in areas such as railroad rolling stock than New York firms, whereas in both cities the distribution of independent inventor patents are more proximate. This difference in technical proximity scores is even more revealing because the choice of cities biases the result in the other direction. New York and Chicago were both diverse agglomerations—probably more so than other U.S. cities—

48 Kim's "Expansion of Markets" study shows that regions became significantly more specialized from the late nineteenth century reaching a high point of regional specialization during the 1930s.

TABLE 6
MATRIX OF BI-REGION TECHNICAL PROXIMITY SCORES
FOR INDEPENDENT INVENTORS AND ASSIGNED PATENTS

	North East		Mid-Atlantic		East North Central		West North Central		South	
	Indep.	Assign.	Indep.	Assign.	Indep.	Assign.	Indep.	Assign.	Indep.	Assign.
Mid-Atlantic	0.83	0.53								
East North Central	0.77	0.48	0.90	0.74						
West North Central	0.64	0.35	0.75	0.56	0.87	0.60				
South	0.68	0.37	0.78	0.59	0.84	0.59	0.85	0.37		
West	0.69	0.40	0.81	0.56	0.86	0.63	0.80	0.51	0.83	0.50

Notes: Regions are as follows: *North East*: CT, ME, VT, NH, MA, and RI. *Mid-Atlantic*: NJ, NY, DE, and PA. *East North Central*: IL, IN, MI, OH, and WI. *West North Central*: IA, KS, MN, MO, NE, ND, and SD. *South*: DC, MD, VA, NC, SC, GA, KY, TN, LA, MS, AL, AR, FL, WV, and TX. *West*: NM, CA, AZ, CO, NV, UT, OK, ID, OR, WA, MT, WY, and AK.

and independents located in those cities may have supplied innovations to the same East Coast or Midwest manufacturing areas.

Table 6 reports values of ρ in region to region comparisons. In every cell of the matrix, ρ for independent inventor comparisons is larger by a multiplier ranging from 1.2 to 2.3 than the ρ for comparisons of patents assigned to firms. These results indicate that the technical profile of patents assigned to firms reflected the regional concentration of industries. The proximate profile of patents granted to independents across regions, on the other hand, is much more consistent with the argument that their technological efforts were directed by a nationwide market for ideas.

THE CHANGING DIRECTION OF INNOVATION

If the quality of independent invention was high and inventors were responding to a broad market for their ideas, why did the importance of independents change over time relative to firm-based invention? One explanation lies in the changing technical structure of inventive activity. As a consequence of the Second Industrial Revolution, which pushed out the frontier of useful knowledge towards capital-intensive innovation, the direction of technological development changed.[49] For example, the

[49] Mokyr, *Lever of Riches* and *Gifts of Athena*. Mowery and Rosenberg, *Paths of Innovation*, find new opportunities created by complex advances in physics and chemistry to be important in explaining investment in lab-based corporate R&D during the early twentieth century.

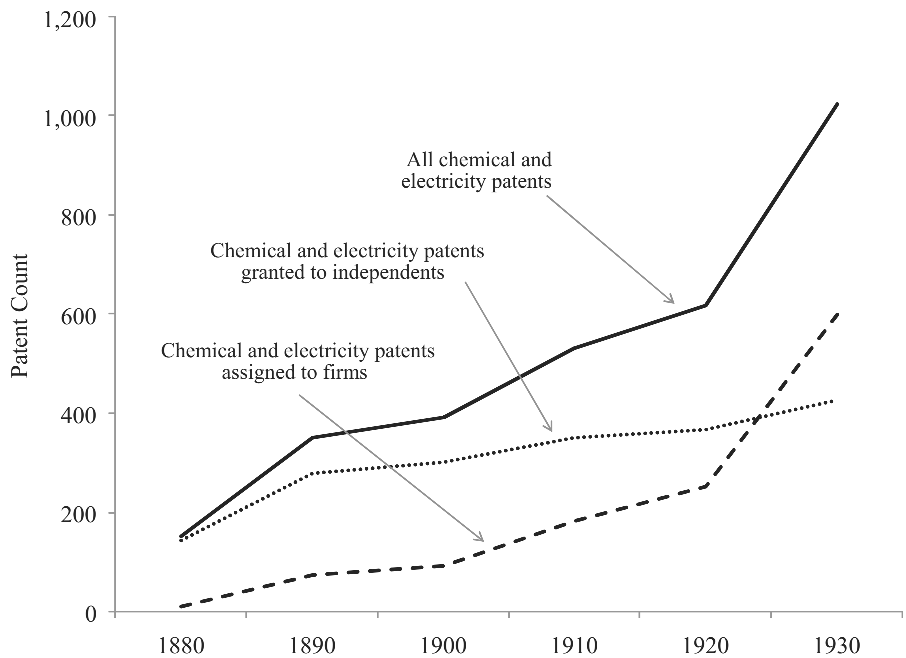

FIGURE 3
PATENTING IN CHEMICALS AND ELECTRICITY, 1880–1930

Notes: Patent categories are defined by merging the USPTO 3-digit codes into the classification in Hall, Jaffe, and Trajtenberg, "Patents-Citations." The *y*-axis shows absolute counts from my random patent samples. These need to be multiplied by 10 to arrive at population counts.

share of patents in electricity rose from 3 percent in 1880 to 11 percent in 1930, while the share in chemicals rose from 8 to 12 percent. The complexity of patents also increased as a larger share of patents was assignable to multiple categories over time. The share of patents assigned to more than one technical category rose from 22 percent in 1880 to 36 percent in 1930. One implication of more complex technologies is that the learning process is protracted and higher levels of human capital and finance are required.[50]

This change in the direction and complexity of innovation affected independent inventors and is highlighted in Figures 3 and 4, which show the number of patents by inventor type in chemical and electricity versus mechanical sectors. Whereas independent inventors accounted for a larger number of mechanical patents than firms did in 1930, in chemicals and electricity they were superseded by firms during the decade of the 1920s. Statistics for Chandlerian and R&D firms confirm the relative movement

[50] Jovanovic and Nyarko, "Learning by Doing."

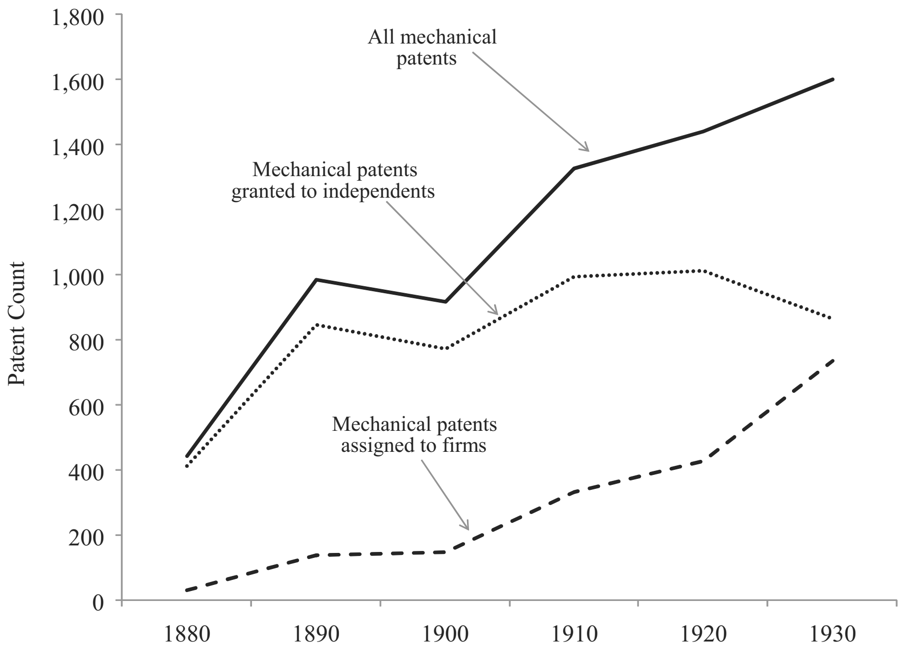

FIGURE 4
PATENTING IN THE MECHANICAL SECTORS, 1880–1930

Notes: See the notes to Figure 3.

of technological development of the progressive sectors inside the boundaries of firms. In 1930 Chandlerian firms accounted for 14 percent of patents in chemicals and electricity, while R&D firms accounted for 29 percent, almost double their respective shares of patents across all sectors in Table 1 (8 percent and 17 percent).

Despite this shift, however, firms in the new high-technology sectors still relied on independent inventions because they complemented formal innovation taking place inside of firms. For example, General Electric actively promoted the purchase of patents to augment its internal stock of knowledge by managers at several levels. In 1929 purchases of outside patents for less than $1,000 could be approved by a manager in the Patent Department, a vice president could approve purchases up to $5,000, while the vice president of the Patent Department and the vice president of the department in which the technology would be used could sanction payments of up to $10,000. Recommendations for further de-layering of the purchase decision were put before the board in April 1933.[51] RCA, another high-tech firm, acquired many television patents in the late 1920s

[51] See further, Minutes of the Board of Director Meetings, General Electric Archive Schenectady. The relevant volumes are August 1st, 1929 and April 28th, 1933.

and early 1930s from independent inventors to complement its own R&D initiatives.[52] Some of Du Ponts' major early-twentieth-century innovations in chemicals originated from the technologies acquired by the company externally.[53] Standard Oil set up a research and development facility specifically to exploit outside innovations.[54]

Transactions between firms and independents were important because R&D firms were more likely to patent in areas in which independents generally patented less. AT&T's central research facility—Bell Labs—in New York focused on innovations related to focal areas such as the telephone and facsimile transmission, and often acquired complementary inventions externally, which were modified by the lab and then absorbed into the firm.[55] Evidence from a broader sample of corporations shows that a specialized structure for technological development existed whereby firms created a balance between technologies they pursued internally and externally.[56] According to William Baumol, independent and lab-based innovation contribute significantly to economic growth precisely because "these two types of activity are complementary."[57] This aspect of technological development remained centrally important even as the organization of innovation shifted toward corporate labs. R&D labs became organizationally more significant in the development of the new capital-intensive and technologically complex sectors, but they still used independent inventions.

CONCLUSION

Despite the rising importance of the modern corporation and the spread of in-house R&D, over half of U.S. patents originated from outside the boundaries of firms by 1930. Comparisons of citations to a broad sample of patents by individuals and firms shows that the quality of independent inventions was similar to or even higher on average than the quality of inventions within firms. As Schmookler once noted about the period, "while large-scale enterprise unquestionably makes a great contribution to modern technological progress, the claim that it alone does so is entirely unwarranted."[58]

[52] Sobel, *RCA*.
[53] Mueller, "Basic Inventions."
[54] Mowery and Rosenberg, *Paths of Innovation*, pp. 15–16.
[55] Reich, "Industrial Research" and *American Industrial Research*.
[56] Nicholas, "Spatial Diversity."
[57] Baumol, *Innovation Machine*, p. 7.
[58] Schmookler, "Inventors Past and Present," p. 330.

Two factors appear to be particularly relevant to explaining why independent inventors made important contributions to knowledge capital accumulation at this time. First, independents were located primarily in cities, which served as hubs of innovation, and they engaged in a geographically broad market for their ideas. Second, as the science-based Second Industrial Revolution led to changes in the industrial organization of R&D, independents continued to create inventions that could be combined with in-house research investments to develop marketable technologies. Firms devoted considerable resources to transactions with independents and they frequently absorbed complementary outside knowledge.

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