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KNOWLEDGE DIFFUSION AND CROSSOVER INVENTIONS: EVIDENCE FROM THE ELECTRICAL INDUSTRIES, 1890-1910

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Knowledge Diffusion and Crossover Inventions: Evidence from the Electrical Industries, 1890-1910.

Abstract

Scholars have long noted the importance of general purpose technologies (GPTs) on the overall economic activity of an economy, and have investigated how such technologies were adopted and what their effects were. However, limited attention has been paid to exploring how a GPT diffuses to other industries, and what mechanisms that may facilitate such diffusion. More generally, we do not fully understand how inventive activity in various industries responds to the arrival of the GPT. This paper studies these issues by investigating the arrival of the electric technology in the late 19th century United States. The results on both the location of invention and the characteristics of inventors suggest that inter-industry knowledge spillovers (based on geographic distance) was less than crucial in the application of electric technology to inventive activity in various industries. Instead, the evidence highlights the importance of learning institutions and environments that promoted inventive activity in general.

Technological progress has long been widely recognized as a crucial source of economic growth. Throughout history, this progress consists of numerous incremental technological improvements and a handful of important technological breakthroughs. Not only have these major technological breakthroughs been widely adopted and increased productivity in a broad range of industries, but also they have spurred inventions in these downstream sectors. Examples of such breakthrough inventions are steam engines, electricity, and information and communication technology (ICT). They are often referred to by scholars such as Timothy Bresnahan, Richard G. Lipsey and Manuel Trajtenberg as General Purpose Technologies (GPTs).[1]

Given the importance of GPTs on the overall economic activity of an economy, a number of studies have investigated how such technologies were adopted and what their effects were.[2] However, limited attention has been paid to exploring how these important technologies affect inventive activity in industries that employ them. Little progress has yet been made in identifying the mechanisms that facilitate the diffusion of GPT breakthroughs to other industries.[3] This is unfortunate because an understanding of such mechanisms may help us better allocate resources to promote more rapid generation and diffusion of new technological knowledge.[4] Moreover, this issue is a growing concern for developing

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[1] For instance, see Bresnahan and Trajtenberg, "General Purpose," Lipsey, Bekar and Carlaw, "General Purpose," and Lipsey, Carlaw and Bekar, *Economic Transformation*.

[2] For example, Atack, Bateman and Weiss, "Regional Diffusion," and Rose and Joskow, "Diffusion of New Technologies" study how steam engines and electric technology were adopted as a new power source in manufacturing. Crafts, "Steam," and Atack, Bateman and Margo, "Steam Power" examine the effects of steam engines on productivity growth. Rosenberg and Trajtenberg, "General-Purpose Technology at Work," and Kim, "Industrialization" look at the impact of steam engines on urbanization.

[3] Much attention has been paid to investigate mechanisms that diffuse new technological knowledge within a single industry. See, for example, Brittain, "International," and Hughes, *Networks*. A key exception to this strand of research is Rosenberg, "Technological Change" that studies the effects of new machine tools on the evolution of various industries. He argues that the mechanical technology of the First Industrial Revolution in the U.S. was diffused through the tools and machinery sector. However, the mechanisms underlying such knowledge diffusions may be very different for other technology.

[4] The term "diffusion" has meanings in many different contexts. For example, Atack et. Al, "Regional Diffusion" and Rose and Joskow, "Diffusion" regard the first use, that is adoption, of new technology as

countries. In recent years, developing countries such as China, India and Malaysia have attempted to attract high-tech firms and their R&D facilities from more developed countries, hoping that such relocation will generate knowledge spillovers to other industries.[5] However, we do not fully understand whether such a policy will be successful, what types of support governments need to provide, and more generally what processes govern the assimilation of a technology developed for one industry into other industries.

This paper therefore attempts to bridge the gap in the literature as well as in policy practice. Our analysis focuses on the introduction of an important technological discovery – electrical technology – in the late 19th century and seeks to address the following questions. How was an understanding of electricity assimilated and used to generate inventions in other industries (henceforth, such inventions are referred to as crossover inventions)? What are factors that facilitated such knowledge assimilation, for example, inter-industry knowledge spillovers, familiarization with the new technology (that is, learning by using), and learning institutions?

To answer these questions, we constructed a unique dataset from U.S. patent records, census manuscripts, and city directories, containing detailed information on the crossover inventions and biographical information about crossover inventors over their career (for example, their educational background and the pattern of their patenting behaviors). Such micro-level information provides us an in-depth account of how knowledge is diffused between industries.

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technological diffusion. In this paper, we use the term diffusion to denote the transfer of new technical knowledge.

[5] For example Malaysia established the Multimedia Super Corridor (MSC) in 1996, hoping to become an international hub for the ICT industries, and eventually an inventive and innovative economy. See, Multimedia Super Corridor, *www.msc.com.my*..

We find that the location of crossover inventions did not correspond to the location of basic electrical inventions. In contrast, the location of these crossover inventions appears to have mirrored the geographic distribution of overall inventions. Moreover, many crossover inventions were generated by individuals who did not work in the basic electrical industry. These individuals were primarily distinguished by their advanced education and skills. The results on both the location of invention and the characteristics of inventors suggest that inter-industry knowledge spillovers (based on geographic distance) were less than crucial in the application of electrical technology to inventive activity in various industries. Instead, the evidence appears to highlight the importance of familiarization with the new technology as well as college education and technical training.

FRAMEWORK

Factors that May Facilitate Crossover Inventive Activity

There are several mechanisms through which knowledge of an important technological advancement may be assimilated and used in crossover inventions.[6] An obvious one is inter-industry knowledge exchange. Close physical proximity between individuals working in the field where a technology breakthrough takes place (the "core" industry) and individuals in other industries provides abundant opportunities to communicate and exchange information. This allows inventors in related industries to acquire the new technical knowledge and exploit it in their own fields. Likewise, inventors in

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[6] This conceptual framework of knowledge diffusion across industries is based on the literature that studies technology diffusion within an industry. See, for example, Jaffe, Trajtenberg and Fogarty, "Knowledge Spillovers" for knowledge exchange; Rosenberg, *Inside Black Box* for learning-by-using; and MacGarvie and Furman, "Early Academic Science" for universities and academic research.

the core industry may learn about potential applications of their knowledge of the new technology in other fields.

Learning-by-using may also play an important role. An individual who works in a related industry which utilizes the new technology is more likely to invest the time and effort to understand the science of the new technology and recognize its potential in various fields, and thereby may be more likely to create crossover inventions. This may also be true for inventors who simply live in an area where the technology is introduced relatively early. For example, as computers were initially introduced in advanced countries, such as the United States and Canada, residents of these countries would have an advantage in learning and applying the potential of computers to other fields over residents of countries where computers were introduced much later. Thus, familiarization with the newly developed technology can be crucial.

Moreover, the scientific principles of such a new technology may be taught in learning institutions. The technologically creative can thus obtain such knowledge directly from formal study and then apply that knowledge to various fields. In addition to direct impacts, learning institutions may raise the level of human capital and indirectly make it easier for a society to absorb new knowledge.

These three mechanisms have different implications for the location and direction of crossover invention. If day-to-day interactions (or knowledge spillovers) between those in the core industry and others are central to the generation of crossover inventions, the location of the crossover inventions should generally be closely tied to the "core" industry. Furthermore, inventors would be likely to switch back and forth between crossover and core-industry inventions throughout their career. On the other hand, if familiarization with the "core" technology (or learning-by-using) matters to a great extent, the crossover inventions would cluster in areas with high rates of utilization or adoption of "core" technology. Finally, if learning institutions help promote diffusion of the technological breakthrough to other fields, places with high concentration of such institutions would yield more crossover inventions and a significant number of the crossover inventors would receive training in the "core" technology (the direct impact of learning institutions) or complementary disciplines that will ease the speed at which one masters the new technology (the indirect impact).

Even if all these mechanisms are relevant and necessary to the assimilation of the technological breakthrough into other industries, they may not be sufficient to stimulate the creation of new technical knowledge in these industries. Other factors, such as market institutions that promote trade and investment in technology, may be prerequisite to crossover inventions and inventive activity in general.[7] Regions where these factors are abundant should have a high level of inventive activity and generate more inventions on the whole. Therefore, the location of crossover inventions may closely mirror the overall location of invention.

To examine these mechanisms and gauge their relative importance in the generation of crossover inventions, we compare the location of crossover inventions with the location of other propagating mechanisms. In particular, was the location of crossover inventions closely related to the location of core electrical inventions? To strengthen our argument, we also explore the biographies and patenting patterns of crossover inventors. For example, who were these crossover inventors: those who also worked in the core field or in other fields? What was the educational and occupational background of crossover inventors? To

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[7] For instance, see Sutthiphisal, "Learning-by-producing" for the importance of technical skills; and Lamoreaux and Sokoloff, "Inventors" for the role of market institutions in inventive activity.

what extent were the direction and location of inventive activity in other industries affected by the arrival of a newly developed technology from the core industry?

Technology Chosen for the Analysis

In order to answer these questions, we focus on the introduction of electrical technology during the so-called Second Industrial Revolution in the U.S. Electrical technology has been widely acknowledged as one of the most important technological breakthroughs (GPTs).[8] Its introduction around the turn of the 20th century brought about many technological advances in a vast array of existing industries. Moreover, electrical technology, in many ways, has characteristics that mirror new technologies of the present day, as noted in David (1990, pp. 355-356),

> [information technology and electrical technology] "each form the nodal elements of physically distributed (transmission) networks. Both occupy key positions in a web of strongly complementary technical relationships that give rise to "network externality effects" of various kinds…"

Another advantage of examining electrical technology is that it is easier to identify inventive activity employing electrical technology from the word "electric," "electricity," or "electro" in patent data than is the case for ICTs or other modern GPTs. For example, an ICT can be described in many ways such as a circuit, signal process, or even an algorithm. Furthermore, detailed biographical information is rarely available for contemporary inventors but U.S. historical records such as census manuscripts and city directories have rich biographical

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[8] Given the broad impact of the electric technology on other industries, many such as Bresnahan and Trajtenberg, "General Purpose" consider the electric technology as a seminal example of GPTs. Moser and Nicholas, "Was Electricity" however argue that the electric technology does not seem to meet the theoretical requirements of a GPT. Whether or not it is a GPT, the electric technology is undeniably one of the most important technologies in the modern era.

information on individuals, allowing us to study inventors over their entire lifespan.[9] Consequently, exploring the introduction of electrical technology during the Second Industrial Revolution in the U.S. is highly suitable for addressing the broader questions this paper poses.

A BRIEF REVIEW OF EARLY DEVELOPMENTS IN THE ELECTRICAL INDUSTRIES

The modern electrical industries can be traced back to the birth of telegraph in the early 19th century. After the successful demonstration of the telegraph over a long distance (Washington to Baltimore) to members of congress on May 24, 1844 and later to delegates of the Democratic National Convention in Baltimore, Samuel Morse together with many others quickly built telegraph lines from city to city and soon these lines spanned the continent. As telegraph signals flew through the wires (often made of copper) as electric currents, continuous improvement of electric dynamos (generators), batteries, and cables occurred simultaneously with the expansion of the electric telegraph industry.

After telegraphy, the second wave of breakthroughs in the electrical industry was in artificial illumination, beginning with arc lighting apparatus. The scientific principle behind the arc light had been known since the early 1800s but it was Charles Francis Brush, a young engineer in Cleveland, Ohio, who overcame many difficulties and introduced the first reliable arc lighting apparatus in 1878. Brush also invented a new dynamo that would provide a constant current to his lighting device. Soon Brush's arc light system appeared as street illumination in a number of American cities, including Cleveland, Boston, New York,

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[9] Although we can infer some forms of knowledge exchange from patent citations, a study of patent citations is not sufficient to identify other mechanisms, and their relative importance, in promoting crossover inventive activity.

and Philadelphia. However, arc lighting systems were not safe for interior illumination because they produced light by burning electrodes made of carbon.

Shortly after the Brush arc light, indoor lighting came to life as the incandescent lamp was introduced by one of the most famous American inventors, Thomas Alva Edison. A former staff member of the Western Union Telegraph Company, Edison first set up a laboratory in Menlo Park, New Jersey in 1876. After numerous trials and errors, in 1879 he found a substance which could light up an incandescent lamp for more than 40 hours. For his system of incandescent lighting to be used commercially, Edison developed other electric devices such as large-scale dynamos which later became central power stations. The first central station in the U.S. was opened in Appleton, Wisconsin in August 1882.[10] Two weeks later, Edison's Pearl Street Station was opened for business in New York City. Central power stations were soon established throughout major American cities in the 1880s. As highlighted in Thompson:

> The incandescent lamp and the central power station, considered together, may be regarded as one of the most fruitful conceptions in the history of applied electricity. It comprised a complete generating, distribution, and utilizing system, from the dynamo to the very lamp at the fixture, ready for use.

The emergence of central power stations provided ample opportunities to employ electricity and apply electrical technology. Electric clocks, electric burglar alarms and electric stoves are a few examples of early applications of electricity to consumer goods. For industrial and commercial uses, as dynamos transform mechanical power into electricity, motors convert electricity back into mechanical power and thus open up many applications

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[10] Milwaukee Sentinel, “Badger City Home of First Electric Plant in America,” November 20, 1921.

in factories. Machinery that had previously relied on steam and other power sources were gradually adapted to take advantage of electricity as central power stations were established across the country. Mining equipment, industrial control devices such as machine stop motion (that is, a machine brake) and boiler alarms were among common applications of the electrical technology in industrial uses.[11]

DATA

Following prior work, we use patent statistics to gauge inventive activity.[12] We construct cross-sections of (utility) patents that employed electrical technology granted in 1890 and 1910 by the United States Patent and Trademark Office (USPTO).[13] To identify whether or not a patent employed electricity, we exploit information in the patent grant document: abstract, specification, claims (and drawing) that describe how an invention can be constructed or used. We first obtain a tentative list of all utility patents granted in the cross-section years listed in LexisNexis, "U.S. Patents" on-line database by using "electric" as the key word for full-text search inquiry.[14] This list contains a total of 3,375 patents.[15]

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[11] For more details on the development of the electric industries, see, for example, Thompson, *Age*; Passer, *Electrical*; Brittain, "International"; Devine, "Shafts"; and Hughes, *Networks*.

[12] For example, see Schmookler, *Inventions* and *Patents*; and Sokoloff "Inventive Activity." Griliches, "Patent Statistics" also provides insights into why patent statistics provide a reasonable indicator of inventive activity. In addition, most technical improvements in the basic electric industry were patented because it was difficult to keep the improvements secret.

[13] The logic behind the two years chosen for this study is two folds. First, there are relatively very few data on the electric industries before 1890. For example, there were only 18 basic electric patents granted in 1870 as shown in Sutthiphisal, "Learning." The U.S. census of manufacturing also did not report any electric production or power usage before 1890. Second, these years allow for comparisons with the random sample of all patents collected by Lamoreaux and Sokoloff, "Inventors, Firms" and the basic electric sample collected by Sutthiphisal, "Learning."

[14] USPTO on-line patent grant database allows for full-text patent search through any key word inquiry for patents granted after 1976, while for patents prior to 1976 this database only allows for search through patent number.

[15] LexisNexis uses imaging technology to transform all USPTO's patent grant documents into a searchable text database. However, the imaging technology used by LexisNexis is not perfect. The word electric referred in some patent grant documents may be mistakenly transformed into words other than electric, and hence these patents are not in our listing. Due to this error from imaging technology, occasionally, we have to verify the data from LexisNexis with those retrieved from USPTO, "Patent Full-Page Image." Moreover,

Our tentative list unavoidably includes inventions such as electric batteries and dynamos that are advances in the essential (or core) electrical industry and inventions such as electric lighting and transportation that apparently have an intimate relationship with the development of the core electrical sector. Given the fact that USPTO classifies patents by their functional use and that there is no classification system which is based on the technology underlying or being employed by each invention, we read through the patent grant documents of these 3,375 patents in our list in order to identify and include the crossover inventions while filtering out others. As shown in Table 1, there are 374 patents classified as crossover inventions in 1890 and 800 patents in 1910. These inventions are applications of electrical technology in various fields. An electric stop motion for warping machines, an electric razor, and an electric safety device for slaughtering animals are a few examples of such inventions. Out of these 1,174 crossover patents, there are 995 patents granted to U.S. residents. We further classify these crossover inventions granted to U.S. residents according to the more likely primary users of the invention: consumers or industrial users. Table 2 shows that the shares of patents that were intended for industrial use are roughly the same as those for household use.

For these 995 crossover inventions, we obtain the name and address of patentees and their assignees (individuals or firms who purchase the ownership of the inventions before the dates that the patents were granted) from the patent records. We then collect similar information for all patents the patentee received over his career, whether or not they have anything to do with electricity. We also retrieve biographical information for these

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although some patents did employ electric technology, they may not use this word to describe the invention in the patent grant documents. For all these reasons, our tentative list may not include all inventions that employed the electric technology. However, a cross check of total number of patents listed by our LexisNexis search with the Lamoreaux-Sokoloff random samples of all patents in "Inventors, Firms" and Sutthiphisal's electric sample in "Geography" suggests that our tentative listing reasonably includes most, if not all, the patents that used electric technology.

patentees (inventors) from the U.S. census of population manuscripts for 1850, 1860, 1870, 1880, 1900, 1910, 1920 and 1930; and from city directories. Among the information collected are: year of birth, birthplace, occupation, place of business, and place of residence at several points during an inventor's life. We are particularly interested in the educational and occupational background of the inventor around the time when he received his first patent as well as in the early years of his inventive career.

In addition to the data on crossover inventions, we employ other datasets on basic electrical inventions and overall inventive activity. The basic electrical invention data come from the cross-section samples collected by Dhanoos Sutthiphisal. They contain similar information on basic electric patents (and their patentees) granted in 1890 and 1910. Data on overall inventive activity are from the cross-section samples constructed by Naomi Lamoreaux and Kenneth L. Sokoloff. They contain similar patent information for all industries from a randomly drawn sample of patents granted in 1890-1891 and 1910-1911.[16]

RESULTS[17]

Knowledge Spillovers across Industries (based on Geographic Distance)

If close proximity between individuals in the core electrical industry (where the technology breakthrough takes place) and those in other fields encourages information exchange, and thereby promotes the diffusion of electrical technology to other industries, the geographic clustering of crossover invention would mirror that of basic electrical invention. The results in Figure 1 however shows that in general the location of crossover invention (as measured by regional shares of crossover patents) was not so closely related to

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[16] See Sutthiphisal, "Geography"; and Lamoreaux and Sokoloff, "Inventors, Firms."

[17] The findings on the geography of crossover inventions are drawn from the entire sample of crossover inventions. The results on the characteristics of inventors are not from the complete sample (100% for 1890 but 70% for 1910). These inventors analysed thus far generated a total of almost 14,000 patents over their career.

the location of basic electrical invention (as measured by regional shares of basic electrical patents). For example, in 1890, Massachusetts, the second largest center of basic electrical inventions, accounted for more than 20% of such inventions for the country, but it only contributed about 7% of crossover inventions. Similarly, in 1910, Pennsylvania's share of basic electrical inventions was slightly more than 20%, nearly twice of its share of crossover inventions (12%). The dynamics of these invention centers also suggests that inter-industry information exchange was not crucial. The centers of basic electrical inventions changed dramatically from 1890 to 1910. For example, the importance of Massachusetts in basic electrical inventions was replaced by Pennsylvania and East North Central in 1910. [18] In contrast, the centers of crossover inventions remained competitive in crossover invention over the same period.[19]

The weak geographic association between basic electrical and crossover inventions is even more apparent if we examine the shares of crossover and basic electrical inventions at the county level. Figure 2 displays these shares for selected cities and their vicinity (county) that had high levels of either crossover, or basic electrical inventions (relative to other cities). The main centers of basic electrical invention: Lynn (home of the Thomson-Houston Electric Company) in 1890, and Pittsburg (Westinghouse Electric Company) and Schenectady (General Electric Company) in 1910 had disproportionately low shares of crossover inventions.

Second, if knowledge spillovers between individuals in the basic electrical industry and those in other industries played an important role in facilitating the assimilation of

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[18] The divergences between the regional shares of electric employment and those of crossover patents are even larger.

[19] We use a mixture between state and broader regional groupings as the unit of observations for Figrure 1. The regional groupings are based on the U.S. Census Bureau. For regions with a high volume of economic (and inventive activity), we further divide such regions into smaller units (states).

electrical technology into inventive activity in other industries, a significant portion of crossover inventions would be made by inventors who began their career as electrical inventors and later applied their electric knowledge to other fields. Similarly, those who started out as creators of crossover inventions would likely have applied their acquired electrical knowledge to generate inventions in basic electrical industry as well. An investigation into lifetime patenting behaviors of crossover inventors suggests this rarely happened. Those who started out as basic electrical inventors were not catalysts in the generation of crossover invention. As shown in Panels A and B of Table 3, inventors whose first inventions were advances in the basic electrical industry created only a small portion of the crossover inventions (13 percent in 1890 and 12 percent in 1910). Conversely, crossover inventors who did not begin their career in the basic electrical industry did not apply their acquired electrical knowledge to carry out invention in the basic electric industry. In both years, a large portion of crossover inventions were generated by inventors whose first patents were not in basic electricity. Indeed, many crossover patents were created by those who started out directly as crossover inventors.[20] Furthermore, as Table 4 shows, on average such inventors throughout their career generated virtually zero electrical invention (column 6), and no more that 6 percent of their lifetime inventions were in the field of electricity (column 8). The patterns in Table 4 still hold, even if we only consider patents that were assigned (sold) at issue, which perhaps were of higher value and utility.[21]

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[20] One may argue that perhaps some of the crossover inventions were trivial improvement with little market value. However, the assignment-at-issue rate of crossover invention is higher than that of overall inventions from the Lamoreaux-Sokoloff sample. In addition, the findings on the relative importance of these three different types of inventors still holds even if we only look at "valuable" crossover patents (that is, patents that were assigned at issue).

[21] Given that it may be too restricted to only categorize inventors according to their first invention, we also employ a more relaxed classification scheme. This scheme instead categorizes inventors by looking at the beginning two years of an inventor's inventive career starting from the date he received his first ever patent. If the inventor generated more electrical inventions than other types within these two years, we classify him as an

These findings from the geographic comparison and lifetime patenting behaviors of crossover inventors suggest that inter-industry knowledge exchange was not so crucial in the diffusion of electric technology to inventive activity in other fields. If it was not the inter-industry spillovers, then what helped facilitate the diffusion of electrical technology?

Other Mechanisms

We thus turn to test our second hypothesis that familiarity may play an important role in the assimilation of a newly developed technology into inventive activity in other industries. If familiarity helped spread electrical knowledge and thereby facilitated the generation of crossover invention, we should observe a close association between the location of crossover invention and that of high utilization or adoption of electric technology. We therefore in Figure 3 compare the regional shares of crossover patents together with two measures of utilization of electricity. One is regional shares of electric power usage in manufacturing (horsepower for 1890 and number of motors in 1910). The other is regional shares of telegraph operators. The second measure perhaps reflects utilization of electrical technology in a broader and more household-use sense.[22] The patterns in Figure 3 show that utilization (at least in manufacturing) mirrors the location of crossover invention quite well, more closely related than the location of basic electrical invention. Although the figure suggests that familiarity seemed important, it would be premature to conclude from such a finding that familiarity with electrical technology played the most critical role in the diffusion of electrical technology.

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electric inventor. We apply the same rule to the other two types of inventors (crossover and "other"). This classification scheme yields similar results as reported in both Tables 3 and 4 nonetheless.

[22] The ideal statistics of electric utilization statistics should include electric power for household use as it may not be necessary to work in factories in order to familiarize the electric knowledge or realize its numerous potentials. Moreover, the number of motors and dynamos would be a better measure than the horsepower because the mechanism behind a dynamo with small horsepower is the same as that with higher horsepower.

Were familiarity with electrical technology the most important factor in the generation of crossover invention, the location of other potential factors should not be as closely related to that of crossover invention as the location of electric utilization. Also, there should not be any distinct characteristics of crossover inventors (as compared to inventors in general) other than their familiarity with the electrical technology.

Using the location of overall inventive activity as a proxy for the location of factors conducive to inventive activity in general, as also shown in Figure 3, the regional shares of overall patenting are equally, if not more, closely related to those of crossover patents than those of electric utilization.[23] This finding suggests that factors other than inter-industry spillover and learning-by-using were more critical to the generation of crossover inventions.[24]

An investigation of biographical information of crossover inventors over their career also supports the idea that other factors rather than inter-industry spillover or learning-by-using (familiarity with electrical technology) played a more important role. Table 5 reports the educational background of crossover inventors. These crossover inventors were markedly distinguished by their advanced education. A much higher proportion of them (29 percent in 1890 and 45 percent in 1910) received a college education than shoe and textile inventors in the same cross-section years (less than 10 percent).[25] The percentage of

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[23] One may argue that perhaps some of the crossover inventions were trivial improvement with little market value. However, the assignment-at-issue rate of crossover invention is higher than that of overall inventions from the Lamoreaux-Sokoloff sample. Moreover, the findings on the relative importance of these three different types of inventors still holds even if we only look at "valuable" crossover patents (that is, patents that were assigned at issue).

[24] The co-location of crossover and overall invention could be a result of the fact that crossover and overall inventors were the same individuals. On the contrary, the evidence on location of invention in Figure 3 combined with information on first patents in Table 3 clearly demonstrates that the majority of crossover inventors and overall inventors were different. The largest shares of crossover inventions came from those who directly started out as crossover inventors not those invented in other fields and switched to crossover later.

[25] For crossover inventors, we infer their educational background from census manuscripts and city directories as well as family and local histories. On the other hand, the educational background of shoe and textile inventors was inferred from mostly census manuscripts and city directories. Thus, we have a higher matching rate for education background of crossover inventors than the shoe and textile inventors. This may partly be attributed to the finding that a larger proportion of crossover inventors received college education

crossover inventors who had a college degree grew even more pronounced in 1910, becoming comparable to that of the core inventors.

Table 6 summarizes prior occupation or training of crossover inventors before they received their first patents and before the sample year.[26] Crossover inventors were also distinguished by their advanced skills. Furthermore, even though they seldom had a prior occupation or training in the basic electrical field, nearly half of these crossover inventors had at least some work experience or training in machinery or sciences. In the population census manuscripts and city directories, many reported their occupation before receiving their first patents as engineers, machinists, chemists, and professionals in other sciences. For example, Byron A. Brooks, a typewriter pioneer, invented many improvements in typewriting machines. Later in his career, he applied electrical technology to his inventions. He began his career, however as a professor of mathematics. The fact that the majority of crossover inventors were individuals like Brooks, who went to college and received training or held an occupation in advanced technical fields but not particularly in the electrical field, highlights the indirect impact of learning institutions (it was easier for those who were educated in complementary fields to absorb the new technology).

The evidence thus far highlights the role of education and training in the assimilation of the electrical technology, which was radically new and science based. Despite the fact that we have yet to gauge the relative importance of familiarity with the electric technology as compared to other factors conducive to inventive activity in general, it appears that

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than shoe and textile inventors in the same cross-section years. Nonetheless, based on the occupational description in the census manuscripts and city directories of shoe and textile inventors, we believe that even after taking into account the matching bias there remains a significant difference in educational background between crossover and shoe-textile inventors.

[26] Ideally, we would like to compare the occupational and training background of inventors across samples. Unfortunately, Sutthiphisal's samples do not contain information on when the core electric inventors received their first patents. Therefore, we can only gauge the difference in occupational and training background of inventors in the sampled years instead of before they received the first patents.

familiarity with the technology alone was not sufficient to promote the diffusion of electrical technology.

Regression Analysis

To examine the findings more systematically as well as further strengthen our argument, we apply a series of regressions to test our hypotheses. We first test the finding that inter-industry knowledge exchange was not so central to the assimilation of electric technology into inventive activity in other industries, but factors that were conducive to inventive activity in general were more important by estimating the following equation:

$$crossover_{it} = \beta_0 + \beta_1 \cdot core_{it} + \beta_2 \cdot overall_{it} + \gamma \cdot pop_{it} + \delta \cdot \ln d_{it} + \varepsilon_{it} \qquad (1)$$

where the dependent variable, $crossover_{it}$, is region *i*'s share of crossover patents in year *t*. pop_{it} denotes the regional share of population, controlling for the possibility that regions with larger population may generate more inventions, ln d_{it} is natural logarithm of population density, a measure of urbanization. ε_{it} is a disturbance term. Most importantly, we include $core_{it}$, region *i*'s share of basic electrical patents in year *t*, so as to gauge the impact of knowledge spillovers between core electrical and crossover inventors. We also add the dependent variable, $overall_{it}$, which measures region *i*'s share of all patents, a proxy for the effects of factors that were important to inventive activity in general.

We begin our analysis at the state level. The estimation results are reported in column 1 of Table 7. Consistent with Figure 1, the positive and significant estimate for $core_{it}$ (0.184) undoubtedly suggests that inter-industry knowledge had some positive impact on the diffusion of electrical knowledge to other industries. However, the effects were much less than factors that were conducive to inventive activity in general; the estimated $overall_{it}$ coefficient (1.076) is much larger and more statistically significant. One may, however, argue that day-to-day interactions and thereby (inter-industry) knowledge spillovers likely take place in a much closer proximity. An analysis at the state level may not be appropriate. Column 2 thus explores the same regression at the county level. The estimates on $core_{it}$ and $overall_{it}$ and their sizes again suggest that factors that encouraged inventive activity in general had larger and positive effects than inter-industry knowledge exchange. Given the potential truncated bias towards zero patents in the column 2 regression, column 3 examines the county level but excludes counties that failed to generate any patent in all core electric, crossover and other fields. Similar patterns emerge.

Columns 4-6 include the interaction terms between the 1910 year dummy and all the independent variables. Such a variation of the specification allows us to examine whether there was any change in their relative importance over time. As columns 5-6 reports, the negative coefficient for the interaction term between year 1910 and $core_{it}$ implies that the impact of basic electric invention on crossover invention declined over time. A similar pattern can be found for overall invention as well.

A concern with the results shown in columns 1-6 is omitted variable bias. Given the fact that learning-by-using (familiarity or utilization of electricity) might help diffuse the electric knowledge to other industries, our regression model should include some measure of familiarity as an independent variable. Similar arguments can also apply to human capital since inventors with technical background or occupation would have an advantage over others in understanding and employing knowledge of a newly developed technology. Thus, regions with high concentration of such individuals are likely to generate more crossover inventions.

To address this concern and, more importantly, examine whether learning-by-using or high-quality human capital facilitated the assimilation of the electrical knowledge into other industries, the specification in both columns 7 and 8 include three additional independent variables. First, the regional share of telegraph operators is employed to reflect the effects of one sort of familiarity: individuals who live in an area where the technology is introduced relatively early likely realize the potential of the newly developed technology relatively early as well. We would also expect that crossover inventions facilitated through this sort of familiarity might be skewed towards household use instead of industrial or commercial use.

In addition, employees who work in factories utilizing the new technology are likely to understand the science of the new technology and recognize its potential in various fields earlier than others, and thereby may be more likely to create crossover inventions, particularly for industrial or commercial use. To capture the effects of such familiarity, we add regional share of electric utilization in manufacturing establishments into the set of independent variables.[27]

Finally, we include regional share of individuals who held an occupation in scientific fields. This allows us to assess what role appropriate human capital played in the diffusion of electric technology.

The results in column 7 again show a large estimated coefficient for overall invention but a much small estimate for basic electrical invention, corroborating the previous finding that inter-industry knowledge exchange was less central than factors that promoted inventive activity in general in the assimilation of the electrical technology into other industries. The evidence also indicates the importance of appropriate human capital. However, it is surprising that learning-by-using played a limited role, if not detrimental, in the process.

Column 8 adds the interaction terms between the 1910 year dummy and all the independent variables. The results on the whole are comparable to those found in both

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[27] Because information on utilization or familiarity with electric technology is not available at the county level, columns 5 and 6 explore the effects of all possible mechanisms at the state level.

columns 4 and 7. However, the effects of familiarity through manufacturing experience became favorable and large in 1910 as the estimation yields a positive and statistically significant coefficient on the interaction term between year 1910 and share of electric utilization in manufacturing establishments. The result suggests that learning-by-using in manufacturing may become increasingly more important to the diffusion of electrical knowledge in other fields. Columns 9 and 10 include more interaction terms. To our surprise, column 10 shows a negative estimate on the regional share of inventors who held an occupation in scientific fields. However, the impact of the concentration of these individuals reversed, becoming positive in 1910. The evidence again suggests the growing reliance on appropriate human capital. These findings should not be surprising, given that electrical knowledge became increasingly more complicated over time. Hand-on experience and appropriate human capital were inevitably destined to be more crucial in the generation of crossover invention.[28]

CONCLUSION

In recent years developing countries such as Malaysia, India and China, have been devising policies to attract ICT firms to relocate their production and R&D facilities. As ICT knowledge likely opens up opportunities for a wide range of downstream industries and fosters applications (new products and processes) of these industries, the primary motivation of these policies is no doubt the hope of realizing the positive externalities that ICT knowledge can bring about, so as to transform their economies to become inventive and innovative. However, we do not know whether the ICT knowledge brought along with the

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[28] Perhaps, it is not surprising that the interaction between 1910 and the share of electric utilization in manufacturing establishments was positive, whereas that between 1910 and the share of telegraph operators (which reflects household electric utilization) was negative. This result seem consistent with the fact that there was an increase in the share of crossover invention for industrial use and a decline in the share for household use during 1890 and 1910 (as shown in Table 2).

relocation of industrial countries' high-tech firms will increase the productivity of R&D (and thereby invention) in these downstream industries.

This paper has sought to improve our understanding of the effects of the introduction of knowledge of an important technology on overall inventiveness of an economy. The historical experience of the electrical industries during the Second Industrial Revolution shows that locations where more basic electrical inventions were concentrated were not closely associated with locations with high levels of crossover inventions, that is, inventions that did not belong to the basic electrical industry but somehow employed knowledge of electricity. In fact, the areas where more crossover inventions appeared mirrored the locations with the most inventions across all types of industries. A close examination of crossover inventors also reveals that individuals with advanced educational and training background created most of these crossover inventions. These findings suggest that the importance of knowledge exchange through physical interactions in the generation of new technical knowledge may have been over-emphasized by prior work, and the contribution from human capital or other factors may have been under-appreciated. Moreover, developing countries that devise policies to attract ICT firms to relocate may not come to realize an increase in invention of an array of downstream industries (one potential gain that ICT knowledge can bring about) unless they first accumulate factors that are conducive to inventive activity in general, for example, human capital.

APPENDIX 1. CLASSIFICATION SCHEMES

The index for invention type is inferred from detailed descriptions of invention including paper drawing, specification, and claims. The scheme that classifies patents into three different fields is as follows. (a) Core electrical patents contain technological advances in the basic electrical industries, for example, telegraphy, electric switches, and electric cables and wires, as well as general propose dynamos and motors. The core electrical category also includes inventions in artificial illumination such as arc lamps and incandescent light bulbs. Another important application of the electrical technology occurred in the field of electric railways and street cars. However, the problems associated with electric railways and street cars as well as the solutions to these problems were similar to those facing the electric power industry. For example, in order to move a car through an electric motor, a constant supply of electricity had to be presented either by electric batteries or by networks of electric wires. Consequently, those who developed inventions in electric railways and street cars were also very much involved in improving the basic electrical technology, particularly in the design of electric batteries and in the distribution of electric power. Given that the growth of the electric railways and street cars was intimately related to the development of the electric power industry, we include inventions in the field of electric railways and street cars in the core electrical class. Another type of patents that we classify into this group is those in the field of electric welding. Electric welding in general utilizes high electrical voltage in order to generate sufficient heat to melt metals or alloys. A large part of inventions in this field thus were centered around electrical resistance substances as well as the apparatus that can create and sustain high voltage. (b) The crossover invention category refers to patents that utilize electricity as power source or somehow employ electrical technology, but not in the fields that are specify in (a). (c) The "other" category refers to patents that neither utilize electricity nor employ electrical technology.

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TABLE 1
DISTRIBUTION OF U.S. ELECTRIC INVENTIONS

	No. of patents		% of total patents	
Class	1890	1910	1890	1910
Other industries that use electrical technology	374	800	1.5	2.3
Core electrical	639	598	2.5	1.7
Electric lighting	190	264	0.8	0.8
Electric transportation	186	134	0.7	0.4
Other electrical (e.g. welding)	127	63	0.5	0.2
Total from "electric" serach in Lexis/Nexis	1516	1859	6.0	5.4

Sources and Notes: *LexisNexis*, "U.S. Patents"; *USPTO*, "Full-Page Images"; and *USPTO*, "Technology Assessment." The percent of total patents is calculated from the number of patents with respect to the total number of patents granted by USPTO in the respective years reported in *USPTO*, "Technology Assessment" (25,322 for 1890 and 35,168 in 1910). Core electric category denotes inventions that are advancements in the basic electric technology such as those for electric generation, distribution, transmission, wiring and machinery parts for general use. Electric lighting category includes patents intended for electric lighting use such as light bulbs and lamp fixtures. Electric transportation category contains patents intended for electric railroad and trolley. Other electric category refers to patents that are not advancement in the basic electric technology (not in the core category) but to some extent of general use and are very closely related to the basic electric industry. Finally, other industries that use electric technology category denotes patents in industries not related to the electric industry but exploited the electric technology, that is, the crossover inventions.

TABLE 2
CROSSOVER PATENTS GRANTED TO U.S. RESIDENTS BY USERS

	No. of cross-over patents by users			% of cross-over patents by users	
Year	Consumer	Industrial	Total	Consumer	Idustrial
1890	185	145	330	56.1	43.9
1910	322	333	665	48.4	50.1

Sources and Notes: *LexisNexis*, "U.S. Patents"; and *USPTO*, "Full-Page Images." Consumer category denotes inventions that are consumer goods (such as an electric razor), whereas industrial category refers to inventions that are not for consumer goods (for example, an electric stop motion for warping machines).

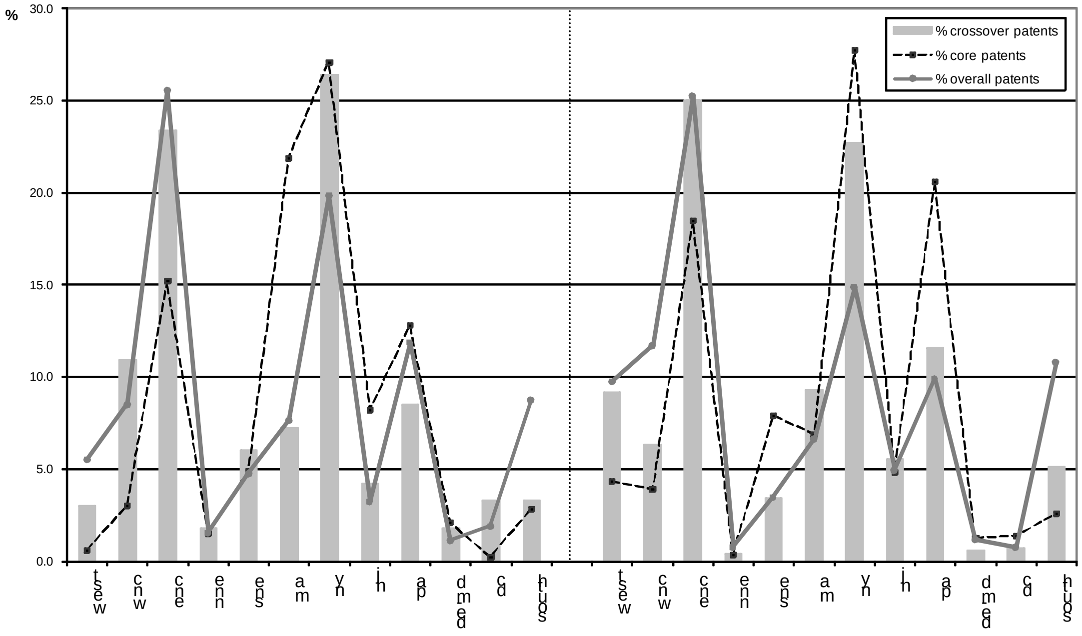

FIGURE 1
REGIONAL SHARES OF CROSSOVER, BASIC ELECTRIC AND OVERALL PATENTS

Sources and Notes: *LexisNexis*, "U.S. Patents"; *USPTO*, "Full-Page Images"; U.S. Census of Manufactures Reports, 1890 and 1910; Sutthiphisal, "Geography"; and Lamoreaux and Sokoloff, "Inventors, Firms." WNC = West North Central, ENC = East North Central, NNENGL = Northern New England, SNENGL = Southern New England. The geographic classification scheme that divides the U.S. into 13 regions are based on the U.S. Bureau of Census' scheme with finer divisions utilized for areas with higher inventive activity such as New England and Middle Atlantic. The regions are as follows. (a) West – AZ, CA, CO, ID, MT, NM, NV, OR, UT, WA, and WY. (b) West North Central – IA, KS, MN, MO, ND, NE, and SD. (c) East North Central – IL, IN, MI, OH, and WI. (d) Northern New England – ME, NH, and VT. (e) Southern New England – CT and RI. (f) Massachusetts. (g) New York. (h) New Jersey. (i) Pennsylvania. (j) DE-MD – DE and MD. (k) District of Columbia. (l) South – AL, AR, FL, GA, KY, LA, MS, NC, OK, SC, TN, TX, VA, and WV. (m) Other – AK and HI.

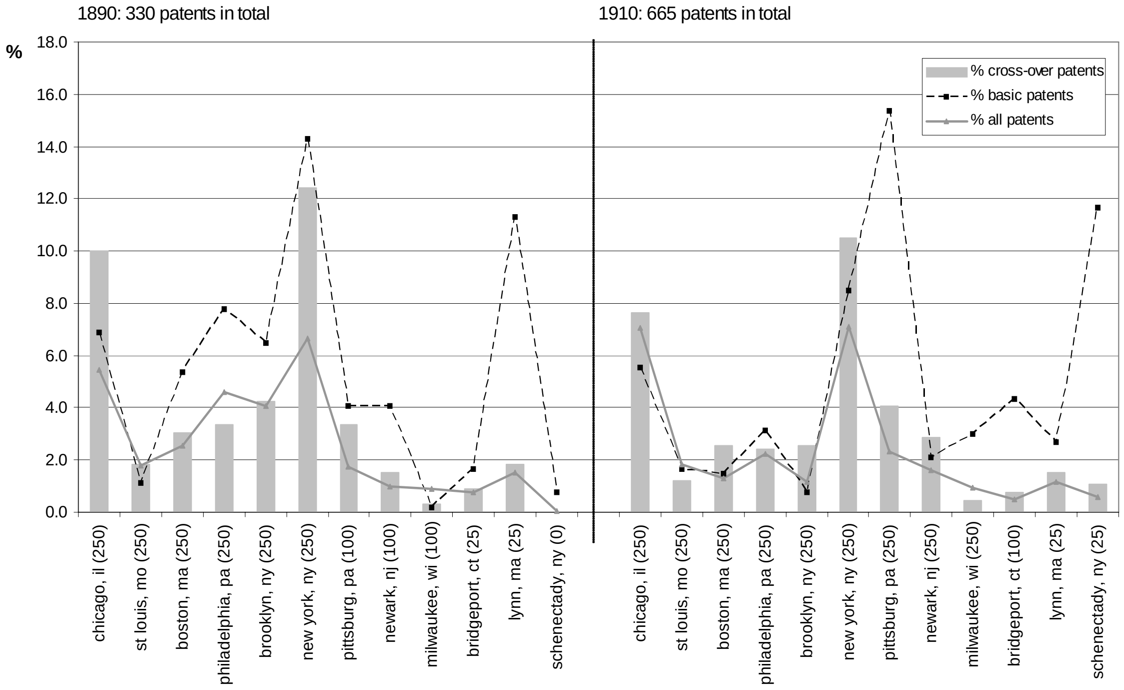

FIGURE 2
SELECTED CITIES (AND THEIR VICINITY) SHARES OF CROSSOVER, BASIC ELECTRIC AND OVERALL PATENTS

Sources and Notes: See Figure 1.

Table 3
Crossover and Other inventions by Types of Inventors and Assignment

	All patents			Assigned patents	
Types of inventors	No. of patents	Share of patents	Share of patent assigned	No. of patents	Share of patents
	Panel A: Crossover Invention in 1890				
First patent was electric	42	13	40	17	14
First patent was other	111	34	35	39	32
First patent was crossover	174	53	37	65	54
All crossover inventors	327	100	37	121	100
	Panel B: Crossover Invention in 1910				
First patent was electric	53	12	53	28	15
First patent was other	152	34	45	68	36
First patent was crossover	245	54	38	92	49
All crossover inventors	450	100	42	188	100
	Panel C: Other Invention in 1890				
Shoes (Sutthiphisal)	270		57		
Textiles (Sutthiphisal)	424		59		
Electric (Sutthiphisal)	539		61		
All industries (Lamoreaux-Sokoloff)	2201		29		
	Panel D: Other Invention in 1910				
Shoes (Sutthiphisal)	417		63		
Textiles (Sutthiphisal)	449		62		
Electric (Sutthiphisal)	670		72		
All industries (Lamoreaux-Sokoloff)	2816		30		

Sources and Notes: *LexisNexis*, "U.S. Patents"; *USPTO*, "Full-Page Images"; Sutthiphisal, "Geography"; and Lamoreaux and Sokoloff, "Inventors, Firms." Unlike others, the Lamoreaux-Sokoloff figures are from a random sample of patents granted in 1890-91 and 1910-11. See Appendix 1 for patent classification.

TABLE 4
LIFETIME PATENTING BEHAVIORS OF CROSSOVER INVENTORS

Types of inventors	No. of inventors	Share of inventors	Career length (years)	Career patents (median)			Share of career patents (average)	
				Overall	Cross-over	Electric	Cross-over	Electric
Panel A: Crossover Invention in 1890								
First patent was electric	24	9	26	27.5	6	9	34	50
First patent was other	95	37	28	10	2	0	26	5
First patent was crossover	141	54	11	2	1	0	73	6
All crossover inventors	260	100	18	5	2	0	52	10
Panel B: Crossover Invention in 1910								
First patent was electric	46	12	28	19.5	4	5.5	32	40
First patent was other	135	35	25	10	3	0	33	4
First patent was crossover	209	54	11	2	1	0	76	3
All crossover inventors	390	100	18	6	2	0	56	8

Sources and Notes: *LexisNexis*, "U.S. Patents"; *USPTO*, "Full-Page Images." See Appendix 1 for patent classification.

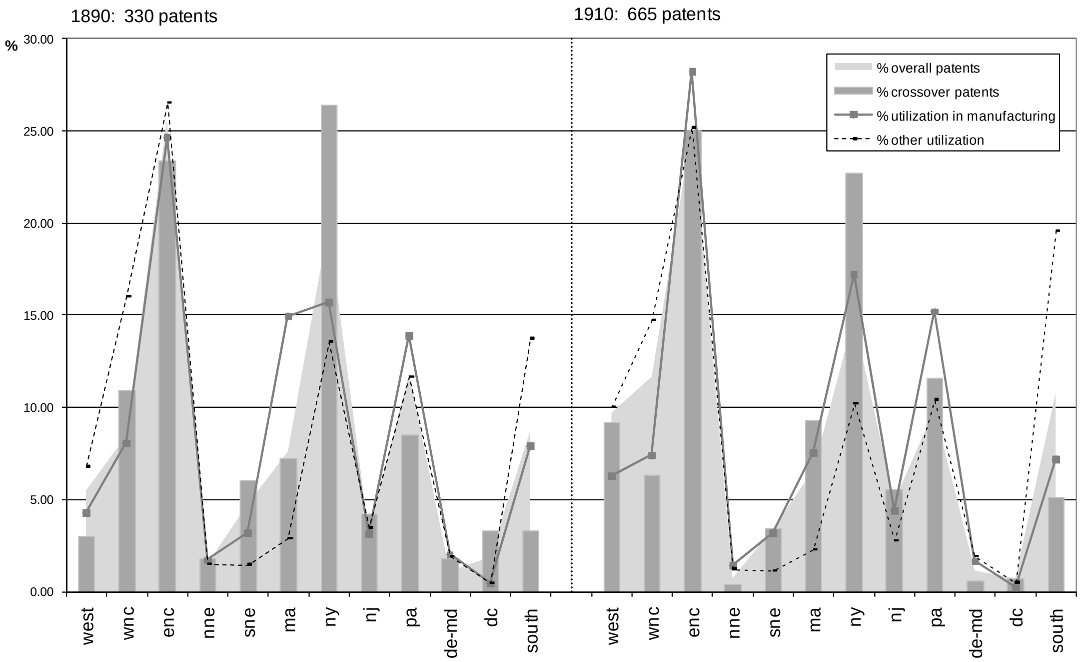

FIGURE 3
REGIONAL SHARES OF CROSSOVER PATENTS, ELECTRIC UTILIZATION IN MANUFACTURING, OTHER ELECTRIC UTILIZATION AND OVERALL PATENTS

Sources and Notes: *LexisNexis*, "U.S. Patents"; *USPTO*, "Full-Page Images"; U.S. Census of Manufactures Reports, 1890 and 1910; Sutthiphisal, "Geography"; and Lamoreaux and Sokoloff, "Inventors, Firms." Shares of electric utilization in manufacturing are calculated from the number of horsepower used in manufacturing establishments for 1890; and from the number of electric motors used in manufacturing establishments for 1910. Shares of other electric utilization are computed from the number of telegraph operators.

TABLE 5
EDUCATIONAL BACKGROUND OF CROSSOVER AND OTHER INVENTORS

		Education		
		Went to college		
Types of inventors	No. of inventors	Unnormalized share	Normalized share	Missing information (share)
Panel A: Crossover Invention in 1890				
First patent was electric	24	17	57	71
First patent was other	95	13	26	52
First patent was crossover	141	11	28	62
All crossover inventors	260	12	29	59
Panel B: Crossover Invention in 1910				
First patent was electric	46	24	52	54
First patent was other	135	19	43	57
First patent was crossover	209	15	45	67
All crossover inventors	390	17	45	62
Panel C: Other Invention in 1890				
Shoes (Sutthiphisal)	228	1	4	75
Textiles (Sutthiphisal)	339	1	6	81
Electric (Sutthiphisal)	312	13	51	75
Panel D: Other Invention in 1910				
Shoes (Sutthiphisal)	278	0	2	80
Textiles (Sutthiphisal)	329	1	8	85
Electric (Sutthiphisal)	468	7	49	85

Sources and Notes: *LexisNexis*, "U.S. Patents"; *USPTO*, "Full-Page Images"; U.S. Decennial Census of Population Manuscripts, 1850-1880 and 1900-1930; Ancestry.com (U.S. City Directories, mostly in 1890); and Sutthiphisal, "Geography." The normalized shares are calculated from the shares of inventors with known information. The normalized shares from all categories, except those in the missing information category, add up to one. See Appendix 1 for patent classification and Appendix 2 for educational and occupational background classification.

TABLE 6
PRIOR OCCUPATION OR TRAINING OF CROSSOVER AND OTHER INVENTORS

	Prior occupation or training before first patent					Prior occupation or training before sampled year		
	Unnormalized share		Normalized share		Missing	Normalized share		Missing
Types of inventors	Electric	Other technical skills	Electric	Other technical skills	inform-ation (share)	Electric	Other technical skills	inform-ation (share)
Panel A: Crossover Invention in 1890								
First patent was electric	0	6	0	11	50	69	15	28
First patent was other	0	40	0	59	33	2	67	17
First patent was crossover	5	29	8	44	34	19	39	29
All crossover inventors	3	30	5	46	35	18	47	25
Panel B: Crossover Invention in 1910								
First patent was electric	41	35	44	38	6	71	24	0
First patent was other	0	36	0	60	40	7	62	22
First patent was crossover	8	30	13	46	34	33	39	26
All crossover inventors	9	33	13	49	33	28	46	22
Panel C: Other Invention in 1890								
Shoes (Sutthiphisal)						0	39	46
Textiles (Sutthiphisal)						0	52	50
Electric (Sutthiphisal)						53	14	47
Panel D: Other Invention in 1910								
Shoes (Sutthiphisal)						1	33	41
Textiles (Sutthiphisal)						2	48	51
Electric (Sutthiphisal)						70	19	36

Sources and Notes: *LexisNexis*, "U.S. Patents"; *USPTO*, "Full-Page Images"; U.S. Decennial Census of Population Manuscripts, 1850-1880 and 1900-1930; Ancestry.com (U.S. City Directories, mostly in 1890); and Sutthiphisal, "Geography." The normalized shares are calculated from the shares of inventors with known information. The normalized shares from all categories, except those in the missing information category, add up to one. See Appendix 1 for patent classification and Appendix 2 for educational and occupational background classification.

TABLE 7
REGRESSIONS WITH SHARES OF CROSSOVER INVENTION AS THE DEPENDENT VARIABLE

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Share of crossover invention	State	All counties	Non-zero patents counties	State	All counties	Non-zero patents counties	State	State	State	State
Constant	-0.086	0.007	0.027	0.026	0.007	0.137	-0.358	-0.204	-0.188	-0.13
	(0.35)	(1.66)	(0.66)	(0.08)	(1.41)	(2.06)*	(1.66)	(0.78)	(0.90)	(0.54)
Share of core invention	0.184	0.124	0.118	0.049	0.167	0.138	0.261	0.272	0.141	0.163
	(3.78)**	(20.83)**	(8.00)**	(0.71)	(16.63)**	(5.44)**	(4.82)**	(3.77)**	(2.34)*	(2.21)*
Share of overall invention	1.076	0.864	0.863	1.283	0.864	0.862	1.158	1.203	1.193	1.119
	(10.23)**	(41.14)**	(15.46)**	(8.81)**	(29.77)**	(10.94)**	(8.89)**	(7.08)**	(9.30)**	(6.62)**
Share of population	-0.196	0.727	0.881	-0.389	0.749	1.207	-0.253	-0.494	-0.226	-0.291
	(1.56)	(14.15)**	(6.11)**	(2.28)*	(8.66)**	(4.77)**	(1.36)	(1.86)	(1.29)	(1.16)
Log population density	-0.013	-0.010	-0.027	0.031	-0.012	-0.066	0.013	0.076	0.075	0.156
	(0.19)	(7.71)**	(2.65)**	(0.32)	(6.85)**	(3.83)**	(0.21)	(0.95)	(1.19)	(1.97)
Dummy 1910				-0.096	-0.001	-0.151		0.063		0.055
				(0.20)	(0.12)	(1.80)		(0.15)		(0.14)
Core invention x 1910				0.236	-0.081	-0.054		-0.181		-0.253
				(2.39)*	(6.49)**	(1.73)		(1.64)		(1.98)
Overall invention x 1910				-0.26	-0.102	-0.106		-0.519		-0.651
				(1.21)	(2.38)*	(0.93)		(1.67)		(2.09)*
Population x 1910				0.163	0.148	-0.242		0.687		0.257
				(0.63)	(1.34)	(0.76)		(1.96)		(0.76)
Log density x 1910				-0.059	0.003	0.054		-0.122		-0.15
				(0.43)	(0.92)	(2.53)*		(1.05)		(1.32)
Share of telegraph operators							-0.283	0.177	-0.105	1.002
							(1.81)	(0.83)	(0.46)	(2.59)*
Share of electric utilization in mfg							-0.468	-0.574	-0.358	-0.447
							(4.95)**	(5.95)**	(3.82)**	(4.63)**
Share of science occupation							0.743	0.405	0.154	-0.906
							(3.73)**	(1.17)	(0.56)	(1.65)
Telegraph X 1910								-1.151		-1.231
								(3.75)**		(2.28)*
Utilization in manufacturing x 1910								0.901		1.211
								(3.73)**		(4.46)**
Science x 1910								0.418		1.007
								(0.87)		(1.52)
Telegraph X Science									-0.035	-0.221
									(1.13)	(2.60)*
Utilization X Science									0.07	0.282
									(2.51)*	(2.89)**
Telegraph X Science X 1910										0.081
										(0.77)
Utilization X Science X 1910										-0.146
										(1.36)
Observations	98	5684	921	98	5684	921	98	98	98	98
R-squared	0.93	0.84	0.83	0.94	0.84	0.84	0.95	0.96	0.96	0.97

Absolute value of t statistics in parentheses
* significant at 5%; ** significant at 1%

Sources and Notes: *LexisNexis*, “U.S. Patents”; *USPTO*, “Full-Page Images”; U.S. Census of Population, 1890 and 1910; U.S. Census of Manufactures, 1890 and 1910; Sutthiphisal, “Geography”; and Lamoreaux and Sokoloff, “Inventors, Firms.” Columns 1, 4, 7 and 8 are regressions at the state level. Columns 2 and 5 are regressions at the county level with all counties existing in the sampled years. Columns 3 and 6 are regressions at the county level with only counties with at least one of either overall, core, or crossover patents in the sampled years. The intercepts for columns 4-6 and 8 are 1890. The shares of science occupation are calculated from the number of architects, chemists, dentists, engineers, physicians and professors for 1890; and from electricians and electrical engineers, mechanical engineers, stationary engineers, civil engineers, mining engineers, architects, chemists, assayers and metallurgists, college presidents and professors, dentists and physicians for 1910. The shares of plant electric utilization are calculated from the number of horsepower used in manufacturing establishments for 1890; and from the number of electric motors used in manufacturing establishments for 1910. See Appendix 1 for patent classification.