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Innovation without Patents: Evidence from World's Fairs

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Abstract

This paper introduces a unique historical data set of more than 8,000 British and American innovations at world's fairs between 1851 and 1915 to explore the relationship between patents and innovations. The data indicate that the majority of innovations—89 percent of British exhibits in 1851—were not patented. Comparisons across British and U.S. data also show that patenting decisions were unresponsive to differences in patent laws. Cross-sectional evidence suggests that high-quality and urban exhibits were more likely to be patented. The most significant differences, however, occurred across industries: inventors were most likely to use patents in industries in which innovations are easy to reverse engineer and secrecy is ineffective relative to patents. In the late nineteenth century, scientific breakthroughs, including the publication of the periodic table, reduced the effectiveness of secrecy in the chemical industry. Difference-in-differences regressions suggest that this change resulted in a significant shift toward patenting.

1. Introduction

On May 8, 1886, Dr. John Stith Pemberton, a pharmacist in Atlanta, Georgia, produced the first batch of Coca-Cola. Pemberton carried a jug of his syrup down the street to Jacobs' Pharmacy, where it was placed on sale for 5 cents a glass and, perhaps due to its light kick of cocaine, became a runaway success. Like most inventors of drinks and medicines, Pemberton decided not to patent;

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"a hopeful inventor would patent the label or trademark for his nostrum, but never its 'secret formula'" (Pendergrast 2000, p. 9). Had Coca-Cola been patented, its recipe would have entered the public domain in 1903, and the company would have missed substantial growth. Between 1899 and 1920, the number of plants bottling Coca-Cola increased from two to more than a thousand; by the year 2000, Coca-Cola had become the world's most ubiquitous consumer product. The recipe for Coca-Cola, which was never patented, remains a notable commercial secret (Pendergrast 2000, p. 348).[1]

Contemporary surveys, such as the Yale and Carnegie Mellon studies of American firms (Levin et al. 1987; Cohen, Nelson, and Walsh 2000), have established that firms consider secrecy and other alternatives to be at least as effective as patents in protecting intellectual property (see also Bachmann and Scherer 1959; Mansfield, Schwartz, and Wagner 1981; Mansfield 1986; Harhoff and Hoisl 2006). A lack of systematic economywide data, however, has made it impossible to measure the share of innovations that occur outside the patent system. As a result, empirical analyses typically use counts of patents per year as a measure of innovation. For example, nearly a thousand empirical studies have used patent counts in the National Bureau of Economic Research patent data set (Hall, Jaffe, and Trajtenberg 2005) largely without controlling for variation across industries and over time in the relationship between patents and innovations.

In addition to measurement issues, knowing when and why inventors choose to patent is essential for the design of patent policies. If, for example, a substantial share of innovation occurs outside the patent system, policies that strengthen intellectual property rights may do little to increase the overall level of innovation (Machlup and Penrose 1950; Moser 2003). If the need for patents varies across industries, radical changes in patent laws may also alter the direction of technical change. Without patent laws, innovation concentrates in a small number of industries that do not need patents. With patent laws, the returns to innovation increase in industries that need patents to protect intellectual property, and technical change becomes more broad based and less concentrated (Moser 2005).

To better understand the relationship between patents and innovations, this paper examines a unique data set of more than 8,000 innovations at four world's fairs between 1851 and 1915. Despite a number of shortcomings, described in Section 2, these data improve over existing sources, which have been unable to capture innovations without patents across industries and over time. Most important, exhibition data make it possible to systematically compare innovations with and without patents across industries, countries, levels of quality, levels of urbanization, and over time.

Exhibition data confirm a key result of modern surveys: patents are just one of many mechanisms that protect intellectual property and may, in fact, play a

[1] Today, competing versions of Coca-Cola's secret recipe are available in print and online (see, for example, Pendergrast 2000, pp. 456–57), but none of these recipes appear to be complete.

limited role in creating incentives to invent. In 1851, 89 percent of British exhibits at the Crystal Palace fair were not patented.

A comparison of U.S. and British data further indicates that patenting decisions are remarkably unresponsive to differences in patent laws. In 1851, Britain and the United States had the same patent duration (14 years), but patent fees were significantly higher in Britain: $37,000, compared to $618 in the United States (in 2000 U.S. dollars) (Lerner 2000). British inventors also faced a drawn-out and expensive process, including legal fees and bribes, while U.S. inventors could mail in their applications (Bentham 1839, p. 214; MacLeod 1988, p. 76).[2] Even after a patent was granted, enforcement remained doubtful, and British courts were biased against patentees (Dutton 1984, p. 84).

Traditional accounts of innovation have argued that the superior design of the U.S. patent system was a main driver of rapid technological progress in the United States (Khan 2005; Sokoloff and Khan 1990; Lamoreaux and Sokoloff 1999). Such analyses, however, had to rely on patents as the only indicator of innovation and therefore failed to capture innovations outside the patent system. Exhibition data indicate that 85 percent of U.S. exhibits in 1851 occurred outside the patent system, which suggests that the effects of the U.S. patent system may have been much smaller than traditional accounts suggest.

If not the characteristics of patent laws, what determines the patenting decisions of inventors? Theoretical models predict that inventors use patents to protect small innovations but keep large innovations secret (Anton and Yao 2004).[3] Exhibition data, however, suggest that high-quality innovations are more likely to be patented than average-quality innovations: in 1851, 15 percent of British exhibits that won prizes for exceptional usefulness and quality were patented, compared with 11 percent of all exhibits.

Another potential determinant of patenting is the location of inventors. Urban inventors may be more likely to patent because they are surrounded by competitors who can reverse engineer their innovations (Mokyr 1995). Urban inventors may also find it easier to access and navigate the patent system, especially if the system is centralized and undemocratic (MacLeod 1988). Exhibition data support this idea: British innovations were more likely to be patented if they originated from London or other cities. In the United States, rural innovations

[2] In 1722 and 1723, Samuel Taylor of Manchester had to come to London for 6 months to complete a patent application for a thread-making machine. Taylor's diary lists nearly £130 in expenses for official and solicitors' fees, gratuities, inn charges, and entertaining the servants of the secretary of state, solicitor general, and lord chancellor (MacLeod 1988, p. 7). "Official fees and stamp duties (introduced in 1694) amounted to approximately £70, but the gratuities payable to everyone concerned—from doormen to high-ranking officials—usually added another £10 to £30 to this cost and might double in some cases" (MacLeod 1988, p. 76). At a time when only 5 percent of the population had annual incomes over £60 (Rubinstein 1981, p. 44), such sums were unaffordable for the majority of people.

[3] The intuition for this result is that firms keep large innovations secret because patents require disclosure, which is risky if patents are ineffective at blocking competitors from using a patented invention (Horstmann, MacDonald, and Slivinski 1985).

were more likely to be patented, which suggests that the ability to register patents by mail may have encouraged rural inventors to use patents.[4]

The most significant variation, however, occurs across industries. In 1851, less than 5 percent of chemical exhibits were patented, compared with 20 percent of manufacturing machinery exhibits. Survey data suggest that variation in the effectiveness of secrecy is critical to the patenting decisions of contemporary firms (Levin et al. 1987; Cohen, Nelson, and Walsh 2000; Harhoff and Hoisl 2006).[5] Intuitively, firms may use patents to protect ideas that are easy to imitate (and therefore cannot be protected by secrecy).[6] Thus, an improvement in the grain reaper may be patented because it is easy to imitate, while an improvement in Coca-Cola is protected by secrecy because it is difficult to copy.

The second step of the analysis takes advantage of an exogenous change in the effectiveness of secrecy in late-nineteenth-century chemicals. In 1851, chemical innovations were virtually impossible to reverse engineer because methods of chemical analysis were relatively crude (Haber 1958, p. 83). In the second half of the nineteenth century, a series of scientific breakthroughs, including August Kekulé's model of the benzene ring in 1865 and Dmitrii Mendeleev's publication of the periodic table in 1869, transformed chemical analysis (Haber 1958, p. 81; Asimov 1975; Maher 1988). With improved tools of analysis, it became much riskier to protect further improvements through secrecy. Scientific progress also facilitated the codification of knowledge in patent applications (Winter 1987; von Hippel 1994; Mokyr 2002), which further reduced the effectiveness of secrecy relative to patents.

Difference-in-differences comparisons reveal a significant shift toward patenting after secrecy became less effective. In 1851 and 1876, 0 and 5 percent of U.S. chemical innovations were patented, respectively. In 1893 and 1915, 19 and 20 percent of chemical innovations were patented, respectively. At the same time, patenting rates for manufacturing machinery, as a control industry in which

[4] Another potential determinant of patenting is variation in firm size, which cannot be examined with the current data set. A survey of 500 firms in 1938, 1948, and 1952 suggests that large firms use a smaller share of the innovations that they patent (Scherer 1965), perhaps because large firms face lower litigation risks (Lerner 1995) and lower marginal costs of patenting. On the other hand, small firms may be more dependent on patents to attract startup funding (Hall and Ziedonis 2001; Mann and Sager 2007) and license innovations (Arora 1997).

[5] In fact, secrecy may be even more important today because changes in the U.S. legal system have strengthened trade secret protection for firms. In the early nineteenth century, employees owned the entire right to their inventions. After 1880, courts began to favor the property rights of firms, so employees had to license inventions to the firms that employed them. By the turn of the twentieth century, firms began to effectively own most of their employees' inventions (Fisk 1998, 2001), and legal mechanisms, such as covenants not to compete, evolved to prevent employees from using trade secrets after they left a firm (Gilson 1999). Secrecy is often used as a complement to other mechanisms such as lead time (being the first to introduce a new product to the market) and the provision of unique complementary assets (see Cohen, Nelson, and Walsh 2000).

[6] Improvements in roses and fruit trees, for example, are extremely difficult to protect by secrecy because competitors can copy a new plant by replanting cuttings. Nursery firms that developed them were among the strongest advocates for plant patents in the early twentieth century, and most plant patent grants between 1920 and 1970 are for roses (Moser and Rhode 2012).

secrecy was ineffective throughout, stayed roughly constant at 44–49 percent. Complementary tests with alternative sources of data confirm that chemical patents became more important over time and relative to other industries.

The remainder of this paper is structured as follows. Section 2 describes the exhibition data and discusses potential sources of bias and measurement error. Section 3 examines cross-sectional variation in the use of patents in 1851. Section 4 presents difference-in-differences tests that compare changes in the use of patents between 1851 and 1915. Section 5 presents tests with alternative sources of data, and Section 6 concludes.

2. Exhibition Data

Previous analyses have measured patenting rates as patents issued per year or, at best, per capita. This paper improves on such analyses by measuring patenting rates as the share of innovations that are patented across industries and over time. To this end, data on innovations with and without patents are drawn from the exhibition catalogs of four major world's fairs: the Crystal Palace Exhibition in London in 1851, the Centennial Exhibition in Philadelphia in 1876, the World's Columbian Exposition in Chicago in 1893, and the Panama-Pacific International Exposition in San Francisco in 1915. These fairs were among the most prominent events of their time (Table 1). In 1851, the Crystal Palace, a 1,848-foot-long greenhouse of cast iron and glass, was the largest enclosed space on earth (Frampton 1983, p. 11). At a time when London had fewer than 2 million inhabitants, it welcomed 6 million visitors and 17,062 exhibitors from 40 countries (BKDZR 1853, p. 674; Kretschmer 1999, p. 101; Kroker 1975, p. 146).[7] The 1876 Centennial Exhibition and the series of U.S. world's fairs that followed were the American response to the Crystal Palace fair. In 1876, exhibitors would walk 22 miles to see the six largest halls of the Centennial Exhibition; 30,864 exhibitors from 35 countries displayed their innovations, and almost 10 million people visited the fair (Kroker 1975, p. 146). In 1893, the World's Columbian Exposition covered 717 acres of land and water in Jackson Park by Lake Michigan, including 49 acres of exhibition space for 70,000 exhibitors from 45 countries. It attracted 27.5 million visitors. In 1915, the entire Marina and Presidio area in San Francisco (by today's Golden Gate Bridge) was converted to a fairground; it welcomed 30,000 exhibitors from 32 countries. Nineteen million visitors attended the San Francisco exposition.

Exhibition data are drawn from catalogs that guided visitors through the fairs. Catalogs include the exhibitor's name, location, and a description of the innovation, for example, "406, Fourdrinier, E. N., 38 Barclay St., Sunderland, Patent safety apparatus, for preventing loss of life and destruction of property when a rope or chain breaks in shafts of mines and collieries" (Royal Commission 1851).

[7] Revenues from entry fees in 1851 endowed several public institutions, including the Victoria and Albert Museum and Royal Albert Hall (Auerbach 1999, pp. 199–200).

Table 1

Statistics for the World's Fairs of 1851, 1876, 1893, and 1915

	Crystal Palace	Centennial	World's Columbian	Panama-Pacific
Location	London	Philadelphia	Chicago	San Francisco
Year	1851	1876	1893	1915
Countries	40	35	45	32
Exhibitors	17,062	30,864	70,000	30,000
Visitors	6,039,195	9,892,625	27,500,000	19,000,000
Area (in acres)	25.7 for exhibition buildings	71.4 for buildings and grounds	717 for grounds; 49 for buildings	635 for buildings and grounds
Prominent exhibits	MacCormick's grain reaper, Colt's revolving handgun, steam engines, typewriter	Corliss steam engine, telephone, Edison's quadruplex telegraph	Electric escalator, electric elevated railway, floodlights, Ferris wheel	Two-color photography, Ford's conveyer belt, a phone line from San Francisco to New York

Sources. Data are from BKDZR (1853) and Kretschmer (1999).

Other examples include Cyrus McCormick's Virginia grain reaper (U.S. exhibit 73 in 1851) and Samuel Colt's revolving cylinder handgun (U.S. exhibit 321). Chemical exhibits included innovations such as "refined Indian blue," and a "newly invented black dye, particularly recommended for silk" (Britain's exhibits 78 and 69, respectively). Innovations in manufacturing machinery included improvements in power-loom lathes for the machine shops at Lowell (U.S. exhibit 447) and the first sewing machines (U.S. exhibit 551, by S. C. Blodgett).[8] Carefully checked by a scientific committee, the *Official Catalogue* (Royal Commission 1851) became a "book of reference to the philosopher, merchant, and manufacturer" (Auerbach 1999, p. 94).

The data consist of 8,079 American and British innovations between 1851 and 1915. For 1851, they include all 6,377 British and all 550 U.S. exhibits. Exhibits are divided into 10 mutually exclusive industry classes that span the entire spectrum of production: mining and metallurgy, chemicals, food processing, engines, manufacturing machinery, civil engineering, agricultural machinery, instruments, manufactures, and textiles.[9] For 1876, 1893, and 1915, the data comprise all U.S. exhibits in two industries—chemicals and manufacturing machinery—yielding a total of 324 exhibits in chemicals and 860 in manufacturing machinery.

2.1. The Process of Selecting Exhibits

In a "remarkably comprehensive national organization" (Auerbach 1999, p. 87), commissioners systematically visited cities and rural areas to advertise the fairs and set up local commissions (BKDZR 1853, pp. 40, 64; Auerbach 1999, p. 55). In Britain, 65 local commissions formed more than 300 subcommissions to advertise the Crystal Palace (Auerbach 1999, p. 32).[10] National newspapers, including *The Times, The Economist, The Sun,* and *Scientific American,* advertised the fairs in regular features (for example, *The Times,* November 14, 1850; November 20, 1850; December 9, 1850; December 9, 1850; December 30, 1850).

As a result, competition to enter the exhibition was fierce. Prospective exhibitors had to show that their invention was "novel and useful" (BKDZR 1853, pp. 37, 90). In 1851, fewer than 30 percent of applicants were admitted (BKDZR 1853, pp. 50, 117). Local committees selected exhibits in the first round; their submissions competed at the national level. National committees selected innovations to represent their country in a hard-fought "contest of industries" to which Britain had "challenged the world" (Kretschmer 1999, pp. 46–48; Auerbach

[8] Unfortunately, there are no catalogs of comparable quality for fairs after 1915. For the Century of Progress Exposition in Chicago in 1933, the only available catalog is for art. For the New York World's Fair in 1939, the only catalog is for the Polish Pavilion, which became a site of pilgrimage after Germany invaded Poland (Kretschmer 1999, p. 216).

[9] This classification is based on the original Crystal Palace system, which was developed by a team of scientists over the course of several months (Auerbach 1999, p. 92).

[10] Local commissions paid more than half of the initial expenses in 1851 and were actively involved in the organization of the fair (Auerbach 1999, pp. 55–56).

1999, pp. 68, 78, 189).[11] Because of its rigorous selection process, the Crystal Palace fair became a "veritable acting industrial encyclopaedia" (Tallis 1852, p. 234). After it closed, many exhibitors were able to secure large orders, as universities, scientists, and museums competed to purchase exhibits (Auerbach 1999, pp. 105, 120). For example, representatives from the University of Edinburgh made several trips to London to purchase machinery, a model of a bridge, and a marine oscillating engine (Auerbach 1999, p. 244). One agricultural firm received £5,000 in orders for equipment (Clark 1851, p. 124), equivalent to £564,000 in 2010.[12]

2.2. U.S. and British Exhibits with and without Patents

The most important benefit of the exhibition data is that they include innovations with and without patents, while existing sources are largely limited to measuring patented innovations.[13] For British exhibits at the Crystal Palace, patented innovations can be identified directly from the catalogs. For example, Fourdrinier's "Patent safety apparatus, for preventing loss of life and destruction of property" was patented. Entries were self-reported but thoroughly checked by jurors and the scientific committee (Auerbach 1999, p. 242).

American exhibits are matched with patent records in the *Annual Reports of the United States Patent Office:* for example, "U.S. exhibit 23; Otis, B. H.; Cincinnati, Ohio; Boring and mortising machine" (Royal Commission 1851) and "U.S. patent No. 4387; Otis, Benjamin H.; Dedham, Mass; Mortising machine; granted Feb. 20, 1846" constitute a match. To capture as many patents as possible, patents are counted as a match as long as they are related to the exhibit. For example, U.S. exhibit 524, G. Borden's meat biscuit, is matched with Gail Borden's patent for the preparation of portable soup bread, a process to preserve the nutrients of meat and vegetables in a breadlike substance (U.S. patent 7,066, granted February 5, 1850).[14] Exhibits are also matched with assignments at issue, which occurs when inventors sell patents to another individual or firms before they are issued.

Exhibition data also capture the entire range of industries, which makes it possible to examine variation in the use of patents across industries. By contrast, historical analyses of patent data typically focus on a small number of industries.

[11] Contemporaries confirm this in personal communications. A Scottish engineer, for example, wrote in his diary that international hostilities were displaced by honest competition of industries at the Crystal Palace (Auerbach 1999, pp. 68–69).

[12] Using the gross domestic product deflator as a conservative measure (Officer and Williamson 2011).

[13] A notable exception is Williams (2010), which links precisely measured scientific progress in the decoding of the human genome with intellectual property rights.

[14] The U.S. patent data were collected by manually searching the full text of the U.S. Patent and Trademark Office's patent documents (http://www.google.com/patents). To check the data, I also looked up each of the 550 U.S. exhibits in 1851 in 20 printed volumes of the U.S. Patent and Trademark Office's *Annual Reports* (1841–61). The two data sets match exactly for the 1850s, but Google misses two patents in the 1840s, probably because of poorer image quality for that decade.

Comparative studies have to omit entire industries because patents are classified by function rather than by industry, and many important inventions cannot be assigned to a specific industry.[15] For example, Schmookler (1972) excludes power plants and electric motors from his study of demand effects because he cannot assign patents for power plants and motors to a specific industry. In the exhibition data, this problem is solved by classifying exhibits according to their industries of use and creating separate classes for engines and other innovations that could be used across industries.

2.3. Prizes as a Proxy for the Quality of Innovations

Exhibition data also include information about prizes, which I use as a measure for the quality of innovations.[16] International panels of six to 12 prominent business people and academics (including, for example, Justus von Liebig [in chemistry] and Hector Berlioz [for musical instruments]) ranked all exhibits according to their "novelty and usefulness" (BKDZR 1853, pp. 37, 90). In 1851, juries awarded gold (council) medals to 1 percent, silver (prize) medals to 18 percent, and bronze (honorable mention) medals to 12 percent of exhibits (BKDZR 1853, p. 707; Haltern 1971, p. 155). All prizes are listed in the reports of the German commission (BKDZR 1853) and can be matched with exhibits in the British catalogs using the exhibit's number, the exhibitor's name, and the description of the exhibit. Fourdrinier, for example, won a silver medal: "Prize medal. Fourdrinier, England. A safety cage for mines." The data include 1,759 British and 112 American award-winning exhibits in 1851.

2.4. Urban versus Rural Innovations

I constructed measures for urbanization by locating exhibits on nineteenth-century maps and matching locations with population data from the census. Historical gazetteers, such as *Bartholomew's Gazetteer of the British Isles* (Bartholomew 1887), identify towns whose names or borders have changed. The data include measures of city size for 5,317 (83.4 percent) of British exhibits. Because cities and towns with missing data are likely to be small, they are included with towns with fewer than 10,000 people. The results are robust to dropping these observations. Exhibits from London are defined as originating within the

[15] As a result, patent classes include innovations from a broad range of industries. For example, the class "dispensing solids" combines toothpaste tubes with manure spreaders (Schmookler 1972, p. 88).

[16] A well-documented problem with patent data is the large degree of variation in the quality of patented inventions (Griliches 1990, p. 1669; Dutton 1984, pp. 6–7). Counts of citations by later patents are the standard measure for the quality of patents (Hall, Jaffe, and Trajtenberg 2005). Trajtenberg (1990) establishes a robust positive correlation between counts of citations and the social value of patented improvements in equipment for computer tomography. Moser, Ohmstedt, and Rhode (2011) find a strong positive correlation between counts of citations and the size of patented improvements in hybrid corn. Citations may, however, be less useful as a measure for variation in the quality of patents across industries if the share of innovations that are patented varies across industries.

county (rather than the city) of London to include districts of today's London, such as Clerkenwell and Islington.

2.5. Bias and Measurement Error

Most important, the exhibition data underestimate the number of innovations that are protected by secrecy. Inventors may have been reluctant to exhibit such innovations because displaying them might threaten the effectiveness of secrecy (Cole 1884, pp. 242–43). Exhibitors, however, found ways to display their innovations without divulging trade secrets by showing samples of output rather than the innovation itself. For example, Drewsen & Sons of Silkeborg in Jutland, Denmark, exhibited specimens of paper, glazed by a machine constructed by the exhibitor, instead of the machine itself (Royal Commission 1851, p. 210). The British government also created a cheap and easy registration system to offer "Protection from Piracy to Persons exhibiting new Inventions."[17] Only 600 exhibitors, fewer than 3.3 percent of Crystal Palace exhibitors, took advantage of this system (Purbrick 1997), which suggests that most exhibitors continued to prefer secrecy. If, however, exhibitors withheld innovations that they protected by secrecy, the data overestimate the share of innovations that were patented.

The data may also underreport process innovations, which are more likely to be protected by secrecy instead of patents. Surveys of twentieth-century research laboratories indicate that inventors consider secrecy to be substantially more effective than patents as a mechanism to protect process innovations (Cohen, Nelson, and Walsh 2000). Firms may also be able to exploit process innovations more easily internally and therefore be less motivated to advertise them at exhibitions. Restrictions on displaying prices may have further discouraged the display of cost-saving process innovations (*The Times,* December 5, 1850).

Another potential problem is that the definition of what constitutes a patentable invention may have varied across industries and over time. This type of bias would be most severe if there was an increase in the patentability of U.S. chemical innovations after 1876. Chemical innovations, however, were patentable in both Britain and the United States until the end of World War I, when Britain limited protection for chemicals to allow British firms to copy German inventions (Davenport 1979, p. 29).[18]

In fact, exhibition data may underestimate the real increase in chemical pat-

[17] This system was created under the Protection of Inventions Act of April 11, 1851 (14 and 15 Vict. c. 8).

[18] "After the First World War, it was evident that the United Kingdom pharmaceutical industry lagged far behind that in Germany. To help the United Kingdom industry catch up, the 1919 Act introduced two measures designed to lessen the effectiveness of patents relating to food and medicines. The first was to prohibit the claiming of a chemical compound, regardless of how it had been prepared: it could only be claimed as the product of a particular process." Thus, a patentee could "no longer control the entire manufacture and importation of a compound" (Davenport 1979, p. 26). The second measure was the compulsory licensing of enemy-owned patents. In the United States, compulsory licensing of German-owned patents after World War I led to a 20 percent increase in patenting by domestic U.S. inventors (Moser and Voena 2012).

enting over time. Under U.S. law, individual inventors can assign their patents to firms that want to market them. Such assignments were rare in the mid–nineteenth century but became increasingly common over time. For example, only one in 454 patents granted to Connecticut inventors between 1837 and 1851 was assigned at issue, which suggests that this problem is negligible for cross-sectional data in 1851.[19] By 1876, however, one in three patents was assigned at issue. If assignments are harder to match with exhibits, the data may underestimate increases in patenting over time. This bias is particularly strong in chemicals, where the share of companies among all U.S. exhibits increased from 15 percent in 1851 to 44 percent in 1876 and to 85 percent in 1915.

Another concern is that patenting rates in resource-based industries, such as food processing and mining, may be low because resources could not be patented. Exhibits in both industries focused on patentable innovations, such as meat extracts, infant formula, or mining equipment (Thomson 2009, pp. 207–8; Auerbach 1999, p. 99), which mitigates this concern. Low patenting rates in mining and metallurgy are also consistent with accounts of collective invention in the British mining and iron industries (Allen 1983; Nuvolari 2004), which suggest that firms shared knowledge of improvements without patenting them.[20]

Finally, the data may underestimate large and heavy innovations that were too costly to transport to the fairs, even though exhibitors only paid for transport to local collection points (BKDZR 1853). Exhibition records suggest that some inventors avoided high transportation costs by exhibiting models or blueprints of their innovations. For example, the suspension bridge that was being constructed across the Dnieper River in Kiev was exhibited as a model at the Crystal Palace (Rolt 1970, p. 157). In 1851, 45 percent of 194 British exhibits in the technology class Civil Engineering, Architecture, and Building Contrivances were represented by models.[21]

3. Cross-Sectional Evidence

The first part of the empirical tests uses data on British and U.S. exhibits at the Crystal Palace fair of 1851 to measure variation in the share of innovations

[19] This count is based on the total number of patents issued or assigned to residents of the state of Connecticut, including patents issued or assigned to companies, from *Annual Reports of the United States Comissioner of Patents* (1836–76).

[20] Exhibits of art, which would generally not be patentable, are excluded from the analysis, even though the organizers encouraged submissions only if they were "connected with mechanical processes" (Royal Commission 1851, p. 819).

[21] To check for bias due to transportation costs, I compare the locations of origin of British exhibits at the Crystal Palace with the locations of origin of all 835 British exhibits at the Centennial Exhibition in Philadelphia in 1876. If transportation costs mean more exhibits originate from London, London's share of innovations should be lower at the U.S. fair when differences in transportation costs within Britain were negligible relative to total transportation costs. London's share of exhibits, however, was almost identical in 1851 and 1876, at 40.7 and 39.1 percent, respectively.

Table 2
Patenting Rates for British and U.S. Exhibits, 1851

	Exhibits	Patented Exhibits		Patent Fee ($)
		N	%	
Britain	6,377	708	11.1	37,000
United States	550	84	15.3	618

Sources. Data on exhibits were collected from Royal Commission (1851).
Note. Patenting rates are calculated as the share of exhibits that are patented. For Britain, patented exhibits are identified from references to patents in Royal Commission (1851), for the United States, by matching exhibits with patents in U.S. Commissioner of Patents (1841–51). Patent fees are in year 2000 U.S. dollars (Lerner 2000) and are calculated for a patent carried to full term.

that were patented across countries, quality levels, rural versus urban locations, and industries.

3.1. Patenting Rates

Exhibition data indicate that the large majority of nineteenth-century innovations were not patented. In 1851, 89 percent of British exhibits were without patents (Table 2). This is especially remarkable considering that the exhibition data are likely to miss many innovations without patents, including processes and other innovations that were protected by secrecy.

3.2. Britain versus the United States

Comparisons of U.S. and British data also show that the share of innovations with patents was relatively unresponsive to differences in patent laws. In the United States, where patents were significantly cheaper and more effective (Dutton 1984; MacLeod 1988; Lamoreaux and Sokoloff 1999), 15.3 percent of innovations were patented, compared with 11.1 percent in Britain (Table 2). Although this difference is statistically significant, it implies a low elasticity of patenting with respect to differences in patent laws. When the fees of $37,000 in Britain and $618 in the United States are compared, the elasticity of patenting with respect to the cost of patenting is .38.[22]

Why are patenting rates so similar in Britain and the United States? One potential explanation for these results is that the real costs of patenting, accounting for the expected costs of disclosure and litigation, may be substantially higher than filing fees suggest. Prior to 1836, when the Patent Act reestablished the examination system, the U.S. law "allowed anyone to claim patents even for manifest copies . . . and true inventors had little advantage until litigation was complete" (Thomson 2009, p. 192). After 1836, inventors became increasingly dependent on the services of patent agents, who charged up to double the cost

[22] With British patenting rates and fees as a reference point, the elasticity is (.153 − .111)/.111 over ($618 − $37,000)/$37,000, which equals .38.

Table 3
Patenting Rates: Average-Quality versus Award-Winning British Exhibits, 1851

	All Exhibits		Award Winners	
Industry	*N*	% Patented	*N*	% Patented
Mining and metallurgy	418	5.0	74	5.4
Chemicals	136	5.1	75	8.0
Food processing	140	7.9	73	9.6
Engines	406	24.6	80	38.8
Manufacturing machinery	242	29.8	70	47.1
Civil engineering	559	13.4	88	15.9
Agricultural machinery	261	19.9	37	40.5
Scientific instruments	581	9.6	139	15.8
Manufactures	1,955	10.2	601	16.3
Textiles	1,679	6.8	522	8.6
All	6,377	11.1	1,759	15.6

Note. For Britain, innovations with patents are identified as innovations whose descriptions in the exhibition catalog refer to a patent. Awards are exhibits that received a prize for exceptional "novelty and usefulness" (BKDZR 1853, pp. 37, 90). Exhibitors were matched with lists of award winners in the report of the German commission to the Crystal Palace (BKDZR 1853).

of patent fees for their services ($526–$1,052 in 2009 U.S. dollars, using the gross domestic product deflator as the most conservative measure [Thomson 2009, p. 194]).

Another factor is that the United States granted patents only to "first and true" inventors, while Britain also granted patents to first importers (Coryton 1855, pp. 235–64). First-to-file rules may encourage inventors to apply for patents at an earlier stage of the innovation process (Scotchmer and Green 1990) and thereby may have driven up patenting rates in Britain relative to the United States.

3.3. High versus Low Quality

Exhibition data also indicate that high-quality innovations are more, rather than less, likely to be patented. Sixteen percent of award-winning British exhibits were patented, compared to 11 percent of all exhibits (Table 3). This result contradicts theoretical predictions for cost-saving process innovations, which should be less likely to be patented if they are more valuable (Anton and Yao 2004). Exhibition data, however, are more likely to capture product innovations (as described in Section 2), and for product innovations different factors may determine patenting.

3.4. Urban versus Rural

In Britain, urban inventors were consistently more likely to patent: 12 percent of exhibits from towns with more than 10,000 people were patented, compared with 7 percent in rural areas (Table 4). Urban patenting rates exceed rural rates across all industries. For example, 31 percent of urban exhibits in manufacturing

Table 4
Patenting Rates in Urban and Rural Britain

	London		Large Cities		Small Cities		Urban		Rural	
Industry	*N*	% Patented	*N*	% Patented	*N*	% Patented	*N*	% Patented	*N*	% Patented
Mining and metallurgy	64	18.8	47	4.3	153	2.0	264	6.4	154	2.6
Chemicals	49	6.1	30	6.7	27	7.4	106	6.6	30	0.0
Food processing	44	11.4	22	.0	33	12.1	99	9.1	41	4.9
Engines	185	27.0	85	24.7	89	27.0	359	26.5	47	10.6
Manufacturing machinery	71	28.2	81	29.6	49	36.7	201	30.8	41	24.4
Civil engineering	251	18.3	79	19.0	113	6.2	443	15.4	116	6.0
Agricultural machinery	53	32.1	45	13.3	96	20.8	194	22.2	67	13.4
Instruments	331	12.1	88	8.0	90	3.3	509	9.8	72	8.3
Manufactures	836	11.8	504	9.3	376	9.0	1,716	10.5	239	8.0
Textiles	608	6.9	446	5.8	416	8.2	1,470	6.9	209	6.2
All	2,492	13.4	1,427	10.5	1,442	10.3	5,361	11.8	1,016	7.4

Source. Data are from Royal Commission (1851).
Note. Innovations with patents are identified in the descriptions of exhibits in Royal Commission (1851). Innovations were matched with location data using nineteenth-century maps and gazetteers. Large cities are those with more than 100,000 inhabitants, and small cities are those with 10,000–100,000 inhabitants. Cities with more than 10,000 inhabitants are considered urban, and towns with fewer than 10,000 inhabitants are considered rural.

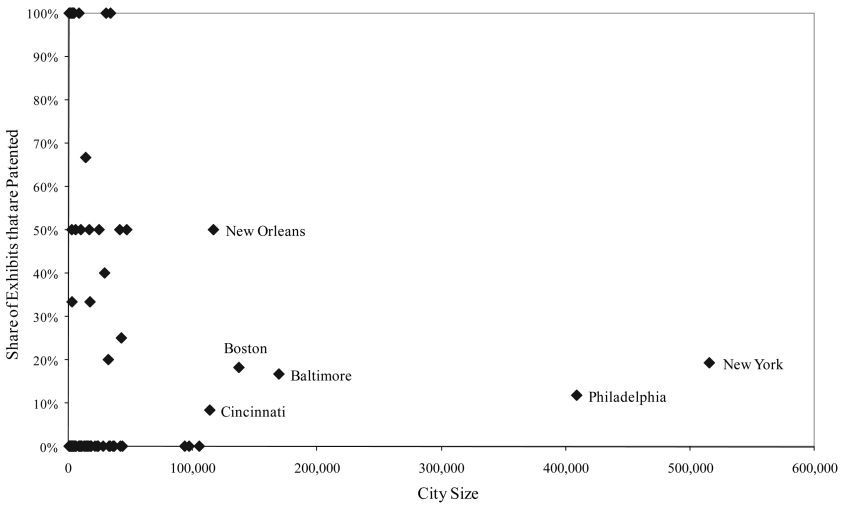

Figure 1. City size and share of innovations with patents in the United States, 1851

machinery were patented, compared with 24 percent of rural exhibits; 27 percent of urban exhibits in engines were patented, and 22 percent in agricultural machinery, compared with 11 and 13 percent of rural exhibits, respectively.

There is, however, no clear relationship between city size and patenting. In five of 10 industries (mining and metallurgy, engines, agricultural machinery, instruments, and manufactures), innovations from London were more likely to be patented. In the remaining industries, the correlation between patenting and city size is sometimes negative. With regard to manufacturing machinery, exhibits from London were less likely to be patented than exhibits from other cities (28 percent in London, 30 percent in other cities with populations greater than 100,000, and 37 percent in cities with populations between 10,000 and 100,000).[23]

In the United States, however, rural exhibits were more likely to be patented than were urban exhibits (except for exhibits from New York), which suggests that easy access to the patent system, such as the ability to mail applications, may have encouraged patenting among rural inventors. As in the British data, there is no obvious relationship between patenting and city size: 16 percent of rural innovations were patented, compared with 19 percent in New York, 15 percent in other large cities, and 10 percent in smaller cities (Figure 1).

3.5. Patenting Rates across Industries

The most significant variation in the share of innovations that are patented, however, occurs across industries. Patenting rates are highest in the manufac-

[23] Alternative categorizations of city size (such as 50,000, 10,000, or 1,000) yield similar results.

Table 5
Patenting Rates by Industry: British versus U.S. Exhibits, 1851

	British		U.S.	
Industry	*N*	% Patented	*N*	% Patented
Mining and metallurgy	418	5.0	52	7.7
Chemicals	136	5.1	32	.0
Food processing	140	7.9	70	7.1
Engines	406	24.6	31	42.0
Manufacturing machinery	242	29.8	32	43.8
Civil engineering	559	13.4	17	23.5
Agricultural machinery	261	19.9	27	37.0
Scientific instruments	581	9.6	74	16.2
Manufactures	1,955	10.2	98	15.3
Textiles	1,679	6.8	117	6.0
All	6,377	11.1	550	15.3

Note. For Britain, patented exhibits are identified as innovations whose descriptions in the exhibition catalog (Royal Commission 1851) refer to a patent. For the United States, patented exhibits were identified by matching exhibits with their patent records in U.S. Commissioner of Patents (1841–51).

turing machinery: in 1851, 30 percent of British exhibits in manufacturing machinery were patented, as were 25 percent of exhibits of engines, and 20 percent of agricultural machinery (Table 5).

By comparison, only 5 percent of chemical exhibits were patented, 5 percent of exhibits in mining and metallurgy, 7 percent of exhibits in textiles, and 8 percent in food processing. Innovations in all of these industries were difficult to copy. Improvements in dyeing and bleaching featured prominently among nineteenth-century innovations in textiles; processes of preservation and secret recipes, such as the one for Coca-Cola, made up most innovations in food processing. Innovations in metallurgy depended on craft-based skills that proved impossible to imitate (Harris 1976, p. 49; Landes 1983, p. 283).

British and American inventors obtained patents in the same industries. Patenting rates were especially high for U.S. innovations in machinery (44 percent for manufacturing machinery, 42 percent for engines, and 37 percent for agricultural machinery) (see Table 5) and low for innovations in chemicals, textiles, food processing, and metallurgy (0, 6, 7, and 8 percent, respectively).

Award-winning innovations were also patented in the same industries. In fact, differences across industries are even stronger for award-winning exhibits. Forty-seven percent of exhibits in manufacturing machines were patented, as were 39 percent of exhibits in engines and 41 percent of exhibits in agricultural machinery, compared with 8 percent of exhibits in chemicals (Table 3). These results are consistent with a simple formalization of patenting decisions, in which the relative strength of patents and secrecy varies across industries and differences in the profitability of innovations amplify the effects of variation in the effectiveness of secrecy (not reported).

3.6. *Logit and Ordinary Least Squares Regressions*

A final test of the cross-sectional data estimates logit and ordinary least squares (OLS) regressions to measure the relative strengths of variation in quality, patent laws, and urbanization and across industries:

$$y = \alpha + \beta_1 \text{Award} + \beta_2 \text{USA} + \beta_3' \text{CitySize} + \beta_4' \text{Industry} + \beta_5' \text{Industry} \times \text{Award} + \varepsilon, \quad (1)$$

where the outcome variable y equals one for exhibits that are patented and zero otherwise.[24] The variable Award distinguishes award-winning exhibits, and USA separates American from British exhibits; CitySize is a vector of dummy variables that distinguish exhibits from London, other large cities (with more than 100,000 inhabitants), and small cities (with 10,000–99,999 inhabitants) from rural areas. The vector Industry includes nine industry dummies that distinguish innovations in mining and metallurgy, chemicals, food processing, engines, civil engineering, agricultural machinery, instruments, and textiles; other manufactures are the omitted control. The interaction term Industry × Award tests whether differences in the quality of innovations amplify industry effects.

Regression results presented in Table 6 confirm that industries are the most powerful predictor of patenting decisions. Marginal effects imply that exhibits of manufacturing machinery were 21 percent more likely to be patented (significant at 1 percent compared with manufactures as a control). Engines were 16 percent more likely to be patented, and agricultural machines were 14 percent more likely to be patented (significant at 1 percent). In contrast, exhibits of chemicals were 7 percent less likely to be patented (significant at 1 percent), and exhibits of textiles and food processing were 4 percent less likely to be patented (significant at 1 and 5 percent, respectively).

Table 6 also indicates that, compared with industry effects, the effects of variation in patent laws, quality, and urbanization are relatively small. Both award-winning exhibits and exhibits from the United States were 8 percent more likely to be patented (significant at 1 percent). Exhibits from London were 7 percent more likely to be patented (significant at 1 percent), while exhibits from other cities were 3 percent more likely to be patented compared with exhibits from rural areas (significant at 5 percent). Regressions that include state fixed effects and OLS regressions confirm the main results.

Regressions for a restricted data set of award-winning British exhibits confirm that variation across industries was even larger for high-quality exhibits (see Table 7). Award-winning exhibits of manufacturing machinery were 28 percent more likely to be patented (significant at 1 percent); award-winning engines were about 20 percent more likely to be patented (significant at 1 percent), and award-winning exhibits of agricultural machines were between 21 and 23 percent more

[24] The main specifications are estimated as logit regressions because robustness checks include state fixed effects; for regressions without state fixed effects, probit methods yield similar results.

Table 6

British and U.S. Exhibits, 1851: Logit and Ordinary Least Squares (OLS) Regressions

	Logit			OLS	
	(1)	(2)	(3)	(4)	(5)
Award	.081**	.081**	.099**	.080**	.080**
	(.010)	(.010)	(.020)	(.009)	(.009)
USA	.077**	.077**	.030	.069**	.032
	(.019)	(.019)	(.024)	(.015)	(.024)
London	.066**	.041**		.061**	
	(.013)	(.008)		(.011)	
Large city	.030*			.027*	
	(.013)			(.012)	
Small city	.030*			.026*	
	(.014)			(.012)	
Mining and metallurgy	−.036**	−.039**	.018	−.029+	−.0043
	(.013)	(.013)	(.030)	(.016)	(.020)
Chemicals	−.066**	−.066**	−.093**	−.08**	−.077**
	(.013)	(.013)	(.018)	(.025)	(.028)
Food processing	−.040*	−.042**	−.026	−.048*	−.038
	(.015)	(.015)	(.032)	(.023)	(.025)
Engines	.158**	.158**	.175**	.162**	.164**
	(.024)	(.024)	(.032)	(.016)	(.017)
Manufacturing machinery	.209**	.208**	.192**	.214**	.212**
	[.031]	[.031]	[.042]	[.020]	[.022]
Civil engineering	.048**	.045**	.082**	.047**	.063**
	(.017)	(.017)	(.025)	(.015)	(.016)
Agricultural machinery	.142**	.139**	.160**	.132**	.132**
	(.029)	(.028)	(.040)	(.020)	(.022)
Instruments	−.003	−.004	.002	−.003	.001
	(.013)	(.013)	(.019)	(.014)	(.015)
Textiles	−.038**	−.038**	−.022	−.035**	−.036**
	(.009)	(.009)	(.014)	(.010)	(.011)
Constant				.039**	.098**
				(.012)	(.009)
Award × Industry	No	No	Yes	No	No
State fixed effects	No	No	Yes	No	Yes
Observations	6,927	6,927	5,772	6,927	6,347
% Predicted correctly	88.6	88.6	87.3		
R^2				.06	.09
Pseudo-R^2	.08	.08	.10		

Sources. Data are from Royal Commission (1851), U.S. Commissioner of Patents (1841–51), and BKDZR (1853).

Note. The dependent variable is patented exhibits. Manufactures is the omitted industry; London and New York are the omitted states. An outcome is defined as correctly predicted if the predicted probability of patenting is at least .5 for a patented exhibit. Large cities are those with more than 100,000 inhabitants, and small cities are those with 10,000–100,000 inhabitants. Values presented for logit regressions are marginal effects. Standard errors are in parentheses.

+ Significant at 10%.

* Significant at 5%.

** Significant at 1%.

Table 7
British Award Winners, 1851: Logit and Ordinary Least Squares (OLS) Regressions

	Logit			OLS	
	(1)	(2)	(3)	(4)	(5)
London	.090**	.023		.076**	
	(.032)	(.018)		(.025)	
Large city	.060+			.047+	
	(.033)			(.026)	
Small city	.136**			.108**	
	(.042)			(.028)	
Mining and metallurgy	−.096**	−.097**	−.058	−.109*	−.051
	(.024)	(.025)	(.051)	(.044)	(.059)
Chemicals	−.071*	−.074*	−.074*	−.08+	−.084
	(.029)	(.029)	(.037)	(.043)	(.052)
Food processing	−.059+	−.059+	−.045	−.068	−.047
	(.031)	(.032)	(.045)	(.043)	(.051)
Engines	.186**	.197**	.198**	.217**	.217**
	(.054)	(.055)	(.063)	(.042)	(.046)
Manufacturing machinery	.278**	.282**	.270**	.307**	.309**
	(.063)	(.063)	(.074)	(.044)	(.051)
Civil engineering	.008	−.002	.044	.008	.036
	(.039)	(.037)	(.058)	(.040)	(.051)
Agricultural machinery	.206*	.231**	.250*	.233**	.224**
	(.082)	(.081)	(.127)	(.060)	(.077)
Instruments	−.01	−.011	−.012	−.011	−.013
	(.029)	(.029)	(.036)	(.033)	(.037)
Textiles	−.084**	−.079**	−.111**	−.086**	−.097**
	(.018)	(.018)	(.023)	(.021)	(.025)
Constant				.104**	.181**
				(.024)	(.020)
State fixed effects	No	No	Yes	No	Yes
Observations	1,759	1,759	1,399	1,759	1,579
% Predicted correctly	84.4	84.4	82.9		
R^2				.08	.15
Pseudo-R^2	.11	.09	.11		

Source. Data are from Royal Commission (1851) and BKDZR (1853).
Note. The dependent variable is patented exhibits. Manufactures is the omitted industry class; London is the omitted state. An outcome is defined as correctly predicted if the predicted probability of patenting is at least .5 for a patented exhibit. Large cities are those with more than 100,000 inhabitants, and small cities are those with 10,000–100,000 inhabitants. Values presented for logit regressions are marginal effects. Standard errors are in parentheses.
+ Significant at 10%.
* Significant at 5%.
** Significant at 1%.

likely to be patented (significant at 1 and 5 percent). By comparison, award-winning exhibits in chemicals were 7 percent less likely to be patented (significant at 5 percent).

Regressions for a restricted data set of U.S. innovations confirm that differences in patent laws had small effects compared with variation across industries. Most significant, American and British inventors obtained patents in the same industries, despite significant differences in patent laws. American exhibits of man-

ufacturing machinery were between 27 and 29 percent more likely to be patented (significant at 1 and 5 percent) (see Table 8 for marginal effects from logit regressions and for OLS regressions); engines were 28 percent more likely to be patented (significant at 1 and 5 percent), and agricultural machinery was roughly 21 percent more likely to be patented (significant at 5 and 10 percent). By contrast, none of the U.S. innovations in chemicals were patented, and chemicals are excluded from logit regressions.

Regressions of the U.S. data also confirm that high-quality innovations were significantly more likely to be patented. Award-winning exhibits from the United States were between 12 and 14 percent more likely to be patented (significant at 1 percent). Estimates for city size are close to zero and not statistically significant.

4. Difference-in-Differences Estimates

Why does the propensity to patent innovations vary so strongly across industries? Contemporary survey data indicate that secrecy plays an important role. An exogenous decline in the effectiveness of secrecy relative to patenting creates a unique opportunity for an empirical test.

4.1. Secrecy in the Chemicals Industry

In the 1850s, inventors of chemicals could rely on secrecy to protect their intellectual property. Chemical innovations were extremely difficult to copy; "processes were simple and crude; exact knowledge was circumscribed and operations proceeded empirically" (Haber 1958, p. 83). For example, European dyers were unable to copy the bright and fast red dyes from madder root that dyers in the Indus Valley had produced as early as 2600 B.C. With crude tools of chemical analysis, attempts at industrial espionage proved unsuccessful.[25] Other valuable dyes, such as indigo, which had been used as a burial offering since the second century A.D. and was worth its weight in gold, proved equally difficult to copy.

Secrecy, however, became substantially less effective after a series of scientific breakthroughs revolutionized chemical analysis. This process began in 1839, when Justus Liebig designed the first chemical research laboratory in Giessen, Germany. "Liebig . . . devised equipment which speeded up and simplified the procedure. The time taken for an analysis was cut from months or weeks to days" (Haber 1958, p. 64).

Liebig's laboratory became a blueprint for methods of analytic chemistry that

[25] In 1579, for example, the English dyer Morgan Hubblethorne was sent to Persia: "[T]hose cities and towns you must repair to, and you must use means to learn all the order of dyeing of those thrums, which are so dyed as neither raine, wine nor yet vinegar can staine" (Chenciner 2000, p. 182), but this attempt was unsuccessful. The production of madder red involved 30 secret steps, including steeping in rancid oil, soda, and sheep dung and dyeing in a batch of ox blood and chalk (Chenciner 2000, pp. 174–204).

Table 8

U.S. Exhibits, 1851: Logit and Ordinary Least Squares (OLS) and Logit Regressions

	Logit			OLS	
	(1)	(2)	(3)	(4)	(5)
Award	.137**	.140**	.109*	.121**	.095**
	(.049)	(.049)	(.046)	(.037)	(.035)
Large city	.012				
	(.034)				
Small city	−.046				
	(.037)				
Mining and metallurgy	−.047	−.054	.013	−.057	−.030
	(.048)	(.046)	(.071)	(.058)	(.063)
Chemicals				−.146*	−.142*
				(.069)	(.070)
Food processing	−.080*	−.085*	−.055	−.095+	−.089
	(.035)	(.034)	(.044)	(.053)	(.056)
Engines	.278*	.285**	.355**	.288**	.284**
	(.109)	(.108)	(.117)	(.070)	(.070)
Manufacturing machinery	.271*	.273**	.299**	.291**	.259**
	(.106)	(.106)	(.111)	(.069)	(.069)
Civil engineering	.054	.059	.153	.073	.094
	(.094)	(.097)	(.135)	(.089)	(.090)
Agricultural machinery	.219*	.203+	.233*	.221**	.175*
	(.109)	(.105)	(.117)	(.073)	(.076)
Scientific instruments	.004	.011	.051	.012	.012
	(.048)	(.050)	(.058)	(.052)	(.053)
Textiles	−.098**	−.099**	−.067+	−.097*	−.091+
	(.033)	(.034)	(.038)	(.046)	(.047)
Constant				.127**	.128**
				(.035)	(.041)
State fixed effects	No	No	Yes	No	Yes
Observations	518	518	442	550	538
% Predicted correctly	84.7	84.7	82.8		
R^2				.14	.21
Pseudo-R^2	.15	.14	.16		

Sources. Data are from Royal Commission (1851), U.S. Commissioner of Patents (1841–51), and BKDZR (1853).

Note. The dependent variable is patented exhibits. In logit regressions, chemicals have been excluded because none of the U.S. exhibits in chemicals were patented. Manufactures is the omitted industry class; New York is the omitted state. An outcome is defined as correctly predicted if the predicted probability of patenting is at least .5 for a patented exhibit. Large cities are those with more than 100,000 inhabitants, and small cities are those with 10,000–100,000 inhabitants. Values presented for logit regressions are marginal effects. Standard errors are in parentheses.

+ Significant at 10%

* Significant at 5%.

** Significant at 1%.

allowed other chemists to discover elements and determine their properties, such as atomic weight, density, and heat point. In 1865, the German chemist August Kekulé identified the chemical structure of the benzene ring (Kekulé 1865). Kekulé's model became widely used to analyze coal tar chemicals in the 1880s (Haber 1958, p. 81). In 1869, the Russian chemist Dmitrii Mendeleev recognized that chemical properties such as valence recur periodically if elements are organized by their atomic weight; he used this insight to arrange all known elements in the periodic table (Mendeleev 1869). Gaps in the periodic table allowed Mendeleev to predict five unknown elements; three of them were discovered shortly after 1869 (Asimov 1975, p. 410; Maher 1988, p. 274).[26]

As the crude empirical methods of early chemistry gave way to a deductive, science-based approach, it became increasingly difficult to protect new dyes through secrecy (Murmann 2003, p. 121). Madder red, for example, was synthesized in the 1870s. In 1869, Carl Graebe and Carl Lieberman managed to produce alizarin, one of the key components of madder red. In 1876, Charles Strobel and Heinrich Caro synthesized alizarin orange; in 1878, Rudolf Nietzki reproduced the scarlet shades of madder (Brunello 1973, p. 301).

Indigo became amenable to chemical analysis and patenting in the 1880s. On December 27, 1881, the U.S. Patent Office granted patent 251,671 for the "Preparation of New Material for the Manufacture of Artificial Indigo" to Adolph Baeyer of Badische Anilin and Soda Fabrik. Baeyer had been able to specify the exact chemical structure of indigo (ortho-dinitro-diacetenyl-phenyl) and included it in his patent application. On July 29, 1890, the U.S. Patent and Trademark Office granted patent 432,989 for a dye of a fine indigo blue shade to Carl Duisberg of the German Farbenfabrik. Duisberg's patent included an atomic model of the improved dye, which illustrates how scientific progress also increased the effectiveness of patents by making it easier to precisely describe a chemical invention.

4.2. A Shift toward Patenting

Did this change encourage inventors to use patents? Data on U.S. exhibits at world's fairs in 1851, 1876, 1893, and 1915 show a marked increase in the share of innovations that were patented. In 1851, none of the U.S. chemical exhibits were patented (Table 9). In 1876, only 7 years after the publication of the periodic table, 3.6 percent were patented.[27] In 1893, 19.0 percent of U.S. chemical exhibits were patented, and in 1915, 18.9 percent of U.S. chemical exhibits were patented. Thus, the share of chemical exhibits with patents increased by a factor of 5 in 1893 and 1915, compared with 1876, which suggests a significant effect of secrecy.

[26] Reflecting its importance, the periodic table was immediately translated into German, to make it accessible to other chemists (Scerri and Worrall 2001, p. 414).

[27] This relatively small initial change is consistent with the idea that applications of scientific theories may take several years to translate into practice. Bowers (1895, p. 431) describes this phenomenon for the late-nineteenth-century manufacture of soda salts: "Theory has marked out a number of paths, but practice has not yet succeeded in following any of these to a satisfactory result."

Table 9
Patenting Rates: U.S. Exhibits of Chemicals and Manufacturing Machinery, 1851–1915

	1851	1876	1893	1915	All Years
Chemicals:					
Share patented (%)	.0	3.6	19.0	18.9	
Exhibits	32	139	63	90	324
Manufacturing machinery:					
Share patented (%)	43.8	44.0	49.4	47.1	
Exhibits	32	468	358	34	892
Both industries	64	607	421	124	1,216

Sources. Data on exhibits are from Royal Commission (1851), U.S. Centennial Commission (1876), World's Columbian Exhibition (1893), and Panama-Pacific International Exhibition Company (1915).
Note. Patenting rates are calculated as the share of exhibits that are patented per industry and year. Patented exhibits were identified by matching exhibits with patent records in the *Annual Report of the United States Commissioner of Patents* (http://www.google.com/patents).

4.3. Manufacturing Machinery as a Control

Although this increase is suggestive, it does not establish causality because unobservable factors, such as changes in the U.S. patent system, may have encouraged patenting across industries, independent of changes in the effectiveness of secrecy. For example, the rising number of professional patent attorneys in late-nineteenth-century New England may have encouraged patenting across industries by creating a market for patented inventions (Lamoreaux and Sokoloff 1999) or by increasing the risks of litigation for inventors without patents.

To control for such factors, I compare changes in patenting rates for chemicals, with manufacturing machinery as a control. Innovations in manufacturing machinery were easy to reverse engineer throughout this period, and secrecy was ineffective. For example, it took Isaac Singer less than 2 weeks in the 1850s to reverse engineer a sewing machine that his competitors, Lerow and Blodgett, had invented (Scott 1880, p. 8).[28] New England mechanics throughout the nineteenth century "made a pilgrimage to England, still the fountainhead of mechanical innovation, in order to acquire technical sophistication (and sometimes to steal industrial secrets and entice away English mechanics). The visits to England of Francis Lowell, who here gained knowledge of the working principle of the power loom, and of Joshua and Thomas Gilpin, who studied textile and papermaking machinery, were well known in their day. Lowell's trip resulted in the Waltham loom and the great industrial growth at Lowell. Gilpin patented his imitation of John Dickinsons' endless papermaking machine (the first introduction of continuous papermaking in America)" (Wallace 1978, p. 217).[29]

[28] Singer then used patents to help turn the sewing machine into one of the nineteenth century's most profitable innovations (Cooper 1968, pp. 13, 42; Lampe and Moser 2010). See Dragon (1995, p. 222) and Korman (2002, pp. 26, 127–28) for additional examples that illustrate the risks of secrecy in the manufacturing machinery industry.

[29] Also see Landes (1983, p. 277): "All a good Swiss maker needed was one example of a British machine and he could make his own with some improvements thrown in."

4.4. *Difference in Differences*

A difference-in-differences comparison of changes in patenting rates for chemicals and manufacturing machinery makes it possible to isolate the effects of secrecy from unobservable factors, such as changes in the patent regime. Both industries were influenced by changes in the institutional environment, but only the chemical industry was influenced by changes in the effectiveness of secrecy relative to patenting. This comparison reveals that the shift toward patenting was unique to chemicals. While the share of patented exhibits in chemicals increased from 0 percent in 1851 and 3.7 percent in 1876 to 19 percent in 1893 and 1915, the share of patented exhibits in manufacturing machinery stayed roughly constant. In 1851, 43.8 percent of exhibits in manufacturing machinery were patented; in 1876, 44.0 percent were patented; in 1893, 49.4 percent were patented, and in 1915, 47.1 percent of exhibits in manufacturing machinery were patented (see Table 9). Using 1876 as a baseline for both industries, this translates to a 5.3-fold increase in the share of patented innovations for chemicals, compared with a 1.1-fold increase in manufacturing machinery.

In difference-in-differences regressions,

$$y = \alpha + \beta_1 \text{Chemicals} + \beta_2 1851 + \beta_3 1893 + \beta_4 1915 + \beta_5 \text{Chemicals} \times 1893 + \beta_6 \text{Chemicals} \times 1915 + \varepsilon. \quad (2)$$

The term Chemicals distinguishes exhibits of chemicals from manufacturing machinery, and the indicator variables 1851, 1893, and 1915 measure changes in the share of patented exhibits over time; data for the American Centennial Exhibition in 1876 form the omitted comparison group. Under the assumption that patenting rates for innovations in chemicals and manufacturing machinery would not have been systematically different without scientific progress in chemicals, the difference-in-differences estimators Chemicals × 1893 and Chemicals × 1915 measure the causal effects of secrecy on patenting.

An estimated marginal effect of −.468 for Chemicals implies that chemicals were 47 percent less likely than manufacturing machinery to be patented across all years (significant at 1 percent) (Table 10). An estimated marginal effect of .385 for Chemicals × 1893 implies that patenting rates increased 39 percent more for chemicals than manufacturing machinery in 1893 (significant at 1 percent). An estimated marginal effect of .403 for Chemicals × 1915 implies that patenting rates increased 40 percent more for chemicals than manufacturing machinery in 1915 (significant at 1 percent).

Table 10 shows that these effects cannot be explained by variation across locations. In regressions with state fixed effects, the estimate for Chemicals is −.463, and estimates for Chemicals × 1893 and Chemicals × 1915 are .373 and .428, respectively (significant at 1 percent). In specifications with controls for Massachusetts, New York, and Pennsylvania, which were most affected by the growing number of professional patent agents, estimates are .035, .050, and .000, respectively (not significant), and do not affect the main results. The es-

Table 10
U.S. Exhibits, 1851–1915: Logit Regressions

	(1)	(2)	(3)	(4)	(5)	(6)
Chemicals	−.468**	−.463**	−.468**	−.481**	−.476**	−.481**
	(.038)	(.038)	(.038)	(.035)	(.035)	(.035)
1851	−.002	−.011	−.020			
	(.082)	(.085)	(.081)			
1893	.049	.075*	.049			
	(.032)	(.035)	(.033)			
1915	.028	.095	.027			
	(.082)	(.093)	(.082)			
Chemicals × 1893	.385**	.373**	.378**			
	(.121)	(.122)	(.122)			
Chemicals × 1915	.403**	.428**	.403**			
	(.132)	(.132)	(.132)			
Post-1876				.0455	.074*	.047
				(.029)	(.033)	(.030)
Chemicals × Post-1876				.429**	.454**	.427**
				(.108)	(.106)	(.108)
Massachusetts			.035			.033
			(.042)			(.041)
New York			.050			.047
			.041			(.040)
Pennsylvania			−.000			.002
			(.040)			(.038)
State fixed effects	No	Yes	No	No	Yes	No
Observations	1,184	1,170	1,184	1,216	1,213	1,216
% Predicted correctly	62.2	65.3	63.7	63.2	66.1	64.7
Pseudo-R^2	.10	.11	.10	.12	.14	.12

Sources. Data are from Royal Commission (1851), U.S. Centennial Commission (1876), World's Columbian Exhibition (1893), and Panama-Pacific International Exhibition Company (1915).
Note. Values presented are marginal effects. The dependent variable patented exhibits. Patented innovations are identified by matching exhibits in Royal Commission (1851) with patent records in the *Annual Report of the United States Commissioner of Patents* (1831–1935) (http://www.google.com/patents). In regressions with state fixed effects, New York is the omitted state. Standard errors are in parentheses.
* Significant at 5%.
** Significance at 1%.

timate for Chemicals is −.468, and estimates for Chemicals × 1893 and Chemicals × 1915 are .378 and .403 (significant at 1 percent), nearly identical to estimates without controls for these states. Regressions that split the sample in years before and after 1876 (instead of distinguishing individual years) and OLS regressions (not reported) yield comparable results.

5. Tests with Alternative Sources of Data

Tests with alternative sources confirm this shift toward patenting in chemicals. Data on changes over time in the lag between patenting and invention suggest that inventors waited up to 40 years to patent dyes that had been discovered between 1851 and 1876 (Figure 2). In the 1860s, the average lag was 28 years,

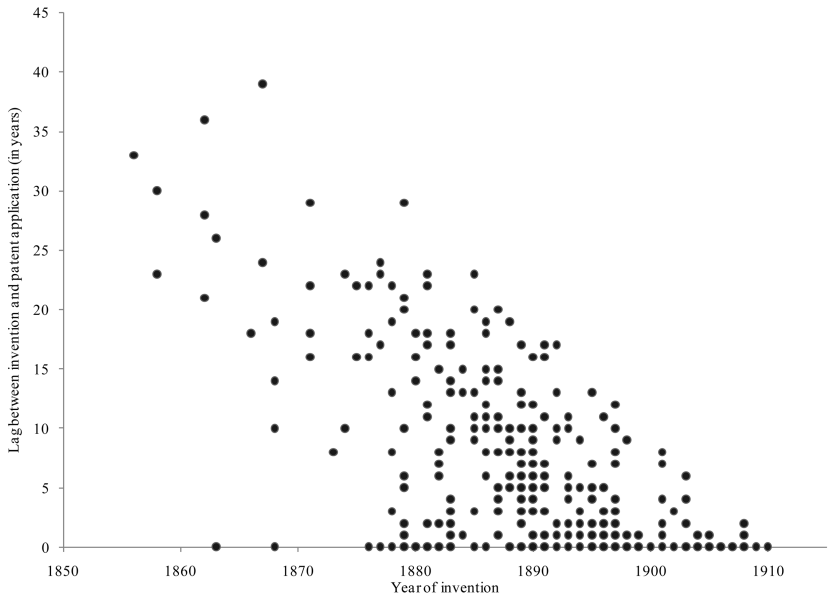

Figure 2. Data on the year of invention and the year of first patent application from Schultz's (1914) list of all chemical dyes that had been synthesized by 1914.

and few inventions were patented within 10 years. After 1870, increasing numbers of inventors decided to apply for a patent within the year. By the 1880s the average lag had dropped to 8 years, and by the 1900s it had declined to 1.4 years.

Data on the share of dyes among all U.S. patents between 1837 and 1915 confirm that patenting became more important in chemicals than in other industries. Between 1837 and 1869, only a handful of U.S. patents (.0 percent) were granted for dyes (Figure 3). After 1869, the share of dyes among U.S. patents increased to .1 percent in 1915 and to .5 percent in 1939.

6. Conclusions

This paper uses a historical data set of more than 8,000 exhibits at world's fairs between 1851 and 1915 to examine the relationship between patents and innovation. These data indicate that the large majority of innovations—89 percent of British exhibits in 1851—were not patented.

Cross-sectional analyses indicate that patenting rates, measured as the share of exhibits that were patented, varied strongly across industries. In 1851, 5 percent of British exhibits in chemicals were patented, compared with 30 percent of exhibits in manufacturing machinery.

Most striking, patenting decisions were remarkably similar in Britain and the

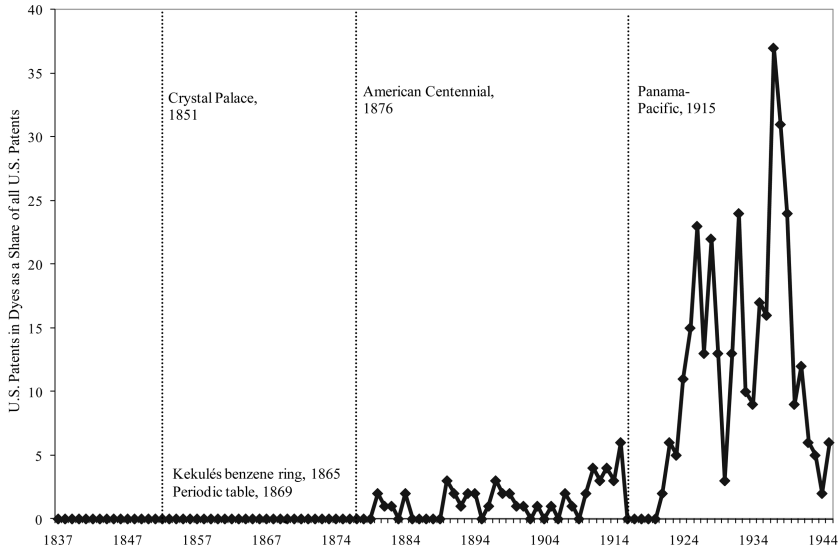

Figure 3. Share of all U.S. patents that are dyes, 1837–1944

United States, despite major differences in patent laws. In 1851, 15 percent of U.S. exhibits were patented, compared with 11 percent of British exhibits, even though patents were significantly cheaper and more accessible under the U.S. system. The same industries had the highest patenting rates in Britain and the United States: exhibits in manufacturing machinery, agricultural machinery, and engines were most likely to be patented, while chemical exhibits were rarely patented. In 1851, innovations in chemicals were difficult to reverse engineer and could be effectively protected through trade secrecy, while innovations in manufacturing machinery were easy to copy and depended on patents.

A difference-in-differences test for chemicals suggests that firms patented larger shares of their innovations after the effectiveness of secrecy declined. A series of scientific breakthroughs revolutionized methods of chemical analysis in the late nineteenth century, so secrecy became less effective. As a result, patenting rates for chemical exhibits increased from less than 5 percent in 1851 and 1876 to nearly 20 percent in 1893 and 1915. By comparison, patenting rates for manufacturing machinery, as a control industry in which secrecy had been ineffective throughout, stayed roughly constant around 45 percent.

If, however, a large share of innovations occurred outside the patent system, patent laws may have a weaker than expected effect on the rate of technical change. In fact, patent laws may affect the direction of technical change if the necessity of patent protection varies across industries (Moser 2005). Without patent laws, inventors focus on a small number of industries in which they can

use alternative mechanisms to appropriate the returns from research and development (Moser 2005). With patent laws, the center of innovative activity may shift to an entirely new set of industries, even as it fails to increase overall levels of innovation.

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