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Did the Telegraph Lead Electrification? Industry and Science in American Innovation

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Radical technological changes involved new knowledge, but how was that knowledge generated? In the case of electrification in the United States, I argue that two sources of knowledge were fundamental to the widening of electrical technology: practical knowledge associated with the telegraph and the conclusions and methods of applied and pure science. The telegraph industry was the most important for-profit antecedent. Its agents, knowledge, and networks were essential to later electrical innovations, as a sample of the 5,300 patents issued to 250 telegraph inventors from 1836 through 1929 demonstrates. These innovations then took on their own dynamics. Scientific knowledge in the not-for-profit sector, often developed in colleges and spread through teaching and publication, solved problems beyond the knowledge of telegraph operators and inventors. A study of 212 major electrical inventors shows that innovators commonly, and over time increasingly, learned off the job through formal and informal education, networked in scientific and engineering societies, published frequently, and taught others in meetings and in colleges. Economic and extra-economic sources of knowledge interfused more tightly as the period progressed.

Though inventions typically aimed at incremental improvements in well-established techniques, some inventions involved more discontinuous changes. The steam engine, interchangeable parts production, synthetic chemicals, penicillin, the semiconductor, and genetically altered crops broke fundamentally with existing methods and with the knowledge on which they were based. Understanding how basically new technological knowledge developed and spread forms a challenging problem.

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Major advances of technological knowledge can develop along three paths: by resolving questions within the inventive process, by capturing spillovers from other industries, or by using extra-economic knowledge sources. In the first path, inventors solve a series of complex problems to arrive at the new technique. Even for a great genius, the process can be prolonged. Some critical need, perhaps prompted by war or natural calamities, may direct large resources toward the problem. In the second, earlier industries provide technological knowledge essential to the major invention. Nathan Rosenberg called this "technological convergence" and showed how innovations to mass produce firearms generated knowledge of interchangeable parts methods that had much wider application. Agents from earlier industries spread the methods to other industries, which then took on their own dynamics. In the third path, knowledge generated outside the for-profit economy informs innovations in the economy. Both the content and methods of pure and applied science may enable new technologies to develop. An "Industrial Enlightenment," in the words of Joel Mokyr, both generates and spreads knowledge that transforms the economy. Still, technological knowledge differs from scientific knowledge, raising the question of just how scientific knowledge can prove useful.[1]

Electrification was a significant instance of a radical innovation. Electricity had little economic significance in 1840, but by the 1920s it had spread to telegraphs, telephones, and radios in communication and to power uses in lighting, railroads, factories, and home appliances. The transition occurred in stages. For the first thirty-five years, the telegraph was the most important electrical industry, raising the possibility that it led electrification. In the next quarter century, the full range of electrical technologies emerged, and they did so with remarkable rapidity. Workable telephones and arc lights developed by 1879, incandescent lights and generators by 1882, motors by 1885, railways by 1890, each within five years after major innovators began their efforts. The wireless telegraph, workable by 1905, took only a few years longer.

To shape electrification, knowledge in the telegraph industry and in the scientific community must have had relevance for electrical problems and must have been communicated to electrical innovators. Both knowledge sources were fundamental to the widening of electrical technology, but in different ways, through different means, and at different times. For-profit and not-for-profit agents differed in kinds of knowledge and diffusion mechanisms. The notable speed of electrification rested on the combination of both kinds of agents and forms of knowledge. The telegraph industry was the most important for-profit antecedent; its agents, knowledge, and networks were vitally important for the birth of

[1]Nathan Rosenberg, "Technological Change in the Machine Tool Industry, 1840-1910," in his *Perspectives on Technology* (New York, 1976), 9-31; Joel Mokyr, *The Gift of Athena: Historical Origins of the Knowledge Economy* (Princeton, N.J., 2002).

later electrical innovations. It provides a good example of a small industry having large effects. These innovations then developed their own dynamics, which affected later innovation and the telegraph itself. Scientific knowledge in the not-for-profit sector, often developed in colleges and spread through teaching and publication, solved problems outside the knowledge of telegraph operators and inventors. A broader applied science community in colleges, the press, and engineering associations was central to applying scientific knowledge in technological innovation. At the same time, electrification reshaped science by posing and solving research problems and by demanding expertise.[2]

For reasons of tractability, I examine electrification in the United States alone, though it was clearly an international phenomenon. The argument proceeds in several steps. The starting point is the dynamic of the telegraph industry, depicted through a sample of telegraph patents, 1840 through 1911, and from industry histories. In the second part, two prominent inventors, Moses Farmer and Thomas Edison, illustrate the spillovers to electrification, and a study 5,300 patents by 250 telegraph inventors demonstrates that these spillovers were widespread. Telegraph firms were not central to the spillovers, but their workers and equipment makers were. Yet, fundamentally different kinds of knowledge were required. In the third part, the experience of 212 major electrical innovators demonstrates the importance of applied and pure science. The final section examines the interfusion of technological and scientific knowledge. Science was not something that mattered only early or only late in the electrification process; it shaped the whole history. Yet the ways it did so changed; from the 1890s, innovation relied more fully on the methods of applied and pure science. Innovators became more educated. Independent inventors persisted, but were now complemented by invention organized in the first industrial research labs.

The Development of the Telegraph

From 1844, when Samuel Morse demonstrated the telegraph's practicality, through 1880, the telegraph was the most significant electrical technology in the U.S. economy. It was not alone; some firms produced batteries and electrical instruments, though the telegraph was the largest market for both, and electroplating had come into use. The evolution of the telegraph increased its potential for shaping other electrical industries by solving electrical problems, training people, and forming networks to communicate knowledge.

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[2] Electrification, of course, depended on other sources of knowledge. The most broadly important was the machinery sector for design capabilities central to electromechanical innovations and production capabilities needed to manufacture electrical equipment. Instruments, chemicals, and other industries also contributed. But for key electrical innovations, the telegraph and applied science provided essential underpinnings.

After Morse's initial success, firms formed quickly to build lines. By the early 1850s, lines connected major eastern and midwestern cities. Morse and his partners had intended to use his patent rights to control development, but competing methods, poorly defined assignments, and licensing led to a great deal of competition and consolidation. By the end of the Civil War, the industry formed a relatively stable structure of firms, occupations, and mode of learning. Western Union dominated intercity telegraphy, and intracity firms, sometimes allied with Western Union, ran fire alarm, police alarm, messaging, and special-purpose telegraphs. Small equipment suppliers emerged, including eight firms in 1860, the largest of which employed only sixteen workers.[3] New occupations accompanied the new firms. Telegraphers formed a highly mobile, national occupation by the 1850s; they had considerable skill in setting up, operating, and maintaining equipment. Occupations of telegraph machinists, electricians, and electrical engineers formed and grew. Telegraph firms and occupations transmitted knowledge of electricity and the more mechanical knowledge of using and designing instruments. Much of this knowledge was tacit, learned on the job, and transferred by the movement of workers. Such workers formed what Paul Israel termed a "technical community," centered in telegraph offices and equipment firms concentrating in cities. Members of the community learned on the job and from equipment manufacturers, but they also studied the more accessible technical literature. As befitting these literate occupations, journals and manuals proliferated, including the *Telegrapher*, published from 1864.[4]

The telegraph industry expanded rapidly and in so doing created conditions for wider electrification. Messages sent by Western Union, which handled three-quarters or more of all messages after the Civil War, increased from 9.2 million in 1870 to 29.2 million in 1880 and to 63.2 million in 1900; growth slowed after 1890 (see Table 1). Telegraph operators increased from 2,000 in 1860 to 22,800 in 1880 and to 74,900 in 1900, before falling in 1910, outnumbered by telephone operators. Telegraphers spread knowledge nationally, though the value of their education was lessened by deskilling beginning in the 1890s.

Telegraph technology changed greatly after Morse's first long-distance line. Patents document major inventions quite well; inventors, even when employed by telegraph firms, typically benefited by selling patent rights or using those rights to form telegraph or telegraph instrument firms. I examined all U.S. patents that the Patent Office classified as telegraphs

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[3]Ross Thomson, *Structures of Change in the Mechanical Age: Technological Innovation in the United States, 1790-1865* (Baltimore, Md., 2009), 244-56; Paul Israel, *From Machine Shop to Industrial Laboratory: Telegraphy and the Changing Context of American Invention, 1830-1920* (Baltimore, Md., 1992), 24-56; James D. Reid, *The Telegraph in America and Morse Memorial* (New York, 1879), 73-111.

[4] Israel, *From Machine Shop to Industrial Laboratory*, 24-86; quote from 57.

(class 178) for all years before 1866 and the first two years in each decade through 1911. I excluded wireless telegraphs, a fundamentally different

Table 1
Growth of Telegraph Output, Workers, and Patents

	Western Union Messages (millions)	Telegraph Operators	Patents per Year	Network Share (%)
1836-45			0.3	100.0
1846-55		500	2.0	57.9
1856-65		2,000	4.9	69.0
1870-71	9.2	8,300	22.0	97.1
1880-81	29.2	22,800	31.5	56.8
1890-91	55.9	52,200	47.0	84.9
1900-01	63.2	74,900	48.5	72.1
1910-11	75.1	70,000	42.0	70.7

Sources: Historical Statistics of the United States: Millennial Online Edition, series Dg9; U.S. Censuses of Population, 1850, 1860, 1870, 1880, 1890, 1900, 1910; U.S. Patent Office, *Annual Report of the Commissioner of Patents,* 1836-1924; Lexis-Nexis Academic; Google patents; Ancestry.com; various city directories.

technology associated with the radio. Class 178 refers to electric patents that conveyed a wide range of information; it excluded electric signaling devices such as fire or police alarms or railway signals that conveyed limited information.[5] In the years examined, 454 such telegraph patents were issued.[6] Patents per year grew from 2 in the 1846-1855 decade to 22 in 1871 and 1872 before stabilizing at around 46 from 1890 through 1911, when the industry matured and its output growth slowed.

The technical community led in patenting. The networks linking components of this community involved telegraph operators and company personnel, telegraph equipment makers, and related applied scientists (including electricians and professors of electrical science). Studies of occupational censuses, city directories, trade journals, biographical dictionaries, and secondary sources help identify the occupations of

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[5] Patents for these other electric communication devices were common; they made up about one-third of all telegraph patents of surveyed U.S. residents who patented telegraphs in the narrow definition of the word.

[6] Eleven percent of patents were issued to foreign residents; the share grew from 2% before 1866 to 15% from 1890 on. Two-fifths of foreign inventors resided in England and one-third in Germany and Austro-Hungary.

inventors. Over the whole period, about three-quarters of patents were issued to inventors with occupations linked to telegraph networks.[7]

The telegraph evolved along two paths. Intercity telegraphy developed based on the Morse system. Relays and repeaters enabled messages to move long distances. Sounders replaced registers, speeding transmission and further simplifying the system. Insulation improved greatly. The Morse-based system of 1865 continued substantially unchanged into the 1890s; Western Union resisted moving toward more automated printing telegraphs. It did adopt more complex duplex and quadruplex systems, which allowed two and then four messages to be sent simultaneously. It also began to substitute dynamos for batteries as power sources on main lines. From the 1890s, printing telegraphs grew significantly, and cables began to replace lines.[8]

The telegraph found major intracity uses. Moses Farmer was the most important inventor of the fire alarm telegraph, in which a series of boxes could call into a central station, which in turn identified the location of the alarm. This invention, first introduced by the Boston city government, soon spread to many cities. Police alarms and private systems that sent signals between two points followed. Printing telegraphs spread financial information about stock, gold, and commodity prices; the inventions of Thomas Edison were highly successful examples utilized by the 1870s. District telegraphs arose around the same time, in which homes and businesses could signal for police, fire protection, messengers, doctors, and other services.[9]

Network communication structured training, equipment production, and invention, as three inventors illustrate. Morse's Boston licensee employed Moses Farmer, who developed the fire alarm telegraph and many other electrical innovations. Farmer benefited from firms he set up but especially from patent licensing. Farmer, in turn, worked with three others who took their skills to other companies. Western Union was a particular beneficiary; Farmer trained its key duplex telegraph inventor and its chief electrician, whose innovations included dynamo-powered telegraphs. The Western Union operator Thomas Edison experimented

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[7] Inventors of electrical apparatus more broadly exhibited the same preponderance of network inventors. The share with work experience in electrical industries, interpreted to exclude generic machinists and others, some of whom had electrical connections, grew from one-half of electrical patents in 1870 to four-fifths in 1910. Dhanoos Sutthiphal, "Learning by Producing and the Geographical Links between Invention and Production: Experience from the Second Industrial Revolution," *Journal of Economic History* 66 (Dec. 2006): 992-1025.

[8] Israel, *From Machine Shop to Industrial Laboratory*, 50-53, 58-61, 128-50, 162-77.

[9] Ibid., 61-62, 100-120; Reid, *The Telegraph in America*, 370-73. Reid says of Farmer that "no more interesting character has appeared in the whole field of electrical inquiry" (370).

with company colleagues in the Cincinnati office, learned about electrical invention in Boston's Charles Williams electrical equipment shop (which housed Moses Farmer's lab), developed telegraphic equipment with New York inventor Franklin Pope (who came to edit key electrical technology journals), and then became a contract inventor for Western Union. Edison formed his own telegraph machinery firm to sell his equipment and to invent. The prolific telegraph inventor Elisha Gray sold patents to Western Union, then formed Gray and Barton, a Cleveland then Chicago telegraph machinery firm that in turn became Western Electric, which was partially owned by Western Union until telephone interests took it over. Farmer, Edison, and Gray each point to the centrality of telegraph machinery firms.[10] This dynamic, in which telegraph firms invented internally but relied more on independent inventors, differed basically from modern R&D.[11]

Many of the same factors linking telegraph networks—the movement of workers, the purchase of capital goods, the diversification of firms, patent licensing from independent inventors—also had the capacity to link those networks to other electrical technologies. If they did, the telegraph could have proved essential to more important technologies. A small dog could have waved a big tail.

The Telegraph as Leader

The great wave of revolutions in electrification began when the telegraph, after thirty-five years of development, had greatly expanded electrical and related mechanical knowledge and spread this knowledge to 23,000

[10] Networked communication began with Morse himself. One of his first operators, Henry Rogers, later superintended four other telegraph companies and helped perfect a printing telegraph. A second operator designed the most common lightening arrestor used in telegraph offices. Three of Morse's instrument makers opened important telegraph instrument shops; one made significant technical improvements. His licensees spread the telegraph. One collaborator, Ezra Cornell, organized several lines connecting New York to the Midwest, and then helped consolidate seven companies into Western Union in 1855. Cornell used some of his wealth to form the New York university bearing his name; its land grant mission would affect later electrification. Israel, *From Machine Shop to Industrial Laboratory*, 25-44, 57-120; Reid, *The Telegraph in America*, 112-41, 268-81; 288-99, 849-57; Stephen B. Adams and Orville R. Butler, *Manufacturing the Future: A History of Western Electric* (New York, 1999), 14-34; *Dictionary of American Biography* (New York, 1964), various inventors.

[11] Occasionally telegraph firms contracted with independent inventors for telegraph innovations, as Western Union and Jay Gould's Atlantic and Pacific Telegraph Company did with Edison. Though corporate engineering departments at Western Union assessed inventions and at times developed them, internal R&D did not come until 1911. Israel, *From Machine Shop to Industrial Laboratory*, 146, 156-57, 179-80.

telegraph operators and to machinery producers and electricians. The telegraph could have led wider electrification if its agents and knowledge shaped development in the new sectors. The telegraph system involved circuitry, electromagnets, receiving and sending apparatus, relays, repeaters, batteries, insulation, and lines. Some of these could have applied directly or been easily adapted to other sectors. The electrical and mechanical knowledge involved in telegraph design and operation could have formed a conceptual basis for solving quite distinct problems. Telegraph networks could have transferred the knowledge. Telegraph equipment firms could have produced other electrical equipment. Telegraph firms could have financed other electrical innovation. In some ways, the telegraph had only modest effects on later electrification. Western Union declined to diversify into other sectors, much to its later chagrin. Initial telegraph inventors did little directly to develop other technology; Morse and his associates concentrated on the telegraph itself. But their actions and those of their successors had powerful, unintended consequences for the spread of electricity.

Two examples illustrate the linkages. Moses Farmer concentrated on telegraphs in the 1850s. Along with the fire alarm telegraph he developed with William Channing, Farmer patented duplex telegraphs, insulators, and repeaters, totaling sixteen telegraph patents in that decade. Called by Paul Israel “the country’s first independent electrical inventor,” Farmer began to venture into other electrical technologies, receiving patents for a battery, an electric clock, and an electric water gauge.[12] He delved into electric lighting from 1858; by 1859 he had invented an incandescent light, which he powered by batteries to illuminate his home. He wrote John Batchelder, a telegraph co-patentee, about his light, and asked him to show it to the eminent scientist Alexander Bache. Farmer knew that batteries were not an adequate power source, and wrote Batchelder, then working at a textile mill, that he hoped his light “will be used in a cotton mill, driven by a magneto-electric machine powered by steam or water.” He did not patent or spend much time developing lighting or power patents; in a later letter he commented that he did not develop his dynamo because “there was no demand for a magneto-electric machine for any industrial use.”[13]

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[12] Israel, *From Machine Shop to Industrial Laboratory*, 61-62.

[13] Quote from letter of 3 Aug. 1860, box 1, folder 8; see also letter from 15 Aug. 1859, box 1, folder 10, 1860; quote from letter to E. M. Barton, president of Western Electric Company, 4 May 1893, all in Moses G. Farmer Papers, 1830-93, Young Research Library, UCLA, Los Angeles, Calif. A dominant theme of Farmer’s correspondence from the 1850s through the 1880s was to gain usage for his patents in his own firms or, more commonly, in other firms, and perhaps securing employment as an inventor in these firms. Farmer did not focus on administering and expanding firms using his fire alarm telegraphs, but instead chose to invent widely, hoping to sell patents or obtain equity in firms using his patents. He was an early example of the independent inventor, a type that

He continued his multiple paths of invention in the 1860s and 1870s, with nine telegraph patents and eleven patents for batteries, electrical lights, dynamos, and electroplating. By 1876 he and William Wallace had developed a dynamo-driven system for electrical lighting, which they displayed at the Centennial Exhibition. In the 1880s his telegraphy interests turned to high-speed cables, but his inventive efforts shifted more to lighting and power. In 1880 the U.S. Electrical Lighting Company purchased his patents and hired him as electrician; the firm ultimately sold out to Westinghouse. He received eight telephone patents and a number of patents for refining copper by electrolysis, and he endeavored to form companies for each. Altogether, Farmer received 84 electrical patents, 30 for telegraphs. The share of telegraph patents fell from 84 percent before 1860 to 22 percent afterward.[14]

Thomas Edison was by far the most important person to use telegraph capabilities to devise other electrical devices. His invention, which led to 106 telegraph patents through 1877, prepared the way for patents in telephones, phonographs, incandescent lights, and generators in 1878 and 1879. Telegraph invention provided applicable technological knowledge of electrical implements, contacts in telegraph networks, knowledge of production of implements, and money to invest. Edison would not have built and staffed Menlo Park without the telegraph, nor could he have succeeded in the revolutionary inventions of the late 1870s.

Edison used knowledge of telegraph design to pose and solve problems in several major new technologies. In his most important contribution to the telephone, the carbon button transmitter, he built on knowledge of the variable resistance of carbon that he had discovered in earlier cable telegraph experiments. His transmitter became an integral part of the practical telephone. He also designed a receiver based on knowledge developed for automatic telegraphs. The motivation for inventing the phonograph was the desire to record messages from acoustic telegraphs and telephones, and Edison initially used a paper-indenting mechanism from an early telegraph invention. The telegraph also shaped the electric light. Edison began his invention by applying knowledge of circuits learned in duplex and quadruplex telegraph inventions to prevent overheating the filaments. Discovering that existing electric generators were inadequate, he designed one based on his current-increasing inventions for acoustic telegraphs. Moreover, the methods he had developed to conceive, draw, and experiment on telegraph systems informed later invention. The new technologies required him to go beyond

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Thomas Hughes felt was essential to late nineteenth-century innovation. *American Genesis: A Century of Invention and Technological Enthusiasm* (New York, 1989), 20-95.

[14] Letters of 16 June 1876, folder 9; 8 Nov. 1880, box 4 folder 4, Moses Farmer Papers; Farmer patents.

his telegraph roots, but those roots provided knowledge that sped invention.[15]

Telegraph networks supplied knowledge and income that Edison put to good use. His contracts with Western Union, Gold and Stock Telegraph, and other firms to which he sold patents provided the finance to set up a series of telegraph equipment firms, and, when he decided to concentrate on innovation in the early 1870s, telegraph invention firms, culminating in Menlo Park. Later Western Union contracts aimed at telephone invention to compete with firms commercializing Alexander Graham Bell's patent. William Orton, the president of Western Union, provided Edison with an early German telephone. Edison's visit to the Wallace and Farmer shop introduced him to their electric lighting and dynamo efforts, which turned his attention to electric lighting. His telegraph equipment shops provided capabilities to manufacture experimental equipment. Several workers in his telegraph machine and invention shops became central members of his inventive team at Menlo Park, including his chief assistant, Charles Batchelder, and his machinist, John Kruesi.[16]

Edison's patenting documents the leading role of the telegraph. Edison received 1,078 utility patents through 1929, and a few more afterward. Nearly 70 percent of them were for electrical devices, reflecting the shared technological principles of such devices (see Table 2). Spillovers among such devices could have run in any direction, but the timing of Edison patents supports the leading role of the telegraph. Telegraphs made up 82 percent of his electrical patents from 1869 through 1879, and 94 percent of his electrical patents before 1878. The share of telegraph patents exceeded 5 percent only in one later decade. From 1878, Edison concentrated on generic electrical inventions and on particular uses such as light, power, and railways. Generic inventions included batteries, circuitry, and measurement instruments. Electric lights made up 39 percent of his electrical patents in the 1880s and 1890s, Edison's most prolific decades, and electric motors and dynamos added another 23 percent. He shifted into electric railway invention in the 1890s. Just as sewing machine firms adopted interchangeable parts techniques from firearms, learning from Edison's telegraph inventions helped develop later ones. The telephone as well as the telegraph affected his phonograph inventions. Electric railway inventions depended more on dynamo inventions than on the telegraph, though railway signaling continued to rely on knowledge of telegraphy.

[15] Paul Israel, "Telegraphy and Edison's Invention Factory," in *Working at Inventing: Thomas A. Edison and the Menlo Park Experience,* ed. William S. Pretzer (Baltimore, Md., 2002), 72-77; see also Thomson, *Structures of Change in the Mechanical Age,* 2-5.

[16] In deciding to concentrate on invention, Edison followed Farmer, but his invention shops were bigger and better financed. Israel, "Telegraphy and Edison's Invention Factory," 68-79; W. Bernard Carlson and Michael E. Gorman, "Thinking and Doing at Menlo Park: Edison's Development of the Telephone, 1876-1878," in *Working at Inventing*, ed. Pretzer, 84-99.

But the broad knowledge he obtained in telegraphy continued to inform his invention even as the content of that invention shifted.[17]

Though few inventors were as important as Farmer and Edison, many followed similar paths. A study of all the patents of surveyed U.S. teleg-

Table 2
Thomas Edison's Patents by Type and Decade

	1869-79	1880-89	1890-99	1900-09	1910-19	1920-29	All
All Patents	146	373	217	164	135	43	1,078
Electrical Patents	141	319	138	80	42	23	743
Shares of Electric Patents (%)							
Telegraph	81.6	4.1	12.3	1.3	0.0	4.3	19.8
Generic	2.8	20.4	13.8	86.3	71.4	65.2	27.2
Particular Uses	15.6	75.5	73.9	12.5	28.6	30.4	53.0
Batteries	0.7	0.9	2.2	81.3	61.9	65.2	15.2
Circuitry & Measuring	2.1	19.4	11.6	5.0	9.5	0.0	12.0
Telephone	7.1	5.0	5.1	0.0	2.4	4.3	4.7
Light	3.5	40.8	35.5	2.5	4.8	0.0	25.3
Dynamos and Motors	2.1	26.6	13.8	1.3	2.4	0.0	14.7
Electric Railroad	0.0	2.2	13.0	1.3	0.0	0.0	3.5
Other Electric	2.8	0.9	5.8	8.8	19.0	26.1	4.8

Sources: Annual Reports of the Commissioner of Patents, Google Patents, and Lexis-Nexis Academic. Where classification was not clear, patents were individually consulted.

graph inventors documents their broader effects. The 250 telegraph inventors are grouped into three periods by the date of their first surveyed patent; 54 first patented from 1840 through 1865, 107 from 1870 through 1891, and 89 from 1900 through 1911. The data set includes all of their patents from 1836 through 1929. About three-quarters of telegraph inventors received non-telegraph patents. Some had mechanical or chemical patents, but over half of all the inventors—and over two-thirds of those with other kinds of patents—invented other electrical devices (see Table 3). The share with other electrical patents was high in each period.[18]

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[17] The phonograph was his most important mechanical invention, with 183 patents, about 17% of all his patents and 55% of his non-electrical patents. The phonograph had an electrical component when powered by battery or motor, but it could function without electricity.

[18] The apparent growth of other electrical patenting after 1865 is largely a statistical artifact. While every telegraph patentee (in class 178) was captured through 1866, surveying patentees in the first two years of later decades misses patents from other years. The data set of all patents would then include electrical patents for those in surveyed years, but omit patents from inventors with only a single patent in those other years. Put differently, Edison, who had telegraph patents in 26 years, would be 26 times as likely to be selected as someone with a

As was true for Farmer and Edison, two factors underlay the large share, technological convergence and technological complementarity. On the one hand, knowledge developed in some electrical invention helped pose and solve questions in other types of invention. On the other hand, every electrical technology was embedded in a system including other types of electrical mechanisms, just as the telegraph required the battery and later the dynamo, circuitry, and measurement devices.

Table 3
Shares of Telegraph Inventors with Non-Telegraph Patents
(%)

	1840-1865	1870-1891	1900-1911	All
Non-telegraph Patents	68.5	74.8	76.4	74.0
Non-telegraph Electric	31.5	57.0	55.1	50.8
Generic Electric	25.9	43.0	43.8	39.6
Particular Electric	20.4	47.7	47.2	41.6
Measurement	3.7	6.5	20.2	10.8
Batteries	11.1	17.8	5.6	12.0
Circuitry	20.4	36.4	37.1	33.2
Telephone	9.3	26.2	21.3	20.8
Light	9.3	18.7	9.0	13.2
Dynamos and Motors	11.1	25.2	15.7	18.8
Railroad Signaling	3.7	10.3	7.9	8.0
Electric Railroad	1.9	14.0	7.9	9.2
Radio	0.0	4.7	9.0	5.2
Other Electric	13.0	26.2	20.2	21.2

Sources and Notes: See Table 2. Only patents for U.S. residents were surveyed.

About two-fifths of telegraph patentees had generic electrical patents for circuitry, batteries, and measurement instruments. By their nature such patents applied to more than one electrical operation. In addition, over two-fifths patented particular non-telegraph electrical products. Many industries benefited, none more than telephones; 21 percent of telegraph inventors also patented telephones. The share for other electrical technologies was nearly as high; 13 percent patented lights, 19 percent generators and motors. Others were well represented but less frequent, including railroad signaling, electric railroads, and radios. The timing of

single telegraph patent. If, parallel to later years, we looked at all patents for the eighteen telegraph patentees in 1850, 1851, 1860, and 1861, the share with other electrical patents would rise to 50%, only a little less than among later patentees. This implies that if all telegraph patentees after 1865 were studied, the share with other electrical patents likely would have declined, because those with more telegraph patents also had more other electrical patents.

patenting was significant. Telegraph inventors were particularly likely to spread to other electrical applications early in their development; one-quarter of those patenting telegraphs from 1870 through 1891 invented telephones and motors, almost one-fifth patented lights, and one-seventh patented electric railroads.

The timing of invention suggests that for most of the period the telegraph affected other electrical technologies more than they affected the telegraph. Similar to Edison, many inventors developed electrical techniques in telegraphy before applying them more widely. To determine how common this was, telegraph inventors who also received other electrical patents were classified by their first electrical patent (or, if they had more than one electrical patent in their first year of inventing, the type with the most patents). If the telegraph led other electrical inventions, then the share beginning with telegraph patents should have been high. Overall, 62 percent of inventors began with telegraphs. Another 12 percent began with generic patents of sorts used in the telegraph system. Only one-quarter began with other patents (see Table 4).

Table 4
Shares of Crossover Inventors by First Electrical Patent
(%)

Inventor Shares	1840-1865	1870-1891	1900-1911	All
Telegraphs	58.8	77.0	44.9	62.2
Generic	23.5	0.0	22.4	11.8
Other Particular	17.6	23.0	32.7	26.0

Source: Calculated from data; see Table 2.

Perhaps more telling, the share beginning with telegraphs or generic electrical patents was very high in the first period, when the telegraph was the principal electrical technology in use. In the second period, when other technologies were originating, over three-quarters of inventors began with telegraphs before moving to other technologies. But in the twentieth century, one-third of inventors began with other particular electrical techniques. For example, Nikola Tesla had already effected a revolution in alternating current technology before taking out his first telegraph patent in 1901. By then, the telegraph no longer led electrical technologies.

Telegraph networks communicated knowledge of wider electrical possibilities. Telegraph equipment firms often made other electrical equipment. Telegraph operators and especially electrical engineers had electrical knowledge relevant to other products, and often took jobs in other sectors. If those in telegraph networks were well positioned to invent in other areas, they should have patented other electrical inventions more frequently, which was in fact the case. Of inventors with known occupations, 67 percent of those in telegraph networks patented other electrical improvements, compared to 43 percent of those outside those networks. As a result, networked inventors, 66 percent of all telegraph inventors, formed 75 percent of inventors with other electrical patents (see Table 5). They were equally likely to patent generic and other particular electrical improvements. Moreover, over the whole period, they received 81 percent of other electrical patents, peaking in the second period with 86 percent of these patents.

Table 5
Telegraph Networks and Crossover Invention
(%)

	1840-1865	1870-1891	1900-1911	All
Network Inventors				
Share of Inventors	56.5	69.5	69.0	65.9
Share, Inventors with other Electric Patents	80.0	75.6	72.7	75.0
Network Patent Shares				
All Electric	78.6	86.7	68.5	79.6
Telegraph	80.7	88.5	62.7	77.7
Other Electric	76.0	85.6	73.9	81.1

Source: Calculated from data; see Table 2.

Telegraph inventors, firms, equipment firms, and networks each had effects on other electrical sectors. The 250 surveyed telegraph inventors concentrated on electrical patents. Fully three-quarters of their 5,264 patents through 1929 were for electrical improvements, and, interestingly, telegraph patents were outnumbered by other electrical patents or were equaled by them if Edison was excluded (see Table 6). Seventeen percent of the electrical patents developed circuitry, batteries, measurement devices, and similar generic devices that could be applied to a variety of electrical uses. Thirty-eight percent of electrical patents had other particular uses, led by the telephone with 8.6 percent of electrical patents over the whole period—or 9.5 percent if Edison is excluded. The share of crossover electrical patents with particular uses more than doubled the share with generic uses.[19] Light, dynamo, and motor patents together made up 15 percent of electrical patents, though Edison had 40 percent of them. Electric railways and radios followed in patent shares. Other patents applied core principles to narrower uses, including alarms, safety apparatus, clocks, locks, elevators, metallurgical methods, automobile parts, appliances, and much else, yet those applications amounted to only 7

[19] One might classify generators and motors as generic, because they could be used to power wide ranges of electrical equipment. If so, the generic share of patents would rise to 24% of electrical patents, still well under the 31% of particular applications.

percent of patents.[20] Telephones, lighting, and motor patents formed the biggest share for telegraph inventors in the 1870-1891 period, and radio patents surged for twentieth-century inventors.

Table 6
Patenting by Telegraph Inventors

	1840-1865	1870-1891	1870-1891, no Edison	1900-1911	All	All, no Edison
All Patents	509	3,077	1,999	1,678	5,264	4,186
Electrical Patents	340	2,311	1,568	1,298	3,949	3,206
Shares of Electric Patents (%)						
Telegraph	56.8	40.5	50.3	49.5	44.9	50.7
Non-telegraph Electrical	43.2	59.5	49.7	50.5	55.1	49.3
Generic	9.4	17.2	12.4	19.2	17.2	14.8
Particular Uses	33.8	42.3	37.3	31.3	38.0	34.5
Measurement	0.6	1.3	0.4	3.2	1.8	1.6
Batteries	3.8	8.1	4.8	2.6	6.0	3.8
Circuitry	5.0	7.8	7.1	13.4	9.4	9.5
Telephone	7.6	10.2	12.8	6.0	8.6	9.5
Light	5.9	10.5	3.5	2.5	7.5	3.4
Dynamos and Motors	7.1	8.4	5.5	4.6	7.1	5.3
Railroad Signaling	1.5	1.5	2.0	1.5	1.5	1.7
Electric Railroad	0.3	4.6	5.1	1.6	3.2	3.2
Radio	0.0	0.9	1.3	9.1	3.5	4.3
Other Electric	11.5	6.2	7.1	5.9	6.6	7.1

Source: Calculated from data; see Table 2.

How important was the telegraph sector for later electrical innovations? As telegraph inventors indicate, the application of telegraph knowledge to other electrical invention was common and extensive. Other

[20] In an important sense, the telegraph, telephone, electric light, electric railway, and radio were also applications of core principles; only generators, batteries, circuitry, and measurement devices would apply generally. These broad applications involved basic principles of electricity, while many narrower applications applied these principles to particular uses. The concentration of telegraph inventors on core principles and applications is consistent with the conclusion of other scholars that those receiving narrower electrical application patents (largely those in our “other” category) concentrated on these applications. Shih-Tse Lo and Dhanoos Sutthiphisal, “Crossover Inventions and Knowledge Diffusion of General Purpose Technologies: Evidence from the Electrical Technology,” *Journal of Economic History* 70 (Sept. 2010): 753-54. In their study, inventors with patents in narrow application sectors received only 18% of their electrical patents in core technologies (all but “other electric” in our Table 6) for those receiving narrow application patents in 1890 and 14% in 1910.

avenues could extend the telegraph's effect. Some telegraph patents directly applied to other sectors without added patenting. Some inventors learned in the telegraph sector but did not patent there. Knowledge of how to make telegraph equipment could have applied more widely in existing or new firms. Consider this range of effects for four major electrical technologies: the telephone, light and power, electric railways, and the radio.

Telegraph inventors moved quickly into telephone improvements. Many telegraph inventions, including repeaters, relays, circuit breakers, insulation, and switchboards, found telephonic uses. Telegraph inventors also patented important telephone improvements such as Edison's transmitter. Elisha Gray wrote a caveat claiming a speaking telegraph in 1876. He had been working on acoustic telegraphs to transmit musical tones telegraphically, which one of his patents called a "telephonic telegraph apparatus." He then took out eleven patents for "speaking telephones" and related inventions through the end of the 1870s. Another six telegraph inventors entered before 1880, some with importance for the telephone industry, including George Phelps, a factory superintendent at Western Union.[21]

Alexander Graham Bell's fundamental telephone invention rested on his interest in speech, acquired as professor of vocal physiology and elocution at Boston University and a teacher to the deaf. It also was shaped by the telegraph industry. Bell was one of the numerous inventors congregating around Charles Williams' telegraph instrument shop, where he learned much about telegraphy and conducted experiments on acoustic telegraphs with the shop's machinist, Thomas Watson. He patented a telegraph in 1875, but unlike one of his sponsors, Gardiner Hubbard, who had invested in telegraphs, Bell was more interested in transmitting speech than simple sounds. His key 1876 patent, titled simply "an improvement in telegraphy," claimed "the method of, and apparatus for, transmitting vocal or other sounds telegraphically." Hubbard then organized the Bell Telephone Company, which employed Bell and Watson.[22]

Telegraph inventors helped make the system practical. George Anders, with twenty telegraph patents to his credit, received another thirty-one telephone patents. He assigned many to the American Bell Telephone Company, for which he worked from 1879, including a patent for the most widely used telephone ringer. Gray undertook a series of improvements, some assigned to Western Electric. George Phelps continued to develop transmitters and switchboards for Western Electric. Ezra Gilliland, a dial telegraph inventor who co-patented railroad signals with Edison, invented widely, including automatic telephone switching devices, which gained use

[21] Elisha Gray patent 175,971; Adams and Butler, *Manufacturing the Future*, 34-35.

[22] U.S. Patent 174,465; Adams and Butler, *Manufacturing the Future*, 36-41.

on small exchanges. Telegraph inventors patented telephone repeaters, relays, receivers, call boxes, transmitters, multiplex transmission mechanisms, and switchboards. Long-distance transmission proved troublesome, and Michael Pupin and other telegraph inventors contributed key inventions such as the loading coil. Telegraph inventors received fifty-three patents for techniques that could be used on either the telegraph or the telephone or for both kinds of messages simultaneously, a manifestation of the convergence between telegraph and telephone technologies.[23]

The success of the telephone focused attention on manufacturing its components. American Bell first turned to Charles Williams, who easily adapted his small telegraph shop to make telephone equipment, and to Ezra Gilliland's Indianapolis telegraph equipment firm for larger scale production. The biggest supplier proved to be Western Electric, which American Bell acquired from Western Union. Watson became the head of Western Electric's patent department in 1880, and received forty telephone patents. Gilliland headed American Bell's experimental shop in 1883. At the same time, one-time telegraph operator Theodore Vail became general manager of American Bell and later president of AT&T.[24] Hence the telegraph industry trained inventors and manufacturers who proved critical to the telephone's quick success. Their production capabilities, product knowledge, inventions, and financing sped telephone development. Telegraph networks spread knowledge and spun off telephone networks. Telephone innovators also inherited an innovation strategy based around acquisition of patents from independent inventors supplemented by invention by company workers.

The technology of electric light and power differed much more from telegraph technology than telephone technology did. While the telephone and telegraph both used battery-powered transmitters and receivers to send low-power messages over lines boosted by repeaters, electric lights used much higher power, requiring generating capability far beyond what batteries could supply, for a purpose involving quite distinct technological problems. Yet the technology, inventive capabilities, networks, and agents of the telegraph system shaped the inception of electric light and power.

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[23] M. D. Fagen, ed., *A History of Engineering and Science in the Bell System: The Early Years (1875-1925)* (no location, 1875), 121, 243, 244, 257, 172, 487, 546; Israel, *From Machine Shop to Industrial Laboratory*, 177-83; Leonard S. Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876-1926* (New York, 1985), 142-43.

[24] Because Western Electric was majority-owned by Western Union, which organized competing (and probably infringing) telephone firms, Western Electric had ambiguous relations to Bell Telephone, yet it did license Bell patents for a private line service. When Western Union agreed to cede its telephone patents to Bell on stiff terms, Western Electric, seeking telephone markets, acquired majority interest in Gilliland's firm, and ultimately it was sold to American Bell as part of the settlement of patent suits. Israel, *From Machine Shop to Industrial Laboratory*, 176-78; Adams and Butler, *Manufacturing the Future*, 38-57.

Farmer and Edison have illustrated the linkages. Both used revenues from telegraph patents to fund light and power improvements, and both built on technical principles of telegraphy. Moreover, they learned from each other when Edison toured Farmer's plant and when Farmer became an inventor for the U.S. Electrical Lighting Company.[25]

Many others followed similar paths. Thirty-three sampled telegraph inventors patented lights, and forty-seven patented motors, generators, and related power equipment. Their role was greatest in the birth of lighting; among those first patenting telegraphs from 1870 through 1891, the shares patenting lights, generators, and motors were 10 percent higher than for inventors in other periods. Moreover, inventors often began with telegraphs and generic inventions and then moved to light and power, including 73 percent of telegraph inventors who patented lights and 64 percent of those patenting generators and motors.

Though a few inventors designed motors or generators to substitute for batteries in powering telegraphs, the vast majority of light and power inventions had wider purposes. Many made use of electrical knowledge acquired in the telegraph industry to develop lighting, including Franklin Pope, who assigned an incandescent light socket to George Westinghouse. Three inventors set up their own light and power firms in Chicago, Detroit, and Pittsburgh. Telegraph inventors concentrated their light and power patents in the early phase of those industries; inventors other than Edison received 47 percent of all their light and power patents through 1929 in the 1880s. They had declined as light and power inventors by the time General Electric formed in 1892.

Many electrical lighting and power pioneers had less connection to the telegraph industry, though the telegraph affected their development. Charles Brush was the first to commercialize arc lights on a large scale; his lighting and dynamo inventions were the basis of a functional system by the late 1870s. Connections to the telegraph proved critical to his success. Cleveland's Telegraph Supply Company, formed in 1872 to commercialize a repeater patent and produce telegraph equipment, allowed him to experiment in its plant, financed his invention, and agreed to sell Brush equipment. Brush assigned several patents to it. The firm was reorganized as the Brush Electric Company, which dominated arc lighting installations in the early 1880s.[26]

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[25] Israel, "Telegraphy and Edison's Invention Factory," 68-79; Robert Friedel and Paul Israel, with Bernard S. Finn, *Edison's Electric Light: Biography of an Invention* (New Brunswick, N.J., 1986), 8-16.

[26] Returning the favor, Brush Electric then supported many other inventors. Naomi R. Lamoreaux, Margaret Levenstein, and Kenneth L. Sokoloff, "Financing Invention during the Second Industrial Revolution: Cleveland, Ohio, 1870-1920," in *Financing Innovation in the United States, 1870 to the Present,* ed. Naomi R. Lamoreaux and Kenneth L. Sokoloff (Cambridge, Mass., 2007), 46-56; Harold C. Passer, *The Electrical Manufacturers, 1875-1900* (Cambridge, Mass., 1953), 14-21. Other arc light inventors were less connected to telegraphs. Edward Weston

Leading incandescent light inventors were also linked to the telegraph. William E. Sawyer patented incandescent lighting methods from 1877 through 1885. He had been trained as a telegraph operator and received thirteen telegraph patents before his first lighting patent.[27] George Westinghouse entered the fray in the late 1880s. Westinghouse, the inventor of air brakes for railroad trains, became involved in electrical technologies through railroad signals. None of his 340 patents was for telegraphs, but railroad signaling, which involved telegraphy or related technologies for sending and receiving messages, introduced him to the power of electricity. The Union Switch and Signal Company, which developed railroad signaling devices that Westinghouse devised or acquired, also employed workers who led the way into electrical light and power, including the prolific inventor William Stanley, an experienced electrical inventor employed by earlier firms, beginning with a telegraph equipment company.[28]

Power applications had similar dynamics. Motors to power factories and railroads had links to telegraphs, but the links were often indirect. Frank Sprague developed the first practical electric motor, which transformed electrical into mechanical power. Sprague learned a great deal from two telegraph pioneers, though not about telegraph operations. He studied Moses Farmer's equipment, especially his dynamo, when the Navy stationed him at Newport, where Farmer was the electrician for the Naval Torpedo Station. He also worked for Edison in designing and installing lighting systems in small towns. Sprague went on to develop the

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developed a dynamo to electroplate metals, and then turned to arc lighting; he had no telegraph patents. Elihu Thomson was broadly educated in electricity, including the telegraph, for which he received his first electrical patent. But his interests were always broader, and he abandoned telegraphs when he turned to lighting. Passer, *The Electrical Manufacturers*, 21-34; W. Bernard Carlson, *Innovation as a Social Process: Elihu Thomson and the Rise of General Electric, 1870-1900* (New York, 1991), 24-80.

[27] Sawyer formed the Electro-Dynamic Company, which failed. Thomson-Houston acquired the firm holding Sawyer's patents, which it used to enter the incandescent light business. It later sold the firm to Westinghouse. Charles D. Wrege and Ronald G. Greenwood, "William E. Sawyer and the Rise and Fall of America's First Incandescent Light Company, 1878-1881," *Business and Economic History*, 2d ser. 13 (1984), 31-48.

[28] In electrical lighting and power, Westinghouse made the greatest use of the alternating current inventions of Nikola Tesla, the great Austro-Hungarian inventor, whose early employment was in telegraph firms. Passer, *The Electrical Manufacturers*, 129-51; Steven W. Usselman, *Regulating Railroad Innovation: Business, Technology, and Politics in America, 1840-1920* (New York, 2002), 293-315. Other lighting inventors had less connection to the telegraph, including Hiram Maxim, who had no background or patents in telegraphs. He patented incandescent lights in 1880 and worked for the United States Electrical Lighting Company, Edison's main competitor through 1885, which also employed Moses Farmer and Edward Weston.

first practical electric railroad. Sprague had no telegraph patents. Tesla designed a polyphase motor that ultimately proved more important than Sprague's direct current motor. Tesla did patent telegraphs, but after his major AC inventions.[29] Electric railway inventors had more modest connections to the telegraph. Twenty three sampled telegraph inventors received 128 patents for electric railways, but they were not essential to the railway's practicality. Using his dynamo and applying knowledge from lighting, Edison was one of the first to enter the field, with little success. Sprague succeeded late in the decade. Westinghouse entered electric railways after observing the railway of Joseph Finney in 1887; Finney had begun his electrical inventions with telegraph, lighting, and current-measuring patents in 1880.[30]

As a wireless telegraph, the radio was also a medium of communication of words and symbols using transmitters and receivers. Yet its core technologies were fundamentally different from the wired telegraph. The key actors were as well. Guglielmo Marconi, Oliver Lodge, Reginald Fessenden, Lee de Forest, and Ernst Alexanderson did not patent (wired) telegraphs (though some of their patents affected telegraphy), nor had they been employed in their operation. Still, a dozen telegraph inventors did patent radios, some with importance for the field. Michael Pupin had eighteen radio patents starting in 1904, yet began patenting in telegraphy (with application to telephony) a decade earlier. His patents provided important elements of successful radio systems and bases for disputing Marconi's patents. He shaped discussion about radio waves, though this was more because of his scientific accomplishments. The most prolific telegraph-radio inventor, Harry Shoemaker, devised mechanisms improving the de Forest triodes and a wide variety of other wireless improvements for a number of companies. He patented seventy wireless improvements through 1929.[31]

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[29] Frederick Dalzell, *Engineering Invention: Frank J. Sprague and the U.S. Electrical Industry* (Cambridge, Mass., 2010), 48-90; Passer, *The Electrical Manufacturers*, 247-49.

[30] Sprague was preceded by two other efforts. Edward Bentley and Walter Knight designed a system in the Brush Electrical Company and sold a few systems before selling out to Thomson-Houston. They began their patenting careers with two joint patents to run telegraph, telephone, and lighting lines together without interfering with each other. With no background in telegraphs or their invention, Charles Van Depoele installed a dozen small systems in the 1880s before also selling out to Thomson-Houston. Passer, *The Electrical Manufacturers*, 216-36, 256-58; Lamoreaux, Levenstein, and Sokoloff, "Financing Invention during the Second Industrial Revolution," 51, 57.

[31] Hugh G. J. Aitken, *The Continuous Wave: Technology and the American Radio, 1900-1932* (Princeton, N.J., 1985); Hugh G. J. Aitken, *Syntony and Spark: The Origins of Radio* (New York, 1972); Reich, *The Making of American Industrial Research.*

Did the telegraph lead other electrical technologies? The telegraph certainly fostered the great flourishing of electrical technologies in the last quarter of the nineteenth century. Knowledge developed in telegraphy applied widely. Telegraph inventors often utilized their knowledge to invent in other sectors. These spillovers were remarkably wide; 56 percent of all telegraph inventors from 1870 through 1911 had other electrical patents. Techniques to make telegraph equipment were used to manufacture other electrical equipment, sometimes in the same firms. Western Electric moved from telegraph to telephone equipment and to electrical lighting and power machinery.[32] Telegraph networks, which linked telegraph companies, telegraphers, and telegraph instrument producers, readily widened into other fields. Revenue from selling telegraph equipment or patents financed the movement into other spheres. The telegraph was most important for the telephone, important in incandescent lighting and power, somewhat less important in arc lighting, and less important still in the electrical railroad and the radio.

The telegraph's effect was greatest in initiating these other technologies; they then increasingly developed on their own. Before other technologies existed, the telegraph was the most significant economic repository of electrical knowledge, and its networks more readily communicated technological problems. When other electrical techniques developed, firms, labor markets, and repositories of knowledge formed that were more relevant to their particular problems. Light and power firms were more relevant to electric railways than was the telegraph, and both light and telephone firms were more relevant than the telegraph to wireless telegraphy. Indeed, technology increasingly flowed into the telegraph from other technologies. Inventors beginning with power improvements, such as Tesla, or radio inventions, including Shoemaker, patented telegraph improvements. When, in 1909, AT&T briefly controlled Western Union, AT&T and Western Electric engineers perfected the high-speed printing telegraphs that Western Union came to use, and AT&T initiated Western Electric's research lab in 1911 to explore the physics of the loading coil and multiplex telegraphy.[33]

Still, the telegraph had a mediated effect on all later electrical industries. Without learning and revenue from his telegraph patents, Edison could not have formed or so effectively utilized Menlo Park to generate inventions and the companies that commercialized them. These labs and firms trained inventors central to later technologies, including Anders in telephones, Tesla in AC power, Sprague in electric motors and railways, Fessenden in the radio, and Arthur Kennelly, who patented measuring devices but more importantly taught electrical engineering at Harvard and developed theories of the ionosphere and its downward

[32] Adams and Butler, *Manufacturing the Future*, 45-70.

[33] Israel, *From Machine Shop to Industrial Laboratory*, 176-77, 182-83; Reich, *The Making of American Industrial Research*, 153.

reflection of radio waves.[34] There could have been paths to newer electrical technologies that did not go through the telegraph, but the absence of the telegraph surely would have slowed wider electrical innovation.

Even so, later electrical innovations depended on more than the telegraph. The core technical problems were different; knowledge of telegraphy could not solve central problems in lighting, motors, or radios. Though non-electrical techniques supplied important inputs—wire drawing, glass blowing, vacuum pumps, and mechanical design and machining skills—those would not solve electrical problems. Either some knowledge source outside the economy would have to solve them, or electrical inventors would have to supply their own solutions.

Science and Electrical Invention

Scientific knowledge relevant to electrification existed before the telegraph and developed with substantial independence from it. The electric telegraph was one of the first beneficiaries; without the discoveries of Alessandro Volta, Hans Oersted, Michael Faraday, and Joseph Henry, it would not have been invented.[35] Science also could have contributed to later electrification. But what kind of science and how? Advances in pure science such as those of James Clerk Maxwell and Heinrich Hertz affected some invention, but many key inventions rested on well-established science. Science also included applied or engineering knowledge, which evolved in ways that were linked to but substantially independent from pure science. Pure and applied science spread through publications, meetings, and education, which were open to those developing electrical technology, so that science could influence industry. At the same time, the needs, problems, and solutions of industrial technology could have directed science and its diffusion.

The fundamental questions of the relations among pure science, engineering, and technology cannot be answered here. But they can be exemplified in the range of electrical innovations. In addition to inter-

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[34] Aitkin, *The Continuous Wave*, 44-45; Reich, *The Making of American Industrial Research*, 218-38.

[35] Morse had studied electricity at Yale. A professor of art at what was to become New York University, he took part in scientific lectures in New York City. His inventive efforts succeeded only after he made use of the efforts of three leading scientists. Leonard Gale, a chemistry professor at NYU, supplied ongoing scientific support. He also introduced Morse to the work on electromagnetism of Joseph Henry, America's most eminent physicist, insights that contributed basically to his telegraph. Charles Page, another accomplished physicist, solved problems in electrical transmission and reception. Thomson, *Structures of Change in the Mechanical Age*, 244-56; Israel, *From Machine Shop to Industrial Laboratory*, 24-37; Reid, *The Telegraph in America and Morse Memorial.* Compared to Morse's experience, the English telegraph, the product of Charles Wheatstone, a professor of physics, was even more directly tied to science.

actions on the job, inventors could have acquired needed knowledge through their own formal education, informal education in engineering and mechanics associations, readings, and by hiring those who could supply knowledge. Inventors in turn could teach others through similar mechanisms. Such extra-economic learning was essential to electrification.

Moses Farmer and Thomas Edison illustrate such learning. Farmer was educated at Andover and then at Dartmouth, acquiring interests in mathematics. The telegraph introduced him to a communications technique, but also to electrical technology itself. He began electrical invention not with the telegraph but with the railway, with a battery-powered locomotive that he constructed and operated. In 1847, he lectured on the electro-magnetic engine, the railroad, the telegraph, and the submarine battery. In this he was following a wider trend; in the same year, the *Scientific American* presented articles on telegraphs and electric lights to add to earlier articles on electric batteries, medical devices, and steering apparatuses for ships. Farmer and his partner William Channing experimented widely. In 1853, he set up an electric battery exhibition at the New York Crystal Palace Exhibition. How widely Farmer knew scientists is unknown, but he did present a paper at the recently formed American Association for the Advancement of Science, and he was well-enough known that Joseph Henry sought electrical apparatus from him in 1864.[36]

Edison, who started inventing a quarter century after Farmer, had a much poorer education but benefited from a far richer technical environment. More and more recent scientific literature had been published, and the technological literature was deeper and more accessible. Edison studied both, including such scientists as Faraday and volumes on principles and applications of electricity.[37] Just established when Farmer turned to electricity, *Scientific American* had an audience in the tens of thousands weekly when Edison was a telegraph operator; its articles on electricity included a report that the Paris Exposition of 1867 displayed electrical devices including lights, generators, railroad signals and brakes, clocks and chronographs, alarms, engraving methods, and a piano.[38] The *Telegrapher* spread knowledge of electrical science, not simply the

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[36] Henry correspondence, box 1, folder "December 9, 1864"; on 1847 lectures, box 3, folder 6; *Scientific American,* various issues, 1845-1847. The Farmer papers do not document how Farmer learned about electrical techniques. They do include correspondence with Channing about scientific issues concerning electricity, light, heat, chemical properties, and refrigeration. Channing letters, 30 May, 26 Dec. 1860, 24 May, 2 Sept. 1861, 23 Aug. 1867, Moses Farmer Papers, box 1, folder 3. We know from this correspondence that Farmer read the *Scientific American* and did experiments based on articles in it, such as on a magneto (Channing letter, 27 Dec. 1873).

[37] Paul Israel, *Edison: A Life of Invention* (New York, 1998), 37-38, 95-96, 182.

[38] "Applications of Electricity as Seen at the Paris Exposition," *Scientific American* 18 (11 Jan. 1868): 18-19.

telegraph; beginning with an article in 1865, Edison would become a regular contributor, using mathematical presentations in some articles. From 1874, Edison published in *The Operator*, for which he was the science editor. He was an integral part of the technical community of electricians who conducted and discussed experiments, such as the group including Farmer, Williams, and Watson.[39]

Such learning, even supported by Edison's substantial resources and the outstanding research team he had formed since 1870, proved insufficient to develop a practical lighting system. The discontinuity of knowledge was too great. Telegraphy had formed a body of knowledge, and had come to communicate it through journals and books such as Franklin Pope's *Modern Practice of the Electric Telegraph*, which, in fifteen editions from 1869 through the 1890s, described the sources of electricity, measurement, electrical action, electromagnetism, circuits, telegraph equipment, and testing. American telegraphy, based on the simple, dependable Morse system, was even less capable of generating other electric applications than was the more sophisticated British telegraphic engineering. American knowledge could solve important telephone problems and provide key inputs into more distinct electrical technologies. But neither American nor British telegraph technologies could solve more complex problems of long-distance telephony or more basic problems of lighting and power.[40]

Edison had to learn, and he and his telegraph team could not do so by themselves. Two sources of external knowledge proved critical. Edison accumulated a fine library of books and journals on science, engineering, and patenting, which enabled his staff to transcend their on-the-job learning. Many people had developed electric lights since the chemist Humphrey Davy demonstrated incandescent and arc lighting methods early in the nineteenth century. Edison's efforts to apply his telegraph knowledge often failed, so he or his workers studied the literature on such issues as filament materials, insulation, and dynamos. His library, and an able chemist who could translate from German or French, was basic to this task. He also hired people whose knowledge of scientific content and methods proved critical to his invention, including Otto Mayer, a college-graduate chemist, Charles Clarke, a Bowdoin graduate and a mechanical engineer, and especially Francis Upton, who had acquired technical knowledge in studies for a Princeton master's degree and in later work with the German physicist Hermann von Helmholtz. They supplied mathematical and technical insights important for studies of lighting filaments, dynamos, measurement, and much else. Edison was the driving

[39] Israel, *Edison*, 23-24, 40-44, 91-92; Israel, *From Machine Shop to Industrial Laboratory*, 71, 78.

[40] Franklin Leonard Pope, *Modern Practice of the Electric Telegraph* (New York, 1899); Israel, *From Machine Shop to Industrial Laboratory*, 175-78.

innovative force; college-trained workers offered essential support but they did so by contributing to a process that Edison defined.[41]

One might conjecture that science would solve problems in early stages of the product cycle, but then learning by using these techniques would contribute later knowledge, eliminating the need for external knowledge. Edison's success in lighting and power did create powerful learning dynamics within the economy. But his dependence on scientists educated outside the economy increased in his later labs. His West Orange lab depended heavily on scientifically trained workers such as Fessenden and Kennelly. They even engaged in basic research, such as Kennelly's work on magnetism, which when published advanced electrical theory. The dependence on science would be far greater in GE's labs in the twentieth century.[42]

The profound effects of Edison on later invention took two forms. Most evidently, others learned from his inventions, used his equipment, or hired his workers. Less directly, ideas were shared outside the electrical industries. Farmer and Edison both presented in meetings of the American Association for the Advancement of Science (AAAS). Both were members of the American Institute of Electrical Engineers (AIEE); in 1889, they were joined by Farmer's associate William Wallace and nineteen of Edison's workers. Kennelly published his findings in the Institute's transactions. Just as Farmer, Edison, and their associates drew on science, so too did they contribute to it. More broadly, Edison and his competitors posed problems that scientists addressed and demanded labor that scientists trained.[43]

Many others also utilized science in their inventions; many also contributed to science and its dissemination. Open-source knowledge was essential to electrification, as a study of major electrical innovators shows—212 listed in biographical dictionaries as inventors with significant electrical innovation or as electrical engineers. These sources exclude minor innovators, and some major innovators were not included. But the list largely matches the inventors and engineers highlighted in histories of electrical innovation. To examine historical trends, innovators are divided into three cohorts by year of birth. Those born before 1831 had their largest effects before 1865, though Farmer and others had important later effects. All but one of those born from 1831 through 1860 had their first major effects from 1860 through the great spread of electrification in the 1880s. Inventors after 1860 had their biggest effects when electrical uses were maturing and when the radio was beginning.

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[41] Friedel and Israel, *Edison's Electric Light,* 36-37, 96-100, 122-28, 135-37, 173-75, 229.

[42] Israel, *Edison,* 306-12; Reich, *The Making of American Industrial Research*, 62-96.

[43] American Institute of Electrical Engineers, "Directory of Members, Honorary Members, and Associates: May 1, 1889."

Telegraph networks educated about one-fifth of all major electrical innovators (see Table 7). Telegraph networks had the biggest effect early, when they trained four-fifths of inventors. One-third of middle period inventors learned in telegraph networks, but such leaning was insignificant among later inventors. Many later innovators learned in telephone, light, power, and radio networks, so that the economy continued to spread knowledge that fostered innovation.

Table 7
Learning by Major Electrical Innovators, by Age Cohort
(%)

	Before 1831	1831-1860	After 1860	All
In Telegraph Networks	81.0	33.8	3.3	20.8
Formal Education:				
High School	66.7	75.0	97.6	87.3
College	42.9	45.6	85.4	68.4
Any Foreign College	0.0	10.3	18.7	14.2
Post-Graduate	0.0	8.8	48.0	30.7
Early Professor	4.8	13.2	30.1	22.2
Federally supported	0.0	16.2	40.7	28.8
Without College:				
Mechanicians	33.3	26.5	10.6	17.9
Electrical Occupations	23.8	25.0	3.3	12.3
In Professional Assns.	9.5	20.6	2.4	9.0
Extra-economic Learning	76.2	72.1	95.9	86.3
With Professional Assns.	85.7	92.6	98.4	95.3

Sources: Dictionary of American Biography (New York, 1964); *American National Biography* (New York, 1999); *National Cyclopedia of American Biography* (New York, 1898-); *Who's Who in Engineering: A Biographical Dictionary of the Engineering Profession* (New York, 1925).

Notes: The first period included 21 innovators, the second 68, and the third 123. The survey is slightly biased in favor of telegraph networks because they were sampled from telegraph inventors as well as from key words in biographical dictionaries, which picked up a few inventors not categorized as inventors or electrical engineers. This is counterbalanced by selecting notable inventors from prominent histories of electrical industries. High school and college education includes those who finished at least half of the years of such education. Federally supported includes the Military Academy, the Naval Academy, and Land Grant Colleges. Mechanicians here include those who were not college-educated but acquired electrical knowledge outside the economy through study, experimentation, membership in scientific organizations, classes, and similar means.

Whether or not inventors learned in telegraph networks, they also learned outside the economy. Their formal education was extensive. Seven-eighths had a high-school education, including two-thirds of the earliest inventors. Though the content of this education varied, it typically involved exposure to math through algebra and geometry and to natural science. For some it was much more, such as at Central High in Philadelphia, whose students learned from Edwin Houston and Elihu Thomson. Sixty-eight percent of innovators were college-educated, and the share rose from about 45 percent in the first two periods to 85 percent for those born after 1860. The vast majority concentrated in science (especially physics and chemistry), math, and, after about 1880, electrical engineering. MIT, Cornell, and Columbia each had at least ten graduates among the major innovators. Science and electrical technologies were international, and 22 percent of the college-educated in the last two periods attended foreign colleges, half in Germany. Increasing shares went onto graduate education in the United States or Europe. In the third period, 48 percent had graduate education, led by Johns Hopkins (where several studied with the physicist Henry Rowland), Cornell, MIT, and Harvard. Twelve undertook graduate studies in Germany, including two who studied with Helmholtz in Berlin. Twenty-two percent taught at colleges shortly after their graduation; in the last stage the share was highest and the large majority had graduate degrees. The college teachers brought an ability to systematize and convey electrical technology to their later innovative efforts.

College education was clearly significant for electrical innovators, especially for those attending college from about 1880 on, when graduate programs in the sciences expanded and the first undergraduate and graduate programs in electrical engineering were formed. Formal education had always been particularly significant in electrical innovation. For major inventors born before 1831, the 43 percent of electrical inventors who were college-educated was well above the 25 percent share for major inventors of all types, and the share with a high school education, 67 percent, was similarly higher than the 43 percent for all major inventors.[44]

The government played an important role in college education. Forty-two percent of the college-educated received a degree at a federally supported college. None did so in the first period, but 35 percent of the college-educated received degrees from such colleges in the second period, and 48 percent did so in the last period. The nature of such institutions changed. Six of the eleven to gain such an education in the middle period did so at the Military Academy or the Naval Academy, while in the last

[44] On all major innovators through 1866, see Thomson, *Structures of Change in the Mechanical Age*, 112. The data differ from those in this paper because they include those born between 1831 and 1835, a group put in period 2 here. Had electrical inventors been reclassified into the first period, the share of high school and college-educated would have risen a bit.

period only one of the fifty educated in federally supported institutions attended either of the military academies. The rest attended land-grant colleges for undergraduate or graduate degrees, led by Cornell and MIT.

One important question is how those without college education learned. Many did so through informal means outside the economy. They studied electrical and related scientific issues through reading and experimenting in their own home labs. Some attended night school or studied informally at Cooper Union, the Franklin Institute, and at German universities. Such individuals who learned informally off the job are termed mechanicians. Mechanicians without college education included 18 percent of all innovators and 57 percent of innovators without a college education. The share was highest early, when they made up 33 percent of innovators. It fell modestly to 26 percent for middle period innovators, and remained a surprisingly high 11 percent of innovators among later innovators, when the share of college-educated innovators rose substantially. Clearly many non–college-educated innovators learned informally off the job. Many with college educations did so as well.

To measure extra-economic technological and scientific learning, mechanicians can be combined with the college-educated. Seven-eighths of innovators gained such off-the-job learning. This estimate understates the role of extra-economic learning. Formal education mattered for the rest; nearly half had a high-school education, and a few attended college for limited periods. Others learned outside formal education without documentation in their dictionary entries. For some this supplied critical technological knowledge. Many learned in engineering organizations after their electrical careers began, but are not counted as mechanicians because they might have joined those organizations after innovating. If those in professional associations were included, the share with extra-economic learning dominated in every period and grew over time.

The role of extra-economic education varied over time. In the first period, when college education was weakest, mechanicians compensated, and 76 percent of all inventors gained substantial knowledge off the job. The share fell to 72 percent of inventors born from 1831 through 1860 (though if membership in professional associations were included, the share rose to 93 percent). Nearly all of the later inventors learned in colleges or as mechanicians. By 1890s, extra-economic learning was vital, and often indispensable, to electrical innovation. Though Edison, Thomson, Westinghouse, and Bell could initiate major changes with modest scientific education, their successors at General Electric, Westinghouse, and AT&T needed and acquired advanced scientific knowledge to solve problems in long-distance transmission of power, high-voltage AC design, and continental telephone circuits. All three companies would develop electronic technologies by World War I.

Learning off the job was necessary for electrical innovation, but not for each innovator. Many who were neither college-educated nor mechanicians learned on the job in electrical occupations with their own networks.

Such network-trained innovators included 12 percent of all inventors, with a peak of 25 percent among middle period inventors. Initially most of them were trained in telegraph networks, but later they spread among other electrical technologies. These innovators also learned off the job. Almost three-quarters of them were members of professional scientific and technical associations, where they had the opportunity to learn from meetings and journals. Though the evidence does not indicate whether they learned through such means before their innovation, surely many did. Of course, the college educated and mechanicians also learned through economic networks; many of the key problems they solved developed in the course of invention and product commercialization.

The beneficiaries of open-source learning, many major innovators contributed to others in the same way. They often did so in professional societies. The Franklin Institute served this function from the 1820s through its journal, meetings, and classes. The American Association for the Advancement of Science did the same from its inception in 1848. More specialized groups, such as the American Chemical Society, formed in 1876, and the American Physical Society, formed in 1899, targeted particular science disciplines. The most important group focusing on electrical engineering was the American Institute of Electrical Engineers, formed in 1884 with the goal of advancing knowledge through meetings of members, including "electrical engineers, electricians, instructors in electricity in schools and colleges, inventors and manufacturers of electrical apparatus, officers" of companies "based upon electrical inventions," and other interested parties. The AIEE had about 330 members (including honorary members and associates) in 1889 and expanded considerably afterward. It held periodic meetings and published the transactions.[45] Four-fifths of major innovators were members of such scientific and engineering associations, with larger shares among later innovators (see Table 8). In these associations, innovators learned from others but also contributed to their advance.

Major innovators often spread knowledge by writing. Two-thirds published articles and books on scientific, engineering or inventive topics, often in the journals of scientific and engineering societies. The share of major innovators publishing technical texts increased from 43 percent of early inventors to 73 percent among innovators in the last period.[46] At

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[45] "Historical Preface," *Transactions of the American Institute of Electrical Engineers* 1 (May 1884), paper 1, p. 1. On 1889 membership, see American Institute of Electrical Engineers, "Directory of Members, Honorary Members, and Associates: May 1, 1889"; Israel, *From Machine Shop to Industrial Laboratory*, 173-75.

[46] Innovators also edited and formed journals. Franklin Pope moved from editing the *Telegrapher* to the *Electrician*, a change that reflected the widening of electrification. He also published in IAEE's *Transactions*, and, in recognition of his inventions, his publications, and his editorships, IAEE selected Pope to be its second president.

Table 8
Knowledge Dissemination among Major Electrical Innovators
(%)

	Before 1831	1831-1860	After 1860	All
Technical Associations	42.9	83.8	85.4	80.7
Authors	42.9	58.8	73.2	65.6
College Professors	4.8	11.8	26.0	19.3

Source: Calculated from data; see Table 7.

times publications propounded the author's own inventions, and were thus adjuncts to their economic interests. But more often, the writings concerned nonproprietary matters of solutions to engineering problems or scientific principles, though they often underpinned inventions. In its first four years, the *Transactions of the American Institute of Electrical Engineers* included many dozens of engineering articles. In the first issue, Edwin Houston published two articles on incandescent lighting and synchronous movements in electrical machinery, and others published on chemistry of the carbon filament. The third volume discussed the Cornell galvanometer, along with telegraphs, telephony, and electric light and power. By 1887, *Transactions* published papers from special meetings on lighting from central stations, electric railroads, motors, and from general meetings, including two papers by Cornell professors. The 1887 volume alone included publications by fifteen of the electrical inventors appearing in biographical dictionaries. Later issues became more technical and mathematical. For example, Michael Pupin published mathematical articles on telegraphy and loading coils as he was patenting those inventions.[47] Through such publication, industrial innovators advanced science, but they also learned from science.

This freely provided knowledge could be and was used to invent, at times by the authors themselves. Pupin presents an interesting example. Having completed a Ph.D. with Helmholtz in Germany, where he witnessed Hertz's experimental justification of Maxwell's theories, he was

[47] *Transactions of the American Institute of Electrical Engineers*, 1-4 (1884-1887). Inventors did not want to forgo their proprietary interests, and this affected the timing of publication. Pupin often published after he had filed patents based on the principles laid out in publications, suggesting that he deferred publishing until he filed patents. Much the same was true for GE and AT&T researchers; the timing and content of publication was controlled so that it would not undercut the company's profitability. Publication was justified because it enabled the firm to attract better researchers, enabled authors to learn from scientific networks, and bolstered the reputation of the firm with potential employees, scientists, and government regulators. Reich, *The Making of American Industrial Research*, 110, 118-20, 189, 195.

appointed a professor of electrical engineering in Columbia's newly established department. There he published important papers in the *American Journal of Science* and *Transactions of the American Institute of Electrical Engineers*. His physics background was displayed in his patents. His first patent, which developed principles of electrical tuning for long-distance telegraph, telephone, or other transmission, read like a science paper. It cited several of his articles, developed his claims from defined physical characteristics, and identified a series of equations that supported the patent claim. His loading coil patents referred to the scientific literature four decades earlier from Lord Kelvin and Gustav Kirchhoff, and based the principles of the patent on the equations in an AIEE paper of the previous year.[48] More generally, published knowledge complemented inventions by identifying materials, testing methods, and circuitry that could render inventions more practical.

Finally, many innovators became professors of physical science, math, or engineering after their innovations. The share increased from 5 percent among the earliest innovators to 12 percent in the middle period, and to 26 percent in the last period. They went mostly to physics and newly formed electrical engineering departments. Cornell, Columbia, and MIT led with five; Harvard had four. As professors, they provided specific knowledge to their students, along with knowledge of how to define questions and investigate them experimentally and theoretically. Some had many students who themselves innovated. Several innovators began whole programs. After a successful career designing motors in his own firm, Francis Crocker created the electrical engineering department at Columbia in 1889 with Pupin as his only initial colleague. After a career at Westinghouse developing Tesla's polyphase motor and methods of long-distance energy transmission, Charles Scott headed Yale's electrical engineering department in 1911. Their background as innovators and industrialists provided the faculty with a kind of applied knowledge that those without practical experience were unlikely to possess.[49] These innovator-professors helped create a supply of innovators and engineers involved in invention, testing, implementation, and, late in the period, organized research and development.

The Deepening Interfusion of Science and Technology

Over its whole technological history, electrification involved economic actors and others acting outside the economy. Science and technology both

[48] U.S. Patents 519,346 and 652,230.

[49] Noting how the content of electrical engineering education was highly technological and how professors were often industrially trained, one scholar argued for "industry-based science" rather than "science-based industry." Of course, both could have been apt. Wolfgang Konig, "Science-Based Industry or Industry-Based Science? Electrical Engineering in Germany before World War I," *Technology and Culture* 37 (Jan. 1996): 70-101.

evolved, but they had different purposes, institutions, and modes of knowledge dissemination. Firms tried to make profits by commercializing innovations through markets for electrical products, patents, specialized labor, and equipment; knowledge spread through product sale and cross-firm networks as well as through publication in Patent Office volumes and trade journals. Colleges, scientific and engineering societies, and individuals pursued wider goals through relations to students and fellow scientists; knowledge spread through education, meetings, and publication. As electrification evolved, so did the relationship between science and technology.

From 1840 through 1865, electrical innovators frequently called on science, but often in a consultative mode. Morse and later innovators learned from scientists and read scientific literature. Occasionally scientists invented, such as Charles Page, but their inventions were not fundamental. In its turn, electrical science advanced largely separately from electrical technology, expressed most strongly in Maxwell's wave theory of electrical and magnetic fields published at the end of this period. Later electrical innovators benefited from electrical knowledge organized through occupations of electricians and self-proclaimed electrical engineers, though they commonly learned on the job and as mechanicians. Innovation improved telegraphs but had little success in other electrical techniques. Moses Farmer's lab at the end of the period, which in the late 1860s impressed Edison for its completeness of equipment and materials, was a leading locus of innovation, though it was a small operation, with Farmer the principal investigator, tucked above Williams' electrical instrument shop.

Science played a more integral role in the great proliferation of electrical innovation later in the nineteenth century. Economic networks, initially organized around the telegraph, structured innovation in other electrical technologies, but innovators drew on extra-economic knowledge from many new sources. Pure science developed, led by Hertz's demonstration of Maxwell's wave theory. Of more practical importance, education in physics and chemistry spread in private colleges such as Johns Hopkins, Harvard, and Columbia and in land grants led by Cornell and MIT. Firms hired increasing numbers of workers trained in colleges and graduate schools. Edison relied on several in his labs. American Bell hired its first two Ph.D.'s, one trained by Rowland at Johns Hopkins and the other at Harvard, to replace two legacies of telegraph networks, Watson and Gilliland, in the firm's Electrical and Patent Department and Mechanical Department, respectively. Mediating institutions linked pure science and industry. Publications proliferated in telegraphy and electricity. Engineering societies expanded, culminating in the formation of the AIEE in 1884. Colleges formed electrical engineering departments from the 1880s, though their big impacts came later. Industry posed problems that academic engineers and physicists addressed. In this transitional period, Edison had the largest lab, aimed at inventing for contract and for patent sale, but it did not integrate into manufacturing. Leading firms conducted organized research, though it was linked closely to their ongoing testing and engineering activities.[50]

Major changes occurred in the twentieth century. Electrical equipment firms and utilities increasingly hired scientists and engineers to solve complex problems requiring mathematical and experimental sophistication. The supply of these workers surged as graduate and undergraduate physics, chemistry, electrical engineering, and mathematics departments were formed or strengthened around the turn of the century. Bachelor degrees in electrical engineering in New York state grew from 43 in the 1880s to 585 in the 1890s and to 2,112 in the 1920s, led by Cornell.[51] The quality of education grew in part because experienced workers and inventors became professors, especially in engineering departments. Major firms had close relations to those departments, often offering internships to promising students. Inventors and workers published extensively, and the publications became more mathematical. Independent inventors still played a major role, especially in newer technologies such as the radio. Contract inventors, whose products were engineering and inventive services, persisted, though they never regained the centrality Edison had achieved in the 1870s and 1880s. But large firms now undertook their own systematic research. Some of this remained located in testing and engineering divisions, but the first modern R&D labs formed, which employed scientifically trained workers in their own division to undertake research into basic technologies that could yield important new products. GE's lab, formed in 1900, justified its existence by developing ductile tungsten filaments, and then ventured into radio and X-ray tubes. AT&T's lab, formed in 1911, adapted the triode to solve problems of long-distance telephony, and then solidified its position in radio and vacuum tubes. Employment in its labs grew to 400 by 1921 and to 3,600 when Bell Labs formed in 1925. Western Union came around only when AT&T reorganized its research arm.[52] The increasing integration of electrical industry and science rested on new, mediating organizations such as college engineering departments, engineering societies, and organized R&D.

Science did not replace industrial leadership. Though the telegraph no longer led in the twentieth century, electric light and power companies vied with telephone companies to dominate the electronics revolution that

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[50] David A. Hounshell, "The Modernity of Menlo Park," in *Working at Inventing: Thomas A. Edison and the Menlo Park Experience*, ed. William S. Pretzer (Baltimore, Md., 2002), 116-33; Reich, *The Making of American Industrial Research*, 143-44.

[51] Michael Edelstein, "The Production of Engineers in New York Colleges and Universities, 1800-1950: Some New Data," in *Human Capital and Institutions: A Long Run View*, ed. David Eltis, Frank D. Lewis, and Kenneth L. Sokoloff (New York, 2009), 202-9.

[52] Reich, *The Making of American Industrial Research*, 62-96, 151-84.

had major commercial payoff with the formation of RCA and the spread of the radio in the 1920s. Leading economic sectors and extra-economic science had combined to spread electrification from the telegraph to illumination, power, telephony, and transportation in the last quarter of the nineteenth century, and those new sectors, ever more tightly linked to science, combined to lead electrical development in the twentieth.