Business and Economic History On-Line
Vol. 2 2004

From the Old to the New: The Social Basis of Innovation in the Antebellum United States

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Between 1830 and 1865, a series of major innovations arose that reshaped the nineteenth-century American economy. These innovations cannot readily be explained by the dynamics of existing industries or firms because they created industries and were developed largely by new firms. In a comparative study of the railroad, the telegraph, the reaper, and the sewing machine, I advance an institutional argument for the origins and development of innovations. Each innovation fundamentally depended on knowledge communicated through machinery sector institutions, the pure and applied scientific community, and institutions surrounding invention. As each developed, it formed its own institutions (including firms, occupations, and relations with government and scientists) that shaped the innovation's development. Innovations followed different paths because they involved different kinds of knowledge, evolved out of different institutions, and built networks with different ties to science, machinery sectors, and users. That so many distinct innovations arose attests to the importance of economy-wide machinery, and scientific and inventive institutions. Patent records, census manuscripts, biographical dictionaries, contemporary documents, and case studies provide evidence for these contentions.

In 1866, the *Scientific American* proclaimed "the last quarter of a century unparalleled in world's history" for its advances in science, invention, and wealth. As evidence, it listed the telegraph, reaper, railroad, steamship, sewing machine, and the growth of new kinds and locations of mining.[1] These were fundamental innovations; in the United States they reshaped transportation, communication, agriculture, and manufacturing in and after the middle third of the nineteenth century.

The origin and development of these innovations cannot be explained by the dynamics of existing industries or firms, because they created industries and were developed largely by new firms. Moreover, they responded to different needs and developed in distinct regions

[1] "Twenty-five Years: A Retrospect," *Scientific American* 15 (15 Sept. 1866), 180.

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URL: http://www.thebhc.org/publications/BEHonline/2004/Thomson.pdf

through differing processes, and so cannot be understood in terms of the same factors. The problem is how a wide range of economy-shaping new sectors arose when no established industries or firms formed them. Given this discontinuity, one might argue, as Joseph Schumpeter did, that economic development was led by the ungrounded action of extraordinary entrepreneurs.

A more institutional interpretation might lead to different conclusions. According to the *Scientific American* the "secret" to this success lay in the activity of "the inventor and the mechanic...the pioneers in the great army of progress." The two groups formed a social basis for understanding innovations. Inventors were organized around a patenting system that transmitted knowledge of technological problems and solutions and that provided avenues for commercializing innovations. The *Scientific American* was part of that system through its descriptions of patented inventions and the activity of its patent agency, the largest in the world. Mechanics were organized in a machinery sector, which applied knowledge of machine design and production. Elsewhere, the *Scientific American* added the scientist to the inventor and mechanic, noting how scientific advances formed new principles with technological uses.[2]

Institutions surrounding machinery, invention, and science provided knowledge, contexts, and personnel enabling potential innovations to be actualized. The origins and development of major innovations can only be understood in the context of these institutions. At the same time, as Schumpeter argues, major innovations were discontinuities that broke with existing patterns and initiated developmental sequences. The challenge is to explain how innovations were both discontinuous and grounded in existing institutions.

Understanding Innovation

In his early works, Joseph Schumpeter provided a classic, perceptive (but I believe flawed), interpretation of innovation. Many notions of innovation share two of its core features. First, innovation is a qualitative break with existing practice, a creative transformation of existing conditions, not a mere adaptation to changed circumstances. As such, innovations are subject to a fundamental uncertainty: innovators cannot know what will succeed or how. Their actions are exploratory, and any act might reveal a series of problems not anticipated when the process began. This sequential, problem-solving, evolutionary character is a fundamental attribute of innovation.

Second, innovations have consequences that shape the future path of growth. For Schumpeter an innovation typically led to the formation of a new firm that invested in producing a new commodity or using a new

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[2] Ibid.; "The Scientist, Inventor, and Mechanic," *Scientific American* 20 (10 April 1869), 233.

technique. The innovator's advantages generate profits and further investment, though perhaps after a protracted period. Investment generates demands for equipment and labor. Perceiving potential profits, other firms enter. The initial innovation leads to a stream of induced innovations by the innovator, entrants, and input manufacturers. Some sectors decline as new ones arise. When others enter using or making the new technique, entrepreneurial profits decline, and the innovation becomes routine. This is a powerful depiction of an endogenous dynamic associated with product cycles or general-purpose technologies.

A third attribute of Schumpeter's formulation is problematic. Schumpeter locates innovation in the confines of a changeless economy in full equilibrium. For him economic theory was the domain of equilibrium analysis, and he insisted that we must think about innovation as a movement beginning from equilibrium. Though he recognized that past changes condition present changes, he considered it illegitimate to explain change through these historical linkages, insisting that we think of present change without regard to the past.[3]

Schumpeter identified the problem insightfully: economic change is an extra-equilibrium, innovational, evolutionary process. However, his strategy, to think of development as though it arose from equilibrium, gets in the way of a solution. The basic flaw is to understand change as disembodied, separated from other changes, and from the institutional context giving rise to it. Wrenched from context, innovation can only be understood as discrete acts of entrepreneurs, development's heroes, making use of extraordinary personal qualities. Innovation becomes an act of will. Schumpeter allows that the entrepreneur can make use of the thoughts of others, but it is the doer, not the knower, who leads economic development. The innovations that lead economic evolution begin from an ahistorical, changeless world.[4]

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[3] For example, "Every process of development creates the prerequisites for the following." *Theory of Economic Development* (Cambridge, Mass., 1991), 64. He equally rejected appeals to underutilized resources as directing innovation. In addition to *The Theory of Economic Development,* Schumpeter develops these arguments in *Business Cycles* (New York, 1939) and many articles. *Capitalism, Socialism and Democracy* (New York, 1942) breaks from this interpretation in some ways in allowing for the possibility of a corporation permanently innovating through organized R&D (Research and Development).

[4] One might wonder why Schumpeter maintained the fiction that innovations began from equilibrium when he recognized the historical origins of innovations. Schumpeter viewed his theory as a complement to neoclassical equilibrium theory, and hence tried to interpret innovation as consistent with that theory. Had he been a modeler, he might also have argued that to isolate the importance of innovation, one needs to simplify by holding constant the environment in which it occurs. The modern literature on general-purpose technology proceeds along these lines; see Timothy Bresnahan and Manuel Trajtenberg, "General Purpose Technologies: 'Engines of Growth,'" *Journal of Econometrics* 65 (Jan.

Another course is open. If capitalism is understood as a historical system, never in equilibrium, the sources and consequences of innovation have a different interpretation. The economy at any time might provide conditions for later and direct innovation in ways that use excess resources, including unemployed plant and labor and especially underused knowledge and skill. Widely available knowledge can direct innovation, while the unevenness of knowledge distribution provides advantages to some. Because the acquisition of knowledge is also socially structured, whole networks of people with useful knowledge have access to others with this knowledge. Interactions that occur in the process of developing knowledge may be central to successful innovation. Non-economic activities can be essential. Though capitalist innovation is inherently economic, intellectual and political forces that shape knowledge and distribute resources can fundamentally condition it. One might even contend that the more radical the technological change (that is, the less grounded in economic knowledge and practice), the greater the role of these non-economic factors.

If an innovation's origin is socially shaped, so too is its further development. Born out of interactions, the innovation creates its own networks of firms and occupations. Through these networks, many more individuals contribute to its evolution. Thus, innovation may be collective, rather than the act of a single individual. The clustering of innovations about which Schumpeter speaks may involve linked innovations within a technological system, or quite independent innovations, perhaps supported by the same institutions. Because of the effects of innovations, the economy may never reach equilibrium, but instead it may create conditions and serve as an agent for further innovations.

This historical interpretation of innovations remains evolutionary, though now evolution has an institutional organization that structures the learning process, akin to modern evolutionary theories of the economy. To concretize this interpretation requires identifying relevant institutions and how they shaped innovation. In looking at several antebellum U.S. innovations, I focus on institutions that structured and spread technological knowledge in the machinery sector, the scientific community, and inventive activity. I argue that these institutions created conditions for disparate innovations to arise and to form institutions that governed their ongoing development. Supporting this thesis requires sources that can illuminate broad networks of interaction, not just individual inventors or firms. Census manuscripts, patents and patent assignment records, biographies, and technical journals, when coupled with strong case studies, help in this task.

1995): 83-108; Elhanan Helpman, ed., *General Purpose Technologies and Economic Growth* (Cambridge, Mass, 1998). Two reflections might be appropriate. First, one must be aware that such theories lead us away from proper historical interpretation. Second, other theories are developed along more historical lines, including Edith Penrose's theory of the firm and the evolutionary theory inspired by Richard Nelson and Sidney Winter.

The Railroad

"Add successively as many mail coaches as you please, you will never get a railway thereby."[5]

The railroad, Schumpeter's classic example of a discontinuous change, was a British innovation led by George Stephenson and his son Robert. They developed successful locomotives and boilers containing the fundamental features of all steam locomotives, put them into use, and in 1830 installed locomotives on the first major railroad line, the Liverpool & Manchester. Their firm became the largest locomotive manufacturer and the railroad quickly diffused. In 1831, a Stephenson locomotive imported by Robert L. Stevens for the Camden & Amboy Railroad first achieved success in the United States. In the next 3 years, steam-powered railroad lines were set up in New Jersey, Maryland, Pennsylvania, South Carolina, Massachusetts, and Delaware. Investment expanded so rapidly that by 1840 the 2800 miles of U.S. railroad track exceeded British mileage. By 1860, the United States was home to half the world's railroad mileage.

How could such a radical change develop so quickly? Constructing a railroad challenged the capacities of even the most advanced countries. A railroad, simply put, used steam locomotives to pull cars on fixed tracks. Though people or animal-driven railways had long been used in European mining, steam engines were practical in England beginning in 1776 and in the United States in 1812. The railroad was qualitatively different. The engine and boiler had to be redesigned for use as a locomotive, and new means to transmit power to wheels had to be developed. Cars had to be designed along with mechanisms to join them together. Producing the thousands of parts of the locomotive, railroad cars, and weight-bearing wheels required sophisticated metalworking capabilities. Brakes, signals, durable track, and adequate roadbed were required. The engineering tasks of identifying track widths, laying out lines, and building bridges were formidable. To these technological requisites were added the economic and legal problems of financing roads, identifying markets, and securing rights of way.

Quick success in the international diffusion of technology was highly exceptional. While textbook economics might suggest that best-practice technology would diffuse immediately, many barriers prolonged or prevented diffusion. The United States was more like the textbook case. The strong demand for land transportation improvements created a potential market in many countries. Two factors contributed to realizing this potential in the United States. First, by 1830 the United States had formed the capabilities and institutions to develop and diffuse machinery, applied science, and inventions, all essential to railroad innovation.

[5] Schumpeter, *The Theory of Economic Development,* 64 note.

Second, networks concerned with railroad development quickly formed, creating conditions for many to innovate.

Embedded Beginnings

Through the construction of turnpikes, canals, and steamboats, Americans had proven quite able to raise large sums of money and organize infrastructural projects. As the Erie Canal progressed and the steamboat system expanded, these investments seemed warranted. However, their very success may have made it more difficult for a new, uncertain technology to compete: at least unless its prospects seemed secure. Institutions developed since 1800 to make machinery, advance transportation, and generate new techniques improved these prospects.

The machinery sector contributed organization, capabilities, and personnel. By 1830, this sector was organized around capital goods markets and the machinists' occupation. Machinery firms designed and made machines, commonly casting and machining parts, and interacting with purchasers around design, servicing, and repair. Locomotive firms adopted this structure; railroads, like steam-engine users, typically did not make their own machines. Machinery firms depended heavily on hand methods, but since the 1820s they had access to industrial lathes and boring machines, and their design skills benefited greatly from their construction of high-pressure stationary and marine engines. American machine shops lagged behind their English counterparts, but not by enough to make them uncompetitive. In the most advanced locomotive shop in the world, Robert Stephenson still overwhelmingly used hand methods in 1837. American firms were not far behind, and benefited from proximity to users and the tariff on imported locomotives.[6]

The machinery sector trained locomotive makers. According to the Steam Engine Report of 1838, which succeeded in listing almost every steam engine in the United States together with its user and producer, 24 domestic firms made locomotives that year. Most of the early locomotive producers had produced steam engines prior to making locomotives. Using steam engine design and production skills, they made over 70 percent of 263 domestically-produced locomotives. The capability to design boilers, engines, and transmission mechanisms, to cast cylinders and valve parts, and to machine engines proved invaluable to locomotive construction. Machinery firms typically made a variety of products, and readily added locomotives. Two textile machinery firms made one-sixth of domestic locomotives, led by the most important textile machinery producer, Locks and Canals, which made machinery for the Lowell factories. At the time it entered locomotive

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[6] Ross Thomson, "The Machinery Sector as a Center of Technological Change in Antebellum America;" paper presented to the University of Vermont Economics Workshop, Burlington Vermont, 2003; Brooke Hindle and Steven Lubar, *Engines of Change: The American Industrial Revolution, 1790-1860* (Washington, D.C., 1986), 133.

production, Locks and Canals was also diversifying into machine tools and other products, wary of the slowing growth of the textile industry. Other producers had been machinists or iron founders.[7] Related metalworking firms made railroad cars, wheels, and auxiliary equipment. Without prior machinery firms, locomotive firms could not have developed as rapidly.

Machinists who made machines also used machines. Steamboat and steam engine firms employed what were called engineers to use and maintain engines, and textile firms employed machinists to set up and maintain machinery and to make tools. Railroad firms followed the same pattern. From the beginning, they hired machinists to operate, service, and repair locomotives and cars. When Robert Stevens needed a mechanic to assemble his first imported engine, he hired Isaac Dripps, who had skillfully repaired Stevens' steamboat engines. Like the steamboat engineer, the locomotive engineer was skilled in engine operation and repair, and often had an effect on engine design. The repair facilities companies built to maintain equipment included foundries, blacksmith shops, and machine shops equipped with boring machines and lathes. Railroad firms designated master mechanics who had responsibility for maintaining, purchasing, and even designing equipment.

Similarly, civil engineers applied skills learned in building canals, roads and bridges to railroad construction. Railroad companies sought engineers to identify routes that minimized ascents, descents, and curves and to build railroad lines, tunnels, and bridges. Canal and turnpike companies employed engineers initially to design and produce the project and then to maintain and improve it. Design and construction work took a year or two, after which many engineers sought employment elsewhere. Through this process, the Erie Canal had become the school for canal construction, and its graduates moved to other canals. After 1830, they also moved to railroads. Like canals, railroads employed teams of engineers to survey routes and build track, bridges, stations, and yards. As the lines opened, head engineers were employed as masters of the road, responsible for maintenance and improvement of the lines and coordination with master mechanics.

The Baltimore and Ohio Railroad Company (B&O) was a leader in construction. As the name suggests, it planned a line from Baltimore to the Ohio River, though it took a quarter century to complete this task. In 1827, it received the aid of three brigades of federal army engineers, who were used to support transportation projects since 1824. The leaders were outstanding, including the great explorer, topographical engineer, and locomotive inventor, Stephen Long, and the canal engineer William McNeill. McNeill, fellow officer and surveyor George Whistler, and Jonathan Knight, former National Road surveyor, joined the mechanic

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[7] U.S. Treasury Department, "Steam-Engine" (1839), 25th Congress, 3d sess. (Serial no. 345), H. Doc. 21; Thomson, "The Machinery Sector."

Ross Winans in the Baltimore and Ohio railroad team examining English railroads in 1828 and 1829. The inclusion of three civil engineers indicated the importance of the road in the company's deliberations. This began a long stream of major engineers associated with the B&O, including Benjamin LaTrobe, son of the eminent early civil engineer, who extended the B&O to Washington, D.C. and west from Harper's Ferry, West Virginia. The B&O quickly and effectively developed its lines through difficult terrain due to contributions from engineers trained on canals and roads, and federally-trained engineers (most from the United States Military Academy) who the government authorized to support private railroad improvement.[8]

The United States already had formed a highly communicative group advocating invention. This group was organized around inventive success and occupations that contributed to it, the patent system, and technological communication. In a country where the steam engine was widely used in river transportation, the railroad was a natural. Early steam-powered vehicles were representative of this interest. The case for railroads was so strong that John Stevens, an early engine inventor and steamboat pioneer, published a pamphlet in 1812 arguing that steam-powered railroads were superior to canals and would be a better investment than the Erie Canal.[9] Stevens secured railroad acts from New Jersey and later Pennsylvania, built a small-scale train, secured two railroad patents in 1824, but did not complete a working railroad. Others followed suit, including the Baltimore merchants seeking Western trade who formed the B&O in 1827. Institutions and individual initiative provided knowledge of English railroad developments. From 1826 *The Journal of the Franklin Institute*, the premier U.S. technical publication of the day, included many often-detailed assessments of British locomotives and railroads. Delegations of interested parties examined British railroads, including the team from the B&O, Robert L. Stevens as his father's successor in New Jersey railroad interests, and Horatio Allen, representing Pennsylvania interests. These groups and others were in frequent communication about internal improvements, making the railroad a matter of international discussion on both sides of the Atlantic.

Making use of these interests and capabilities, the United States became a fast emulator. It did so by forming networks making use of its advantages and connections. Even before railroad success, a network arose that dispersed learning across the railroad sector, and this network would develop alongside the railroad. Networks developed within firms,

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[8] Colleen Dunlavy, *Politics and Industrialization: Early Railroads in the United States and Prussia* (Princeton, N.J., 1994), 56-59; *A Biographical Dictionary of American Civil Engineers*, 2 vols. (New York, 1972, 1991); Daniel Hovey Calhoun, *The American Civil Engineer: Origins and Conflict* (Cambridge, Mass. 1960).

[9] John Stevens, *Documents Tending to Prove the Superior Advantages of Rail-ways and Steam-Carriages over Canal Navigation* (1812; Boston, 1936).

but also between them. American delegations to Britain were given wide access to locomotives and the layout of railroads. American locomotive producers emulated British success, including Peter Cooper, whose Tom Thumb, built for the B&O, was designed, according to his autobiography, to show that locomotives could run effectively on sharply curving tracks. Most domestic producers copied the Stephenson locomotive, which was not patented in the United States. Matthias Baldwin, a Philadelphia machinist, engine-maker, Franklin Institute officer, and builder of a model train for Philadelphia's Peale Museum, was asked to build a locomotive for a local firm. He closely copied the Stephenson locomotive after having observed its assembly for the Camden and Amboy. Railroad companies showed their locomotives to others, including prospective locomotive makers such as Baldwin, whose observations of two engines shaped his own locomotive design.[10]

The sale of locomotives formed networks spanning many railroads. The large majority of railroad companies bought locomotives rather than making them in-house, and locomotive firms offered standard models that varied only in detail. Locomotive firms sold their product on national and international markets. Whereas English steam engines were never numerically significant in the United States, English locomotives dominated the early industry and even in 1838 comprised one-quarter of all U.S. locomotives (see Table 1). Interestingly, use of English locomotives was concentrated in the South, which had less than one-quarter of all locomotives but more than half of English imports. Domestic producers were somewhat concentrated by region, with over three-quarters of their output used within the region of production. However, interregional locomotive sales were important, especially for leading firms. Baldwin was the most diverse. Its locomotives, which comprised 26 percent of the national total, were used by 23 railroads, 9 outside the Mid-Atlantic states. Railroad master mechanics often worked closely with locomotive producers. Railroads often ran locomotives from different producers: in 1838 the Boston and Providence used locomotives from Baldwin, Norris, Locks and Canals, the Newcastle Manufacturing Company, and three British firms. The Philadelphia and Columbia employed machines from five domestic and one foreign producer. Master mechanics knew the strengths and weaknesses of all and communicated this information to locomotive companies.[11]

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[10] Peter Cooper, *A Sketch of the Early Days and Business Life of Peter Cooper* (New York, 1877); John H. White, Jr., *A History of the American Locomotive: Its Development, 1830-1880* (New York, 1968); Hindle and Lubar, *Engines of Change*.

[11] The Steam Engine Report of 1838 reports the firms that made the locomotives operated by each railroad, providing knowledge of the diversity of locomotive firms used by the same railroad and the diversity of railroads to which a locomotive firm sold.

TABLE 1
Regional distribution of locomotives, 1838

		Regional Shares of Use			
Construction Location	**Number**	**Mid Atlantic**	**New England**	**South**	**West**
Atlantic States	203 (58.7%)	82.3%	3.9%	9.9%	3.9%
New England	42 (12.1%)	78.6%	21.4%	0%	0%
South	15 (4.3%)	0%	0%	100%	0%
U.S. Total	260 (75.1%)	66.9%	15.6%	13.3%	3.0%
England	86 (24.9%)	29.1%	14.0%	54.7%	2.3%
Overall	346	58.1%	15.3%	23.7%	2.9%

Source*:* U.S. Treasury Department, "Steam-Engine" (1839) 25th Congress, 3d sess. (Serial no. 345), H. Doc. 21.

Notes*:* Regions are conventionally defined. Regional share of use is the share of the number of locomotives produced in a region used in each region; for each construction region the shares of use sum to 100%.

Machinists and civil engineers' mobility among railroads and locomotive firms also helped spread knowledge. The B&O experience was repeated around the country. Early railroads all sought experience from trained surveyors and civil engineers, typically trained in other sectors. A study of biographical dictionaries of civil engineers who had begun their careers by 1835 suggests the dimension of the transfer to railroads was massive. Of 81 civil engineers active through 1835, railroads employed 49 by 1840. Given that a dozen early engineers were inactive by 1830, about two-thirds of active engineers were involved in railroads in the 1830s. At least half had been trained in canals; many others had worked on surveying, water supply, and bridge-building. However, unlike machinists, many engineers were trained in colleges, including one-half of early engineers. Clearly, railroads benefited from this combination of training in colleges and in earlier infrastructural employment. The government also contributed mightily; one-half of the college-trained received their degrees from the Military Academy. Many others who did not merit biographies were also trained in canals and surveying, though no doubt a lower proportion had college degrees. The government's role was wider yet; 14 army engineers worked for the B&O through 1830, and in 1837, 54 Military Academy graduates, many now out of the Army, worked in railroad surveying and construction. The prior history of transportation improvements and military training provided strong underpinnings for early railroad success.[12]

Locomotive firms interacted closely with users concerning the design and servicing of their engines. After having visited England for the Delaware & Hudson, Horatio Allen moved to the South Carolina Railroad early in the 1830s and to the New York & Erie late in the decade. Machinists also moved among locomotive firms, including James Harrison, who was trained by Norris but worked for another Philadelphia firm, Eastwick and Garrett, where he ultimately became a partner. Early B&O construction trained later prominent engineers, including Wendel Bollman, who became foreman of bridge and master of the road for the B&O, Ellis Chesbrough, who later worked with Long and McNeill and was engineer on New England and Ohio railroads, Henry Ranney, who was chief engineer for the Lexington & Ohio and the New Orleans & Nashville in the mid-1830s, and Squire Whipple, who surveyed other railroads and developed bridge designs. Civil engineers such as George Whistler occasionally moved into locomotive construction, demonstrating the embeddedness of railroad development. A Military Academy graduate, Whistler was taught mechanical drawing at West Point and surveyed before joining the B&O delegation to England. On returning, he worked with the B&O and four other railroads. In 1834, he became the superintendent of the Locks and Canals machine shop, where he organized that firm's entry into locomotive construction.

Publications provided a more public form of knowledge integrating the railroad sector, widely spreading knowledge. The *Journal of the Franklin Institute* was a regular source of information, presenting two-dozen articles in the decade after 1826, including descriptions of British railroads and assessments of locomotives of Baldwin and Winans. From its inception in 1831, the *American Railroad Journal* discussed business conditions and described new innovations, and quickening diffusion. A flow of other publications, often issued by railroad engineers, addressed topics such as railroad design and bridges. Stephen Long, after surveying the B&O, was author of a series of books, including the *Rail Road Manual* in 1829, which provided studies of track grades and curvatures, and two later publications on railroad bridges.

Practical locomotives spread and developed through railroad networks. Network linkages spread knowledge of the Stephenson locomotive from the Camden and Amboy through Baldwin to Locks and Canals. This locomotive was not fully practical, and Americans had to adapt it to their own circumstances. American railroads were not easy on locomotives. Tracks navigated mountainous terrain with substantial inclines. Lower population densities reduced expected usage per mile.

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[12] Prominent engineers were identified using *A Biographical Dictionary of American Civil Engineers*. On the importance of military engineers and shared knowledge, see Dunlavy, *Politics and Industrialization*, 58-64, 154-55.

While these factors lowered land prices per mile of track, they increased distances, reduced expected revenues, and required means to transverse greater altitude changes. American roads accepted greater inclines and curves to secure savings in construction costs. In these contexts, the Stephenson locomotive had two major defects. It was too heavy for American tracks, which were typically wood with an iron covering. Even with adequate tracks, the Stephenson locomotive was too long to navigate the sharp curves of U.S. tracks without derailing.

Invention to solve these and other problems began even before locomotives were imported. While sailing to England to purchase his engine, Robert Stevens designed the T-rail, a rail shape that supported the train and controlled its motion, which was also cheaper than British rails and attachment mechanisms. This solution was applicable in the United States as well as elsewhere, but spread slowly in the United States. John Jervis overcame the second defect in 1831. Jervis was involved in the railroad from its beginnings. As engineer of the Delaware and Hudson, a coal canal in Pennsylvania, he ordered four locomotives from Britain to be used in mountainous parts of the route. Used in 1829, these were the first locomotives in the United States, though they failed at their task and were put in storage. Jervis then became chief engineer on the Mohawk and Hudson Railroad, where he noticed the problem of the instability of Stephenson's locomotive on American tracks. His solution was to design a six-wheel engine in which the front four wheels were located on a truck disconnected from the rear wheels, and hence capable of turning independently. The engine powered only the rear two wheels. Such a locomotive, called a 4-2-0 because it had four leading wheels, two driving wheels and no trailing wheels, was far more stable on the curving, uneven American tracks.[13] Unpatented by Jervis, the 4-2-0 became the dominant American design of the 1830s, as distinct from Stephenson's 0-4-0.

Stevens and Jervis typified railroad invention in one important regard: improvements came overwhelmingly from practitioners in railroads, locomotive firms, and other suppliers. Matthias Baldwin is a good illustration. After seeing Jervis's innovation, Baldwin became a leader in 4-2-0 locomotives. He undertook no fundamental changes, but in five patents through 1836 he introduced important modifications aimed at efficient operation, including a crank mechanism moving the wheels, new wheel-making methods, and means to redistribute weight between leading and driving wheels. The most important innovation was the process of grinding joints for steam pipes, which replaced the earlier technique of using red-lead and canvas packing. This formed a better seal, enabling steam pressure to rise from 60 pounds per square inch to 120 pounds. Many of Baldwin's innovations involved production methods that improved efficiency and durability. He first exhibited such concerns in the

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[13] White, *A History of the American Locomotive*, 33-34, 239-241; Hindle and Lubar, *Engines of Change,* 129-143.

mid-1820s when he developed one of the first U.S. improvements on the engine lathe (the most important industrial machine tool, which had just arrived from Britain).[14]

Others fleshed out the railroad system. Many locomotive details were improved, resulting in better articulation of its thousands of parts. Only details of boilers changed. The use of wood as a fuel created problems of fires from live embers, and numerous spark arrestors were invented to solve this problem. Other changes, including coupling mechanisms, were made to improve freight and passenger railroad cars. Braking mechanisms evolved. Wooden ties soon replaced stone in railroad tracks. Sidetracks and switching mechanisms evolved to allow safer, intensive use of tracks. New manufacturing techniques increased the durability and reliability of engine parts and wheels. The design of curves and inclines were refined, and bridges were improved to accommodate the weight and speed of trains.

Input manufacturers such as Baldwin in Philadelphia, Ross Winans in Baltimore, and railroad master mechanics accomplished these improvements, which were largely incremental in nature. Other contributors included civil engineers such as Jervis, and two of the early, important surveyors for the B&O, Stephen Long and William Howard. Inventors' location provides further evidence of the ties of invention to practice; inventors concentrated in cities making inputs and along railroad lines. Inventors in the three earliest centers, Baltimore, Eastern Pennsylvania, and the Camden-Amboy route to New York City, received 70 percent of 190 surveyed railroad and locomotive patents through 1839. Those in secondary centers along upstate New York, Massachusetts, Virginia, and South Carolina lines received another 20 percent of patents.

By 1838, 9 years after the first imported locomotive was fired up, practical railroads had come to the United States. Railroad firms proliferated, with 59 listing locomotives in 1838. American firms had laid almost 2000 miles of track and produced three-quarters of the country's locomotives. Innovation came without a dominant U.S. innovator; rather many innovated together in a social process that depended on interaction and quick learning. This simultaneous action of many was grounded in machinists' inherited skills and institutions, formed largely in the steam engine and textile sectors that entered locomotive production, maintenance, and invention. Without this background, innovation would have been far slower and less creative. Engineering knowledge, itself based in colleges and occupational networks, was equally important, supported by the policy of lending army engineers until about 1837. Railroad invention was grounded in earlier invention. Many innovators had invented in other domains, including Robert Stevens (steamboat propellers), Baldwin (precision machinery), Winans (cloth-fulling

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[14] M. Baird & Co. Baldwin Locomotive Works, *Illustrated Catalogue of Locomotives* (Philadelphia, 1871).

machinery and a plow), and Long (steam engines and bridge designs). Jervis had developed mixtures to stop leaks on the Erie Canal. Prior invention provided conceptual and design skills applicable to railroad invention.

The railroad of 1838 had developed along with, and by means of, a network connecting practitioners. The network was linked by mobility of engineers and machinists, a dominant design centered on the 4-2-0 locomotive, locomotive firms and inputs suppliers selling inter-regionally, and publications. The network was national, or at least Eastern, in scope, extending from New England through the Carolinas.

Networked Development

The railroad network structured a dynamic that would continue through the Civil War. Like a new product that had just achieved practicality, the railroad faced large potential markets, and with rapid investment realized much of this potential by the Civil War. From 2,300 miles in 1839, railroads expanded to 7,400 in 1849, and 28,800 in 1859, a dozen-fold increase. Total railroad receipts grew from $7.4 million in 1839 to 29.3 million in 1849, and $118.8 million in 1859, a modest increase in receipts per mile. Passenger-miles and freight-ton miles increased faster yet, due to falling rates in the 1840s. Over these two decades, receipts were ten times higher in both the Mid-Atlantic and southern Atlantic states, and fourteen times higher in New England. The Midwest and non-coastal Southern states lines grew from five percent of national output in 1839 to 37 percent in 1859.[15]

Expansion followed methods established in the 1830s. For new construction, railroads contracted with civil engineers, now experienced in railroad design, either redeploying them within firms or hiring them from the outside. The government stopped loaning army engineers, except to the transcontinental railroads, but their training still benefited railroads when engineers retired. Senior engineers trained some assistants and hired others. Engineers moved into New England and the west. Some took responsibility for road maintenance. Master mechanics led the mechanical side of expansion; they helped order and design machinery and rolling stock and ran the machine shops that repaired, and in some cases made, equipment. These shops employed many workers; a study of the manuscripts of the manufacturing censuses for selected counties in 1860 listed 18 railroad repair shops with capital of about $3.5 million, employing more than 3400. A few made locomotives in modest numbers, but most repaired locomotives and cars. Repair shops, most of which were not surveyed, may have employed more than locomotive firms.

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[15]*Historical Statistics of the United States, Colonial Times to 1970* (Washington, D.C., 1975), Series Q 321; Albert Fishlow, *American Railroads and the Transformation of the Ante-bellum Economy* (Cambridge, Mass. 1965), 315-340.

Expanding railroads relied in part on existing locomotive producers. Already major producers in 1838, Baldwin and Norris remained central suppliers throughout the period. A textile machinery firm with three locomotives in 1838, Rogers, Ketchum & Grosvenor grew rapidly and by 1860 equaled the 1000 locomotives the two leaders had supplied. Locks and Canals, the other major early starter, largely stopped after the boom of the early 1850s. After losing B&O contracts, Ross Winans stagnated as well. These firms produced over half of the locomotives made in 1860. New entrants, mostly from steam engine and textile machinery industries, supplied the rest. New England's important stationary steam engine producer, Holmes Hinkley, entered locomotive production in the early 1840s, and produced 660 locomotives by 1860. Boston's Globe Locomotive Works and the Taunton Locomotive Company both emerged from steam engine firms or those they trained. Using their machinery-design and construction skills, textile machinery producers such as Amoskeag in Manchester and William Mason in Taunton entered production. In the Mid-Atlantic region, Patterson, New Jersey, entrants included another textile machinery maker, Charles Danforth, who formed the Danforth Locomotive Company.

Census manuscripts document some aspects of locomotive firms. By machinery firm standards, they were large, averaging $230,000 in capital, 260 workers, and a product valued at $260,000: four to five times the average for machinery firms surveyed. Some specialized in locomotives, but others were quite diversified. Four produced large quantities of textile machinery. William Mason of Taunton Massachusetts produced locomotives valued at $80,000 and textile machinery valued at $250,000. In addition to textile machinery, Thomas Rogers made 90 locomotives valued at $765,000. The Danforth Locomotive Company made 36 locomotives and textile machinery that sold for $268,000. Amoskeag was even more diversified, making 12 locomotives valued at $100,000, 75 steam engines averaging $1000, and $320,000 worth of other machinery and castings. Others continued to produce steam engines, woodworking equipment, and additional machinery. Locomotive firms were concentrated geographically in Philadelphia and Paterson. Baldwin and Norris maintained Philadelphia's status as a center, producing about 160 locomotives in 1860, approximately 36 percent of the national total. Paterson made about the same share, led by Rogers and Danforth. Boston and Taunton were lesser centers. Western firm production was minor.[16]

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[16] Thomson, "The Machinery Sector"; White, *A History of the American Locomotive*, 19-21. The census states that Baldwin and Norris made 168 locomotives in 1860, which is higher than other estimates. The census also overstates Amoskeag's output, listing 37 locomotives while the census manuscripts list 12.

Locomotive firms utilized the heavy machining capabilities developed since the 1830s. By the 1850s, many had formed large, well-equipped machine shops, foundries, and forging shops. Although lathes, boring machines, and planers were common, much work was still done with the skilled use of files and chisels. Purchases from the newly developed machine tool forms of Bancroft & Sellers and Bement & Dougherty improved the quality of machine tools in the 1850s. The first movement towards interchangeable parts production occurred in the 1850s, which aimed to ease repairs and reduce turnover time by making distinct parts simultaneously, not sequentially, relying on their uniformity to allow later assembly.[17]

Mechanics and designers in railroads, locomotive firms, firms making cars, wheels, and other inputs, and machine tool firms formed a communications network that structured the mechanical aspects of railroad development. Baldwin's partnerships illustrate such ties. In 1839, he took on two partners, George Hufty, a Baldwin machinist, and George Vail, the son of the Stephen Vail, who supplied wheel tires and axles. In 1842, Baldwin formed a partnership with Asa Whitney, who used his contacts as the superintendent of the Mohawk and Hudson Railroad to gain orders. Whitney formed a railroad wheel factory in 1846. Matthew Baird, who became a partner in 1854, had been Baldwin's foreman since 1838, when he left his job as superintendent of the Newcastle and Frenchtown Railroad repair shops. These firms were tied to machine-tool companies by purchase and by proximity. Within a twenty-block area of Philadelphia, Baldwin's plant abutted the Pennsylvania and Reading Railroad, Asa Whitney's car wheel shop, and the country's largest machine tool firm, William Sellers.[18]

Technological change was built into this system: it was largely incremental and based on the practitioners' experience. Some changes were qualitative; the most important was a new driving system. While the 4-2-0 overcame the instability problem of 0-4-0 engines, it had its own defects. With only two driving wheels, traction was often limited, and it was too small to pull the increasingly longer trains. Numerous efforts to balance or shift weight on the locomotive did not solve the traction problem. The solution came by doubling the driving wheels without eliminating the four-wheel leading truck. The resulting 4-4-0 had better traction, greater power, and more stability. A practical 4-4-0 had emerged by 1840. Henry Campbell, who, as an associate of Baldwin and the chief engineer at the Philadelphia, Germantown, and Norristown Railway, was firmly ensconced in the railroad network, initially developed it in 1836.

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[17] John K. Brown, *The Baldwin Locomotive Works, 1831-1915* (Baltimore, Md., 1995), 165-183; William Sellers & Co. "Order Book," Hagley Library, Asc. No. 1466, Wilmington, Delaware.

[18] Baird, *Illustrated Catalogue*; White, *A History of the American Locomotive*, 449-50; Brown, *Baldwin Locomotive Works*, 46.

His design was insufficiently stable, in part because the power to the four driving wheels was not well-balanced. Andrew Eastwick, an early locomotive builder, advanced an imperfect solution to coordinate power to the two driving axles, and Joseph Harrison, who was trained by Norris and employed by Eastwick, overcame the defect with his equalizing bar, which gave the 4-4-0 stability around curves and on uneven track. From 1840, Norris, Rogers, and others built many 4-4-0 engines. As the boiler lengthened over the 1840s and the lead truck and driving wheels were increasingly separated, the 4-4-0 became the dominant nineteenth-century U.S. locomotive.[19]

Incremental changes continued throughout this period. Valve gear evolved to better use steam's expansive power, culminating in the link-motion form of cut-off valve, widely used on both sides of the Atlantic beginning in the late 1840s. The wagon-top boiler created a reserve of steam to prevent the notoriously impure water used in American locomotives from fouling the cylinders. Metal jackets for boilers prevented heat loss. Many spark arrestors were invented to prevent fires from embers escaping wood-burning engines. In 1858, French engineer Henri Giffard, through systematic scientific study designed a water injector to replace the boiler's feed pump. The Giffard injector was quickly disseminated in the United States during the 1860s. Improved wheel and tire materials and auxiliaries such as sandboxes, headlights, and cowcatchers improved the durability and flexibility of the locomotive. New switching mechanisms; larger, more specialized cars; superior couplings; and brake improvements added to the railroad's usefulness and safety. Still wider ranges of changes refined the design and construction of railroad lines and bridges.[20]

Baldwin exemplified the path of locomotive change. He was a conservative designer who favored using fewer, simpler parts, and as such opposed the 4-4-0. Recognizing the need for more traction and power, he developed two new forms of six-wheeled engines that had four or even six driving wheels. By 1845, he licensed the Campbell and Harrison patents and adopted the more powerful 4-4-0, which weighed 20 tons. From the early 1840s, Baldwin and other manufacturers increased fuel efficiency by using more complicated engine cut-offs. Baldwin only reluctantly adopted simpler link-motion cut-offs in the 1850s. Altogether, Baldwin took out ten patents for locomotives through 1865, four related steam engine patents, and one patent for railroad wheels. Most were failures, and none were revolutionary. However, several improved engine durability and performance. His workers were also inventors. Matthew Baird, a foreman and master machinist of the Germantown Railroad, co-patented a spark arrestor in 1842. In the mid-

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[19] White, *A History of the American Locomotive*, 47-50, 151-157, 167-169, 452-53.
[20] Ibid., 128-32.

1850s, Baird, now a partner of Baldwin, developed a fire arch to improve combustion in coal-burning furnaces.[21]

Advances in railroad technology were reflected in patenting, even though not all inventions were patented. A study of locomotive, railroad design, car, brake, and switch patents through 1865 reveals several trends.[22] Patenting accelerated with locomotive usage. Of the 508 total patents, 1 percent were received through 1830, 2-6 percent in the 5-year periods through 1850, 13 percent from 1850 through 1855, 37 percent from 1856 through 1860 and 30 percent during the Civil War years. Patenting accelerated around 1850 just after the jump in new track mileage in 1848.

The occupation of patentees and the location of patents suggest that patenting was closely linked to the networks that spread railroad knowledge. Machinists working for the railroads or locomotive firms were frequent inventors. The occupations of inventors can be determined from city directories and census manuscripts, augmented by contemporary industrial surveys. Inventors with known occupations received 53 percent of all patents (see Table 2). Machinists led the way, with 48 percent of patents with known inventors. Machinists making or maintaining railroad equipment received half of these patents, which understates their share because many with railroad employment were listed simply as machinists. Scientific and inventive professions, including engineers, physicians, chemists, patent agents, draftsmen, and model-makers, received another 11 percent of patents, though some listed as engineers were machinists who operated locomotives and steam engines. Other manufacturing inventors featured metalworkers and woodworkers. Over one-third of trade and service workers were employed in the railroad sector in service capacities, many with mechanical skills. Altogether, known railroad sector employees received about 30 percent of patents issued to inventors with known occupations, and their share was surely higher.

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[21] Baird, *Illustrated Catalogue*; White, *A History of the American Locomotive*; Baldwin patents.

[22] Patents were selected from a listing of all patents through 1873 based on these key words: locomotives, car brakes, railway car couplings, railway cars, railway switches, and railways. Other categories, including spark arrestors and car couplings without reference to railways, are not included, though many patents pertained to railroads. This sample omits some railroad inventions, but it has the merit of consistency across the entire period.

TABLE 2
Railroad patenting and inventors' occupations

	All	Locomotive & Generic	Car & Coupling	Brakes	Switching
Patents	508	188	88	160	72
Share, Urban	53.9%	69.1%	46.6%	44.4%	44.4%
Share, Known Occupation	52.6%	70.7%	38.6%	39.4%	51.4%
Occupation Shares					
Machinists	47.6%	72.1%	17.2%	23.3%	25.0%
Science & Invention	11.4%	11.6%	17.2%	10.0%	8.3%
Other Manufacturing	26.8%	13.2%	44.8%	38.3%	41.7%
Trade & Services	16.5%	6.2%	31.0%	26.7%	25.0%
Agriculture	2.8%	0.0%	6.9%	6.7%	2.8%

Sources: U.S. Patent Office. *Subject Matter Index of Patents for Inventions Issued by the United States Patent Office from 1790 to 1873, Inclusive*, (Washington, D.C., 1874).

Notes: Locomotive patents include 11 generic railroad patents. Occupations were determined from city directories and from Population Census Manuscripts for 1850 and 1860, as examined in http://www.ancestry.com.

The share of machinists and scientific and engineering professions was highest in locomotive design, where they received 84 percent of patents with known occupations. They were mostly urban. Other kinds of patents depended less on knowledge of mechanisms, and machinists played a more modest role. However, even here their share of patents, which ranged from 17 to 25 percent, was far higher than their share of all occupations (about one percent in 1860). Carpenters and metalworkers were important, among many other occupations. As the railroad infiltrated the economy, so did railroad invention.

If knowledge communication was linked to the extent of the railroad network, then patenting would have spread with the railroad's geographical spread. Railroads were primarily located along the Atlantic seaboard until 1849, when Western investment grew. The relation to invention should be reflected in a comparison of the years before and after 1848. Mileage is the most common measure of railroad expansion, but railroad receipts present a better measure of economic impact. Patenting concentrated overwhelmingly in the East through the mid-1840s, but after that paralleled the westward spread of the railroad (see Table 3). Yet, over the whole period, invention occurred disproportionately in the mid-Atlantic and New England states, where locomotive production and machinists were concentrated.

Persistent railroad inventors formed an important part of the internal dynamic of railroad development. Locomotive inventors received 526 patents through 1865, averaging 4.4 patents per inventor (see Table 4). Two-thirds of them received more than one patent, and one-half received more than one patent for locomotives, other railroad techniques, and related equipment such as steam engines, boilers, and steam gauges. Inventors averaged 1.6 locomotive patents, added 0.7 in engines, boilers and similar techniques used in the railroad system, and another 0.5 for railroad cars, brakes, and switches. Inventors persisting in railroad invention averaged 4.6 patents in these areas, not including metalworking and generic machine design patents that could have applied to the railroad and its parts.

TABLE 3
The Regional Distribution of Railroad Receipts and Patents

Region	**Receipts 1839 (millions)**	**Receipts 1839, share**	**Patent Share, 1824-1845**	**Patents/ receipts, 1824-1845**	**Receipts 1856 (millions)**	**Receipts 1856, share**	**Patent Share, 1846-1865**	**Patents/ receipts, 1846-1865**
Mid-Atlantic	4.28	58.0%	83.3%	14.03	42.05	41.1%	51.6%	5.35
New England	1.23	16.6%	9.7%	5.71	17.72	17.3%	22.0%	5.42
South Atlantic	1.47	20.0%	2.8%	1.36	10.57	10.3%	3.7%	1.51
Southwest	0.22	2.9%	0.0%	0.00	3.32	3.2%	1.6%	2.11
Midwest & West	0.18	2.4%	4.2%	17.14	28.56	27.9%	21.1%	3.22
All	7.37			9.77	102.22			4.27

Sources: For patents, see Table 2. For receipts, Albert Fishlow, *American Railroads.*

The commitment to railroad patenting varied among occupations. Railroad-related occupations, including locomotive and wheel producers and railroad mechanics and engineers, learned in railroad networks and concentrated the most on railroad patents. They received three-fifths of their patents in railroads and four-fifths on railroad, engine, and boilers, dedicating 5.8 patents to the railroad system. Other occupations, with half of their patents in unrelated sectors, averaged only 2.4 patents in railroad techniques. Among occupations, machinists were the most prolific inventors. They received 63 percent of the patents issued to those with known occupations and averaged 4.2 railroad patents.

TABLE 4
All patenting for locomotive inventors by occupation

	All	**With Known Occupation**	**Railroad-related**	**Not Railroad-Related**	**Machinists**	**Science & Invention**	**Other Manuf'g**	**Trade & Service**
Inventors	119	75	23	52	44	14	12	5
Share, multiple patents								
All Patents	66.4%	74.7%	87.0%	69.2%	79.5%	64.3%	75.0%	60.0%
Railroad & Related	48.7%	60.0%	78.3%	51.9%	65.9%	50.0%	58.3%	40.0%
Patents per Inventor								
All Patents	4.4	5.6	7.3	4.8	6.0	3.9	7.1	2.8
Locomotives	1.6	1.8	3.1	1.2	2.2	1.5	1.2	1.0
Other Railroad	0.5	0.6	1.3	0.3	0.7	0.4	0.5	0.6
All Railroad	2.0	2.4	4.4	1.5	2.8	1.9	1.7	1.6
Related to Railroad	0.7	1.1	1.4	0.9	1.3	0.9	0.7	0.2
Railroad & Related	2.8	3.5	5.8	2.4	4.2	2.8	2.3	1.8
Unrelated	1.7	2.1	1.5	2.4	1.8	1.1	4.8	1.0

Sources: See Table 2; U.S. Patent Office. Edmund Burke, *List of Patents for Inventions and Designs, issued by the United States, from 1790 to 1847* (Washington, D.C., 1847); *Annual Report of the Commissioner of Patents* (Washington, D.C., 1839-1865).

Railroad dynamics continued to rely on developments in other sectors to supply knowledge, inventors, and inputs. In many cases, invention outside the railroad sector created capabilities that supported railroad invention. Over one-quarter of railroad inventors began with patents outside the railroad sector, and they received about 40 percent of all patents. Some of these individuals helped create the railroad, transferring knowledge acquired from other inventions. Most moved into railroads after the railroad was well-established. Jordon Mott was a prominent New York stove manufacturer who began his inventive career with a dozen stove patents beginning in 1838. His casting prowess first brought him to railroads, when in 1841 he developed a damp-sand mechanism for increasing traction on railroad tracks. In 1848, he received patents for chilling castings, a common procedure for making railroad wheels, and later received two patents for railroad wheels and one for cars. Mott used casting skills acquired in stove-making to enter new markets for locomotive sandboxes and cast wheels. Others followed similar paths into railroad invention, including inventors of steam engines, boilers, and steam gauges. Henry Waterman invented brick and cotton presses and nail-cutting machines before turning to locomotives, cut-off valves, boilers, and car springs, interspersed with ships, saws, reaping machines, gas regulators, and steelmaking techniques. For him invention had become a way of life. The railroad clearly benefited from invention outside it.

The railroad also benefited from the largely independent development of machine tools and metalworking techniques. Always dependent on craft skills, making and maintaining locomotives increasingly relied on the use of machine tools. Machine tools that could hold and move cutting tools with some accuracy were used prior to the railroad, especially when, aided by Baldwin’s improvements, the engine lathe came into use in Philadelphia in the 1820s. The planer used in locomotive construction spread from textile machinery and steam engine firms, which first used the English planer. Firms making machine tools found locomotive and wheel firms an important market, but one dwarfed by demands from engine-makers, textile machinery firms, press-makers, and others. Two Philadelphia machine tool firms, William Sellers and Bement & Dougherty, formed close relations to railroad and locomotive firms, but sold much more widely. Brown & Sharpe, the emerging leader in precision and mass-production machine tools, sold universal milling machines to four locomotive firms and screw machines to seven, which represented about 6 and 9 percent, respectively, of the sales of these machines. Furthermore, machine-tool inventors did not come from the railroad sector and took out only 2 percent of their patents in that sector, far less than in firearms, iron products, air and liquid mechanisms, and about the same as textile machines, sewing machines, and agricultural implements. Machine-tool firms such as Seller, the American licensee for the widely adopted Giffard injector, played a more direct role when they designed railroad equipment.[23]

How did the railroad develop so quickly, widely, and creatively in the United States? Techniques diffused and developed through the knowledge and communication channels that social institutions provided. Although funding sources and large potential demand were required, without the institutional spread of these techniques, railroads would have developed more slowly, with fewer advances in domestic machinery and civil engineering capabilities. Three types of institutions were especially important. The machinery sector trained agents and organized firms that entered locomotive and railroad production, bringing design and production capabilities with them. The evolution of the machinery sector continued to play a role as the railroad matured. Applied science institutions shaped the civil engineering capabilities to plan and construct railroad lines. Although these skills came from canal and other infrastructural development, they depended on a college education and, initially, on government loan of military engineers. Innovation was thus grounded in extra-economic institutions. Engineers' publications codified railroad practices. Inventive institutions were the third source of innovation. Railroad inventors learned from their past inventions of engines, boilers, steamboats, bridges, and machinery. Engineers and machinists communicated new knowledge through journals, mechanics' institutes, and the patent system itself, which made patent specifications and models available for examination and published summaries in the annual reports of the Commissioner of Patents.

The proprietary role of patents played two roles. On the one hand, railroad development benefited from the availability of British and American inventions such as the Jervis truck without U.S. patent protection. Here the absence of patents supported diffusion, but only when other institutions communicated knowledge that included the sale of locomotives, the mobility of machinists and engineers, and publications. On the other hand, many later inventions such as Campbell's 4-4-0 and Harrison's equalizing bar were patented. Baldwin and important railroad companies purchased licenses for these patents. However, as invention accelerated, the prospect of licensing and litigation costs increased, and railroads became reluctant to purchase patent rights. By 1865, an article in *Scientific American* included the statement that railroad companies have "never manifested a willingness to pay patentees," and this policy would be institutionalized in railroad trade associations.[24]

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[23] Brown and Sharpe, *A Brown and Sharpe Catalogue Collection* (Mendham, N. J., 1997); Thomson, "The Machinery Sector."

[24] "Our Patent System," *Scientific American*, 13, (1 July 1865), 7; White, *A History of the American Locomotive*, 48; Brown, *Baldwin Locomotive Works*. On the centralized organization of the market for inventions and the importance of insiders, see Steven W. Usselman, *Regulating Railroad Innovation: Business, Technology, and Politics in America, 1840-1920* (Cambridge, U.K., 2002).

The broad institutions of machinists, engineering, and invention helped shape and reshape networks that connected railroad companies, locomotive and car firms, and wheel and other input manufacturers. Almost from their beginnings, these networks were tight and national. Locomotive producers sold nationally, beginning with Baldwin in the 1830s. Railroad companies compared information about equipment and often communicated their knowledge to other railroads, with which they rarely directly competed. Interactions between master mechanics and locomotive firms directed design and invention. Mobility among railroads, locomotive firms, and suppliers disseminated techniques and posed problems for all to address. This system, which perhaps Civil War coordination made more coherent, set the stage for the great postwar railroad expansion.

The Diversity of Innovation Paths

Before the Civil War, the railroad was one among many great innovations. The telegraph rivaled the railroad in the public imagination. By 1865 over, 75,000 miles of telegraph lines were in operation. The reaper, in mechanizing wheat harvesting, was perhaps the symbol of American ascendance in the 1851 Crystal Palace Exhibition, and spread rapidly during the 1850s. In 1860, 17,000 reapers were sold and American firms were making 110,000 sewing machines annually.

The railroad example carries lessons for understanding how all these innovations originated and developed. Three features of railroad development applied more widely. First, established institutions organizing machinery, engineering, and invention structured the origin and development the innovation. Second, interactions among innovators spread knowledge and formed institutions that shaped ongoing development that led to practicality. Third, once practical, the innovations diffused in an expanding, cumulative process that added to capabilities and solved problems largely through the operation of machinery, engineering, and patenting institutions.

The importance of access to knowledge and institutional structure suggests ways in which innovations should have developed differently. Some depended more on science and civil organizations (the railroad, telegraph, and the incipient petroleum industry), others more on government policy (armaments, but also railroads and telegraphs), and still others more on private action (the reaper, sewing machine, Corliss engine, and cylinder press). They faced different markets, scales of investment, and locations. Correspondingly, innovators varied in background, and innovations were realized through different institutions.

Originating Innovations

Innovations effecting major economic changes typically had clear social antecedents. The need for the innovation, its technological underpinnings, and the conceptual systems through which it was understood all predated the innovation. These antecedents differed among innovations, which is one reason why they followed different paths. Relevant institutions formed one dimension of difference, including the reliance on economic or non-economic institutions.

The electromagnetic telegraph depended the most on non-economic institutions. Joel Mokyr called it a macro-invention, because it introduced wholly different technologies than had ever been used commercially, and relied on a kind of knowledge just coming into being. The value of communication faster than people could travel provided a basis for optical and auditory signals over many centuries. An organized system for military communication over long distances existed from the eighteenth century, and the French optical telegraph, which could transmit messages with remarkable rapidity, was a well-known Napoleonic creation. An electric telegraph served the same purpose, but it was a far more radical change than the locomotive, which used a well-established commercial product, the steam engine, to move mass along tracks. The evolution of electrical knowledge, occurring virtually entirely within pure science, established the conceptual basis for the electric telegraph. Volta's discovery of the battery, Oersted's discovery of the relation of electricity and magnetism, and the electromagnetism discoveries of Faraday and Henry formed part of what Mokyr called the epistemic base of the telegraph. The international community of scientists spread this knowledge widely; it was recorded in European journals and American journals including the *American Journal of Science and Arts* and the *Journal of the Franklin Institute.* Experimental electric telegraphs quickly followed scientific advances, beginning with impractical electrostatic telegraphs. Using early nineteenth-century advances, techniques emerged in Britain, Germany, and, in Joseph Henry's 1831 experiment, in the United States. The telegraph depended, of course, on instruments and chemical inputs, and hence on the occupations of instrument-makers and chemists. However, instruments and measuring devices were often the product of scientists.[25]

The reaper and sewing machines also broke with existing institutions but rested far less on extra-economic developments. The desire to reduce private costs was well understood, and the bottleneck in labor supply during harvesting season was an added stimulus. No formal science was involved, much less frontier science. Knowledge of mechanisms and production techniques was needed and available in the economy. Irregularly and in isolation, many had tried to solve these problems without success. Through 1831, 33 reapers were invented in Britain, 22 in the United States and two each in France and Germany. Similarly, 17 machines to form a stitch

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[25] Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress* (New York, 1990), 13, 122-24; Joel Mokyr, *The Gift of Athena: Historical Origins of the Knowledge Economy* (Princeton, N.J., 2002). For an overview of telegraph development, see Alexander J. Field, "Telegraph" in *The Oxford Encyclopedia of Economic History*, 5 vols., ed. Joel Mokyr, (New York, 2003) 5: 90-92.

preceded Howe's invention. The nearly simultaneous, but unconnected inventions of Walter Hunt, John Greenough, and George Corliss in the United States attests to the recognition that mechanized sewing was possible and advantageous. Each became successful inventors, but not in sewing.[26]

Possible innovations are not necessarily realized. Inertia can limit development, including not only vested interests but also existing conceptions, even by proponents of innovation. In 1828, shortly before electric telegraphs were developed, the *Journal of the Franklin Institute*, while lauding electrical advances in other articles, described how optical telegraphs had "been brought to so great a degree of perfection."[27] The very enthusiasm for invention was coupled by an often-justified skepticism about practicality. Uncertainty was greater when no model could be copied, as was the case of the railroad. In this context, innovations may well appear to be the result of extraordinary individuals, such as the heroic images of Samuel F. K. Morse, Cyrus McCormick and Elias Howe. These are not false perceptions because each inventor solved fundamental technical problems and persisted in bringing solutions to practicality. Neither are they the entire truth, because they abstract innovators from the social sources of their success.

The importance of social sources was most evident when the private economy was least capable of solving technical problems. That one underappreciated artist, Samuel Morse, could in the 1830s solve an important technical problem without interactions with others was just as unlikely as another such artist, Robert Fulton, doing the same 30 years before. Fulton was a civil engineer and naval innovator who knew virtually all the major steamboat inventors. Morse was less connected, in part because there were few electric telegraph inventors when he began to invent. Yet, Morse had several advantages. At Yale, he had studied sciences, and had been introduced to electrical issues by professors including Benjamin Silliman, a leading American scientist and, as editor of the *American Journal of Sciences and Arts*, the leading scientific publicist. Silliman would continue to inform Morse through the practicality of his invention. Morse had a history of invention, including a pump that he and his brother Sidney patented in 1817. In New York, where he became a professor at what would become New York University (NYU), Morse attended electrical lectures and talked with science professors. No itinerant portrait painter was he.

These contexts were critical to his success. Several other efforts to develop an electric telegraph occurred about the same time as his, but he claimed to know nothing about them when he introduced his basic invention. Given the timing and distinctiveness of his invention, this seems quite possible, which made his quest more challenging. The fabled trip

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[26] William T. Hutchinson, *Cyrus Hall McCormick: Seed-Time, 1809-1856* (New York, 1930); Ross Thomson, *The Path to Mechanized Shoe Production in the United States*, (Chapel Hill, N.C, 1989), 78.

[27] *Journal of the Franklin Institute,* 2 n.s., (1828), 51.

across the Atlantic, when he conceived key elements of his telegraph including the precursor to his famous code, was broadly documented, but he would not have become so engrossed in this invention without prior exposure to science and European discussions about electricity. Others anticipated his ingenious ideas, and he suffered for not knowing this. The key elements of the electric telegraph were the use of electric circuitry to send messages, adequate sending and receiving systems, and a code to represent the content of communication. Other inventors were developing each element, including leading scientists, such as Charles Wheatstone, who measured the speed of light before turning to transmissions occurring about as fast. That Morse succeeded facing such competition relied in part on the simplicity of his solution compared to Wheatstone's needle telegraph. However, it would have remained an impractical idea had others not entered the picture. Like many brilliant first ideas, it might have failed, only to be resuscitated later by antiquarians and patent lawyers.[28]

The case for individual innovation is more easily made when changes evolved within the economy, and especially in isolated locations. McCormick presents the strongest case. He grew up on a prosperous Virginia farm in the Appalachians. His county did not possess a machine shop in 1840 or 1860, but his farm did possess a blacksmith shop. He was not entirely isolated from the broader world. His father invented a threshing machine, a hemp-breaking machine, a horsepower, a bellows, and a gristmill improvement, and received four patents. He also had experimented with reapers over a 15-year period. Cyrus produced and sold some of his father's machines in small numbers. He also inherited his father's interest in invention, and journeyed to Washington to take out his first patent for a hill-side plow in 1831, received another plow patent in 1833, and made and sold modest numbers of plows. Knowing first-hand the requirements of grain harvesting and recognizing the deficiencies of his father's reaper, Cyrus developed and used a machine with all the design features of an adequate reaper in 1831, though in primitive form. It was an impressive accomplishment for an inventor with no knowledge of harvesting inventions other than his father's. He patented his machine in 1834, prompted by a notice of Obed Hussey's patented reaper in 1833.[29]

Howe, too, labored in private to develop his sewing machine, hiding his innovation from public view. However, he labored in a very different environment. As a machinist working in Lowell and Boston, he could hardly

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[28] On the birth and development of the Morse system, see Robert L. Thompson, *Wiring a Continent: The History of the Telegraph Industry in the United States, 1832-1866* (Princeton, N.J, 1947); James D. Reid, *The Telegraph in America and Morse Memorial* (New York, 1879), and Paul Israel, *From Machine Shop to Industrial Laboratory: Telegraphy and the Changing Context of American Invention, 1830-1920* (Baltimore, Md., 1992), 24-56. On Morse' life, see Carleton Mabee, *The American Leonardo: A Life of Samuel F. B. Morse* (New York, 1969).
[29] Hutchinson, *Cyrus Hall McCormick,* 28-98.

have had more favorable training and social connections in the United States. They provided knowledge of designing and constructing machines, invention, and the particular technology of the manipulation of thread. Conversations around work informed him of opportunities for invention, including the possibility of a sewing machine. His lockstitch machine, taking 2 years to develop and patent, was a successful solution to an important problem. However, it was a solution he was well prepared to undertake, and one that one U.S. inventor had already developed, and another, without knowledge of Howe's invention, was about to undertake.[30]

Towards Practicality

The remarkable telegraph, reaper, and sewing machine inventions of the 1830s and 1840s would bear fruit by the Civil War, but their inventors did not achieve success by themselves. In each case, interaction with inventors and producers was required. Practicality occurred faster when networks were already in place. These institutions surrounded Howe, and even through he did less than Morse or McCormick to bring his machine to practicality, he was quickest to achieve success. Morse and McCormick first had to forge connections to new groups.

Morse developed a practical telegraph only by forming associations with scientists and machinists quite outside his previous awareness. His prior knowledge of electricity was much too shallow to develop his ideas to practicality. After having worked alone for 4 years, he formed several contacts critical to his success. Leonard Gale was the most important. He was a trained scientist who taught geology at NYU and was a friend of Joseph Henry. Gale introduced Morse to Henry's work on electromagnetism, and in particular, an 1831 article in Silliman's *American Journal of Science and Arts* that described the principles of an electric telegraph that Henry had designed as an experiment. Henry's article suggested two major changes: the use of multi-cell batteries to increase voltage, and the redesign of the electromagnet. Morse worked with Gale on the design of his electric relays. Gale would bring scientific knowledge to the Morse enterprise, which he joined as a partner and owner of one-sixteenth of Morse's patent. Morse also relied on the scientific expertise of others, including Charles G. Page, second only to Henry among U.S. physicists, who helped solve a problems beginning with Morse's Baltimore-Washington telegraph and continuing through the design of the receiving magnet.[31]

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[30] Thomson, *The Path*, 73-79.

[31] Thompson, *Wiring a Continent;* Reid, *The Telegraph in America;* Mabee, *The American Leonardo.* On the role of networks, see Israel, *From Machine Shop to Industrial Laboratory*, 57-86. On Page's contribution, see Robert C. Post, *Physics, Patents and Politics* (New York, 1976). For a contemporary examination of that system, see *Journal of the Franklin Institute* 20 (Nov. 1837): 323-325. Alfred Vail wrote one of its first histories, *The American Electro-Magnetic Telegraph* (Philadelphia, Pa., 1845), which angered Joseph Henry for ignoring his

If Gale tied Morse to the world of science, Alfred Vail linked him to the world of machinery. Vail was the son of Stephen Vail, owner of the iron-working firm that made car wheels for Baldwin. Alfred Vail had headed the machine shop in his father's factory. Morse recognized that his machinery was primitive, and when Vail, just graduated from NYU, became interested in the telegraph, Morse formed a partnership in which Vail got one-eighth of Morse's patent right in exchange for constructing equipment and financing patent applications. Vail designed much of the equipment, and in the process became involved in electrical technology, including the magneto that Charles Page designed.

With Gale's scientific insights and Vail's design skills, Morse formed and demonstrated a telegraphic system that communicated over a few hundred feet of wire, then 1700 feet, then 10 miles. He received a caveat from the Patent Office in 1837. His team improved the telegraph in many ways, some embodied in the 1840 patent. In one of the most visible changes, Morse dropped his earlier coding system, which translated words into numbers using a dictionary he compiled, and numbers into sequences of dots and dashes, with the direct depiction of letters as a sequence of dots and dashes. He chose representations for the new system by examining the frequency of letters in writing. The first Morse code was adopted in 1838, refined in 1844, and later modified in International Morse code, when the familiar three dots, three dashes, three dots came to represent S-O-S.

Practicality could not be demonstrated without use, and Morse sought, and in 1843 found, public support in the form of a federal appropriation of $30,000, which he used to fund a Baltimore-Washington telegraph located along the spur line of the B&O. In this case, public policy was used to fund a project of such scale and uncertainty that private financing would have been hard to secure. The project required construction capabilities to erect the telegraph, and Ezra Cornell entered the picture. A mechanic and sales representative of patented plows, Cornell built a plow for laying underground cables and, when these failed, joined Morse, Vail, and Charles Page in designing a system of above-ground poles carrying telegraph wires. In May 1844, the words "What hath God wrought?" were sent from Washington to Baltimore. A year later, when the government failed to buy his patent, Morse organized the Magnetic Telegraph Company and began to sell rights to use his system.

Morse took a dozen years to develop a practical telegraph, and was forced to enlist science, machinery, and government in his quest. McCormick took even longer without the same institutional complexity. Though his 1831 machine embodied all the core features of a practical reaper, McCormick would take another 15 years to bring his idea to practicality, largely because of his isolation from institutions of the

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contribution. Soon after, world histories of the telegraph were published, including Tal P. Shaffner, *The Telegraph Manual* (New York, 1859).

machinery sector and difficulties in penetrating the potential market. From his first efforts to commercialize the reaper, McCormick recognized that he or another mechanically competent worker would have to assemble, test and overcome limits in the machine, train users, and undertake repairs. For this reason, he confined early sales to nearby counties. Making a few successful machines a year proved difficult; a dozen years after the machine had been invented, McCormick still had to have the knives made 20 miles away.[32]

As he expanded into other regions, McCormick introduced design improvements; including adding a seat on the reaper for the worker who raked the cut grain. To gain wider sales, he began to license patent rights in Virginia and in centers of wheat production in western New York, Ohio, and points west. The quality of licensees' products was often poor, and his reputation suffered. Some licensees produced good machines, notably one upstate New York firm. It was not until 1846 that he produced as many as 100 machines of adequate quality or until 1848, the year his patent expired, that he produced 700 machines. By then, he decided to build his own factory in Chicago.

While McCormick was involved with every step of the painful evolution of his machine, Elias Howe was the exact opposite; his machine achieved practicality quickly though he had little to do with it. After demonstrating his machine in Boston and finding no takers, in 1847 he sought greener pastures in England, where he sold his patent rights and adapted his machine to corset making. Returning to the United States 2 years later, Howe found many sewing machines in use; virtually all were infringing on his patents. His future role would be largely in the courtroom. Howe's machine developed in classic network fashion, centered mostly on Boston. It had been observed by two sets of people: tailors and those interested in invention. John Bradshaw, like Howe a machinist trained in Lowell, improved the loop-forming mechanism. Based on Bradshaw's invention, Charles Morey and Joseph Johnson designed a chain-stitch machine, at least fifty of which were sold. In a basic improvement of the Morey & Johnson, John Bachelder introduced continuous feed and a horizontal, reciprocating needle. Sherburne Blodgett, a tailor, developed a defective machine in 1850, which proved important because Isaac Singer observed it and invented his machine to overcome its defects. The Blodgett also influenced a second major company, Grover and Baker. Bradshaw's invention occasioned the third major machine, the Wheeler and Wilson, when its owners sued Allen Wilson for infringement. To avoid the infringement, Wilson and his partner Nathaniel Wheeler, designed a rotating shuttle and, in 1854, a fully adequate feeding mechanism. Through communications links around nodal machines, a community of machinists and mechanics had brought the sewing machine to technical practicality by 1854. The machine became commercially feasible when property rights were

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[32] Hutchinson, *Cyrus Hall McCormick*, 174-249.

sorted out, cross-licensing occurred, and a patent pool was established in 1856.[33]

Like the railroad, these innovations became practical through the presence of social institutions that communicated knowledge and skill. The telegraph depended on formal science and the applied science that quickly developed from it. Each depended on the machinery sector to produce and develop equipment; the reaper developed more slowly than the sewing machine in part due to the absence of a machinery sector in rural Virginia and its primitive state among McCormick's contractors. Each sector depended on patenting as an essential way to gain financing and appropriate returns, and in each sector, later patents improved on initial ones. Morse and McCormick took out their own follow-up patents, but because many improved Howe's patents, commercial viability depended on new arrangements to allow widespread licensing.

As innovations became practical, internal technological dynamics deepened. Some were cooperative, especially Morse's relation with his team and consultants. McCormick assigned patents or licensed production rights and cooperated with the purchasers, including sending his brother Leander to work with a Cincinnati contractor who made faulty reapers. Others were largely competitive. Morse argued for his system against optical telegraphs when the federal government considered financing a system. When trying to patent his telegraph in England, he met Charles Wheatstone and learned of other telegraphs; he no doubt worried about Wheatstone's system when it received a U.S. patent just before Morse's 1840 patent. McCormick competed actively with Obed Hussey, who received his patent months before McCormick. They vied for agricultural society prizes, competed in the field, and came up for patent renewal about the same time. Even then, the communication system surrounding the reaper was thin, involving two competitors with modest sales and largely segmented markets, and a few contractors. Inventors of sewing machines developed the strongest interactions, unsurprisingly because they were embedded in a mechanized, urban machinists' network.

Realizing Potential by Deepening Networks

The realization of an innovation's potential depended not only on practicality but also on the path through which practicality was achieved. Practical innovations led to rapid growth that greatly broadened the groups involved in the new technique, spreading learning and invention. Because innovations originated through different processes, growth and ongoing innovation processes differed according to the institutions that brought the innovation to practicality.

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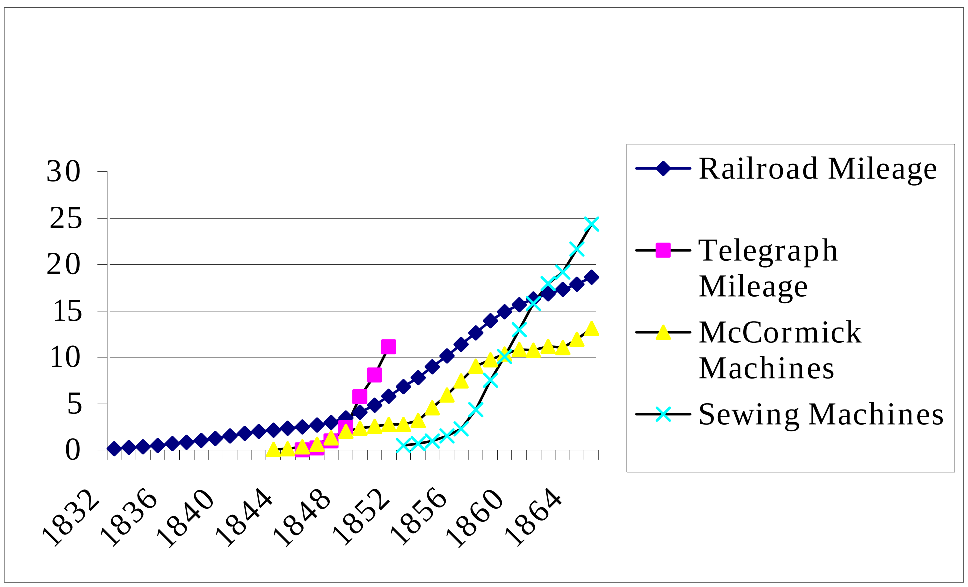
[33] Thomson, *The Path*, 73-92; Grace Rogers Cooper, *The Invention of the Sewing Machine* (Washington, D.C., 1968), 19-38.

Once practical, each of the innovations grew rapidly. By 1865, output was from 18 to 40 times higher than when practicality was first achieved, as depicted in Figure 1, which shows an index of output set at one for the year of practicality. Just as railway track from grew from 1900 miles in 1838 to 35,000 in 1865, so telegraph track increased from 2100 miles in 1847 to about 80,000 in 1866. Reapers sold by McCormick grew from 450 in 1847 to 7000 at the end of the Civil War, and because of entry, total harvesting machinery grew at three times the rate. Sewing machine sales grew even faster, surging form 3700 in 1854 to 85,000 in 1865.[34]

FIGURE 1
Output indices of innovations
(5-year moving averages; year of practicality= 1)



Source: See footnote 34.

The firms that first achieved practicality led the market penetration. After the success of the Baltimore-Washington telegraph, Morse and his new business partner, Amos Kendall, former Postmaster General, started the Magnetic Telegraph Company. Its chief asset was a patents assignment giving it the "exclusive right to constructing a line of telegraph under said

[34] Output data for railroads from *Historical Statistics of the United States*, Series Q 321; for telegraphs from Thompson, *Wiring a Continent*, 240-42; for sewing machines from Thomson, *The Path*, 103 and Cooper, *The Invention of the Sewing Machine*, 40, 89, 112; for reapers and mowers, from David A. Hounshell, *From the American System to Mass Production, 1800-1932* (Baltimore, Md., 1984), 161.

patents from the City of New York, to the cities of Philadelphia, Baltimore, & Washington." After failing to get the government to buy his patent, Morse and Kendall licensed Morse's patent rights to newly organized telegraph companies formed to connect various areas, taking stock as partial payment. Morse hoped for an orderly expansion under its organization, and assigned rights to specific lines, such as Samuel Colt's line "from New York City to Sandy Hook, Long Island, other parts of Long Island and the New Jersey Shore."[35] Alternative telegraphs and dissention among Morse's partners and assignees undercut the plan for orderly expansion, and a stampede of ill-designed lines using incompatible kinds of telegraphs ensued. The need for consistent national standards called for cooperation, and Kendall organized firms toward this end. Ultimately competition, bankruptcies, and consolidation led to a coordinated system under the control of a single firm, Western Union, in 1866.[36]

McCormick continued to lead reaper production, but when his 1834 patent expired in 1848, many others entered the market. McCormick tried to extend his patent and sued others under his 1845 and 1847 patents, but failed on all counts. Entrants such as J. H. Manny, Ephraim Ball, and Cornelius Aultman became more formidable rivals than Hussey had ever been.

In the case of sewing machines, the three firms dominating the industry at the time of practicality continued to dominate throughout the Civil War, bolstered by their leading position in the patent pool. They produced about 80 percent of known machines in 1854, 60 percent of the 111,000 machines recorded in the census of 1860, and two-thirds of the machines licensed by the patent pool in 1867.

Each innovation formed a system of interacting agents. Like the railroad, the telegraph became a large-scale national system that required standards about telegraph methods, equipment, language, and message priorities, though agreement on standards was slow in coming. The telegraph had its own construction engineers, who moved among the lines. It led in forming two new occupations, electrical engineers to establish and maintain service and design equipment, and telegraphers, who required some technical knowledge to operate and maintain equipment. The telegraph required little machinery, especially the simple instruments in the Morse system. A few, small, urban instrument-makers made telegraph equipment, electrical testing devices, and other electrical equipment. The

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[35] On Morse's patent assignments, see patent assignment records, Letter M, vol. 1, quoted from pages 50, 67, U.S. National Archives, College Park, Maryland. The dozens of Morse patents assignments provide good evidence for the expansion of the telegraph.

[36] Thompson, *Wiring a Continent*; Reid, *The Telegraph in America*. On the relation to state government policies, see Tomas Nonnenmacher, "State Promotion and Regulation of the Telegraph Industry, 1945-1860," *Journal of Economic History* 6 (March 2001): 19-36.

system extended to battery producers in the chemical sector and makers of telegraph wire insulation. A few independent urban electrical engineers and electricians filled out the system. As a radical innovation, the telegraph brought about wholly new professions.

Machinery firms were the dominant agents developing reapers and sewing machines. Because users were smaller and less technically skilled than in telegraphs or railroads, they did not impose standards or designs on machinery firms. Networks formed around firms' agency systems demonstrated, sold, and repaired machines, and in the process learned from users' complaints. The surge in reaper sales in the early 1850s was dependent on its profitable usage, which, given the capital costs of the reaper, was affected by the size of the farm, the price of labor and grain, and the extent of cooperative usage of reapers, as well as improvements in reaper productivity. Machinery firms centralized production, largely to eliminate poor quality and its reputation effects. McCormick concentrated production in his own plant in 1850, though he continued to contract out for specialized parts. Leading sewing machine firms built their own plants in the mid-1850s. Both industries drew from well-established markets for machinists, blacksmiths, and carpenters.[37]

By 1860, each major innovation was well established. Each entailed machinery and machinists, but machinists and machinery firms played very different roles, reflecting the distinctive structure of the innovations. A study of the 1860 census manuscripts illuminates these differences. The study includes counties with about 60 percent of all machinery employees in the

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[37] Hounshell, *From the American System to Mass Production*, 153-64; Thomson, *The Path*, 93-105. On technological change in agriculture, see Leo Rogin, *The Introduction of Farm Machinery in its Relation to the Productivity of Labor in the Agriculture of the United States During the Nineteenth Century* (Berkeley, Calif., 1931); John Nader "Learning Effects and the Pace of Technological Change: The Case of the Midwestern Farm Implement Industry, 1850-1890," (Ph.D. Diss., New School for Social Research, New York, 1991); John Nader, "The Rise of an Inventive Profession: Learning Effects in the Midwestern Harvester Industry, 1850-1890," *Journal of Economic History* 52 (June 1994): 397-408. The large and strong literature on the diffusion of the reaper began by pointing to the importance of a threshold farm size large enough to spread the cost of the reaper over its output, which depended on the quantity of output and the price of wheat. Subsequent debate concerned whether or not reapers were shared, and if reaper improvements improved productivity. See Paul A. David, "The Mechanization of Reaping in the Ante-Bellum Midwest," in *Industrialization in Two Systems: Essays in Honor of Alexander Gerschenkron*, ed. Henry Rosovsky (New York, 1966), 3-39. Alan L. Olmstead, "The Mechanization of Reaping and Mowing in American Agriculture, 1833-1870," *Journal of Economic History* 35 (June 1975): 327-352; Alan L. Olmstead and Paul W. Rhode, "Beyond the Threshold: An Analysis of the Characteristics and Behavior of Early Reaper Adopters," *Journal of Economic History* 55 (March 1995): 27-57.

United States and virtually all of the output of locomotive and sewing machine industries, which the census separately enumerated. The railroad sector employed over 4000 workers making locomotives, but employed at least as many in railroad repair shops (see Table 5).

TABLE 5
Innovation and Machinery Firms, 1860

	Locomotive	**Railroad Repair**	**Telegraph Instruments**	**Reaper & Harvester**	**Sewing Machine**
# of Firms	19	18	8	38	57
Capital	$233,300	$216,500	$5,900	$44,800	$24,500
Value of Product	$262,800	$154,400	$15,800	$71,100	$98,300
Average Employment	259.7	191.1	6.9	44.3	36.4
Median Employment	175	95	6	25	10
Maximum Employment	720	990	16	200	570
Largest Employer	Rogers Locomotive	B&O	Thomas Hall	McCormick; C Aultman	Wheeler & Wilson
Surveyed for Patents	13	0	7	13	37
Principals with Patents Share	69.2%		100.0%	100.0%	78.4%
Patents per Inventor	10.4		2.0	6.5	5.0

Sources: U.S. Census Office, Manufacturing Manuscripts from the Eighth Census, 1860. Available in National Archives and state archives in Conn., Del., Md., N.J., N.H., N.Y; U.S. Census Office, Manufacturing Manuscripts from the Seventh Census, 1850. Available in National Archives and state archives in Conn., Del., Md., N.J., N.H., N.Y. Methods are discussed in Thomson, “The Machinery Sector.”

Railroad firms were the largest in the machinery sector, with locomotive and railroad repair shops each averaging 200 or more. Their substantial capital costs and high median employment help explain why most entering firms would have first accumulated capital and knowledge in related firms. Telegraph instruments were more modest. Some were produced in-house, including one firm included in the 1860 manuscripts. However, there were several small firms, averaging only seven workers, the progenitors of the great electrical machinery industry. Harvesting and sewing machine firms were more typical of the machinery sector in investment and employment. Especially in sewing machines, it was possible to enter with small investment, as reflected in the median employment of ten workers. Large firms that led in achieving practicality continued to lead in most sectors, including Rogers and Baldwin in locomotives and McCormick in harvesting. However, many other firms competed effectively, with the result that by 1860, McCormick's thirty-seven competitors reduced its share to one-quarter of the market for reapers, mowers, and harvesters.

Though organized research and development was far in the future, most firms in innovative sectors patented as part of their regular activities. Among machinery firms lasting at least 4 years, patenting by principals (typically partners) was more the norm than the exception. For firms operating in 1860, at least one principal invented in close to 70 percent of locomotive firms, 80 percent of sewing machine firms, and all harvester and telegraph instrument firms. Principals invented extensively; those with patents averaged ten in locomotives, five to six in sewing and reaping machines and two in telegraph instruments. Many of these firms were also assigned or licensed patents. Firms had ongoing innovation.[38]

TABLE 6
Major Innovations: The Time Path of Patenting

	Railroad	**Telegraph**	**Reapers**	**Sewing Machines**
1821-1825	2		1	
1826-1830	5		1	
1831-1835	19		3	
1836-1840	33	1	0	
1841-1845	13	4	3	4
1846-1850	29	30	9	13
1851-1855	67	24	20	104
1856-1860	189	62	274	381
1861-1865	151	57	253	339

Source: See Table 1.

As output and learning grew, invention accelerated. The pattern was similar for each innovation; practicality led to learning and more invention. Practical in the late 1830s, railroads had six times as many annual patents in the period after 1855 (see Table 6). After gaining practicality around 1847,

[38] On the methodology and results of the survey of machinery principals, see Thomson "The Machinery Sector." John Nader points to the importance of owner-inventors in harvesting firms in the 1850s, which gave way to invention by employees and independent inventors in the upcoming decades. See his "Learning Effects and the Pace of Technological Change" and "The Rise of an Inventive Profession."

telegraphs doubled their annual patenting a decade later. Invention in sewing machines tripled after it became practical, and harvesting machines, with the multiple stimuli of practicality, accelerating diffusion, and the expiration of key patents, grew from under two patents annually in the late 1840s to over fifty after 1855.

Invention was the product of the expanding learning of those within innovating networks. The paths differed among innovations. Knowledge bases differed fundamentally, and so did inventors. Close to two-thirds of telegraph patents were issued to inventors in scientific occupations, especially those requiring knowledge of electrical science (see Table 7).

TABLE 7
Major Innovations: Patents by Occupation and Networks

	Railroad	**Telegraph**	**Reapers & Harvesters**	**Sewing Machine**
Occupational Shares				
Machinist	45.7%	4.9%	44.6%	64.5%
Applied Science	7.9%	64.6%	0.0%	2.4%
Invention	2.6%	6.9%	22.3%	13.6%
Other **Manufacturing**	25.5%	16.7%	7.6%	16.6%
Trade & Service	25.7%	6.3%	2.5%	1.2%
Agriculture	2.6%	0.7%	22.9%	1.8%
In-Network Inventors	30.7%	66.0%	56.7%	54.4%
Invention Location				
Mid-Atlantic States	56.1%	64.0%	54.1%	46.3%
New England	20.1%	23.6%	2.9%	43.6%
South	5.1%	3.9%	4.4%	2.6%
West	18.7%	8.4%	38.5%	7.5%
Urban	53.5%	74.2%	27.3%	64.8%

Source: See Table 1.

Some scientific knowledge had been internalized within occupations. Telegraphers and equipment designers required learning about recently-discovered principles of electrical science, and many telegraph inventors frequently interacted with scientists and engineers. Machinists were prominent inventors in each sector except telegraph patenting, although there, too, some inventors were instrument-makers similar to machinists in design and production capabilities. Professional inventors were important in designing sewing and harvesting machinery. Most of these were patent agents who invented widely, but some were professional inventors of the sort that became more common in post-bellum harvesting firms. The role of farmers among reaper inventors was an important difference reflecting their learning conditions.

Though different in many particulars, innovation paths were similar in two important ways. They all relied on invention by occupations with substantial technological knowledge applicable to many industries. Machinists and engineers shared this knowledge, as did those from other occupations that made instruments or shaped metal. The universal dimension helps explain the success of innovations. Yet, each innovation acquired its own history, in part because of the distinctive networks of learning and invention among its practitioners. The 31 percent of railroad patents issued to occupations tied to this sector underestimates that sector's contribution for reasons already noted. In other sectors, in-network inventors took out most patents, some were principals of machinery firms, other principals of using firms, and yet others were managers and employees. Networks were differentiated by location, with upstate New York and small-town Illinois and Ohio leading in reaper invention and usage, while telegraph invention was localized in eastern cities.

Ongoing invention overcame limits to the use of the core technology in ways that furthered the innovation's spread. This was an immensely complex process that can only be alluded to here. This advance had three elements. First, invention aimed at overcoming problems in the core technology. Telegraphy relays were developed to allow for long-distance communication. Underwater cables were designed to cross rivers and channels, culminating in the short-lived triumph of the Atlantic Cable, the failure of which led to further invention. Invention was often competitive, such as the House printing telegraph and the Bain electrochemical telegraph, which were used to form parallel routes when a company controlled the Morse route in an area. Details of reapers were constantly modified to increase durability and usability under varying climactic conditions; McCormick's model changed each year to this end. Some changes were more fundamental; many firms developed self-raking reapers to replace hand-rakers, thereby reducing labor requirements. Competitors developed harvesters that were more complex, and binders that would dominate the field after the war. Invention by suppliers improved the product, including superior insulation and wire manufacturing, often the product of established wire and rubber firms seeking new markets.

Second, innovations found wholly new uses. One of the most important was the extension of the sewing machine into shoemaking. Waxed-thread machines were developed in the early 1850s to sew heavy shoe uppers. The bottom-sewing machine was invented in the late 1850s by a shoe-stitcher and developed during the Civil War. The sewing machine, hence, revolutionized two of the three largest industries, clothing and shoes, by means of knowledge and agents from the third, cotton textiles. In addition, consider the fire-alarm telegraph. Trained at Dartmouth, Moses Farmer superintended repairs of a Massachusetts telegraph from 1847. An active experimenter, he invented an automatic circuit-closer, which became the basis for his fire-alarm telegraph. He and a partner got an appropriation from the city of Boston to develop and introduce the telegraph, which spread to other cities through patent assignments. He later developed batteries, duplex telegraphs, rubber insulation, and a host of other electrical improvements.[39]

Third, the production process evolved to improve the quality of the product and reduce costs. The growth of the scale of output enabled the use of mass production techniques. Some targets were quite specific, such as the firm that made 250,000 locomotive and car springs in 1860. Reaper and sewing machine firms were large enough to fundamentally change production. Two sewing machine firms led the process. Wheeler and Wilson built a factory using mass-production machine tools developed in the firearms sector to attempt to produce interchangeable parts sewing machines. The Willcox and Gibbs firm took another route when they employed Brown and Sharpe to mass-produce their sewing machines.[40]

In the development of innovations, as in their emergence, internal networks spread knowledge that led to ongoing invention, which furthered the development of the innovation. The development of the core technology was largely a result of this internal dynamic. At the same time, developments outside these dynamics, including machine tools, wire-forming, woodworking machinery, casting methods, design knowledge, electrical knowledge all supported the internal dynamics of innovations. The combination of internal dynamics and external support elevated Americans to leaders. Americans were recognized as such in the Paris Exposition of 1867, when they received a gold medal for locomotives, Chevalier of the Legion of Honor awards for sewing machines and reapers, and two grand prizes for telegraphs and another for reapers.

Conclusion: Social Processes of Innovation

The social quality of innovation is clear. Innovations embodying new technological knowledge were social products in two senses. First, innovators make use of knowledge generated for other purposes by participating in socially constructed communications networks. Institutions of the machinery sector, science, and invention were especially important. Because not everyone had access to this knowledge, those who did had advantages in innovating. Yet, many did have access, and could undertake innovation. Second, the process of innovating involved interactions, and these interactions, whether cooperative or competitive, were sources of learning that advanced the innovation. By developing

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[39] James D. Reid, *The Telegraph in America*, 370-76; Thomson, *The Path*, 118-132.

[40] Joseph W. Roe, *English and American Tool Builders* (New Haven, Conn., 1916); Nathan Rosenberg "Technological Change in the Machine Tool Industry, 1840-1910," in *Perspectives on Technology* (Cambridge, Mass., 1976); Hounshell, *From the American System to Mass Production*, 67-83; 159-70.

their own networks through which problems were solved, innovations shaped their own development, though always in relation to social need and outside changes. We can partially solve the puzzle of discontinuous innovations emerging from existing institutions by noting that innovations developing out of existing institutions built new institutions as they evolved: new firms, new kinds of markets, even new occupations.

It is equally clear that innovations followed different paths, distinguished by the kinds of knowledge and institutions involved. We can more systematically consider these differences by examining 103 major innovators identified in biographical dictionaries, drawing together our analysis in the process. They varied from "typical" inventors because they were more successful, invented earlier in the innovation's development, and received more patents, but they broadly mirrored other patentees in occupational mix and location. Differences among innovations began with the core technological principles involved in the innovation. While the locomotive, reaper, and sewing machine involved mechanical principles, railroad design built on civil engineering, and the telegraph relied on advances in physics. Knowledge differences, in turn, distinguished the institutions through which knowledge was acquired (see Table 8). Locomotives, reapers, and sewing machines all required the knowledge of the machinist, as did the telegraph to a lesser extent. This general knowledge was combined with awareness of particular applications in steam engineering, agriculture, and thread-manipulation. Civil engineering institutions were most widely developed in canal construction. The telegraph relied on electrical engineering, which was emerging from the scientific community, but had no economic significance in 1830.

Innovators acquired needed knowledge through a great variety of means, even within any innovation. This variety is part of the problem in understanding innovation, because the variety of paths followed in any innovation—think of the artist Morse, the scientist Wheatstone, the postmaster Kendall and the schoolteacher House—makes it difficult to understand how any institutional analysis can succeed. The answer lies in the contrasting of ways of learning between innovations and their complementarity and interaction within innovations.

Innovators learned through formal education, occupations, and invention itself. Two groups had substantial shares of inventors with college educations: civil engineers working on the railroad and telegraph inventors. Several of the civil engineers were trained at the Military Academy and were loaned out to railroads in the 1830s. About half of telegraph inventors were college-educated, and typically had extensive preparation in science. Not all telegraph inventors required college training, but it would have been hard to explain the innovation if none had been to college. Overall, the share with college educations is far higher than the one percent of college-aged students in college in this period.

TABLE 8
Major Innovations and Major Innovators

	Railroad: Mechanical	**Railroad: Civil**	**Telegraph**	**Reaper & Harvester**	**Sewing Machine**
Core Technology:	**Mechanical**	**Civil**	**Electrical**	**Mechanical**	**Mechanical**
Institutions of Knowledge Acquisition	Machinists, Steam Engine	Civil Engineers, Canals	Physicists, Electrical Engineers	Machinists, Agriculture	Machinists, Textiles & Clothing
Innovators	35	16	24	18	10
Education					
College	22.9%	62.5%	47.8%	16.7%	0.0%
High School	28.1%	21.4%	18.2%	18.8%	20.0%
Mechanician	38.2%	75.0%	60.9%	13.3%	11.1%
Prior Invention	37.1%	18.8%	41.7%	22.2%	40.0%
Occupation					
Science & Invention	14.3%	93.8%	50.0%	0.0%	0.0%
Machinist	60.0%	0.0%	33.3%	61.1%	60.0%
Other Manufacturing	5.7%	0.0%	4.2%	0.0%	30.0%
Trade & Service	17.1%	6.3%	12.5%	0.0%	0.0%
Agriculture	2.9%	0.0%	0.0%	38.9%	10.0%
Location					
Mid-Atlantic	74.3%	56.3%	79.2%	11.1%	30.0%
New England	11.4%	31.3%	16.7%	5.6%	60.0%
South	2.9%	0.0%	0.0%	11.1%	10.0%
West	11.4%	12.5%	4.2%	72.2%	0.0%
Urban	88.6%	100.0%	91.7%	44.4%	100.0%
Consequences					
Patenting	80.0%	87.5%	87.5%	94.4%	90.0%
Patents Per Inventor	9.6	4.4	5.4	7.4	12.0
Mode of Diffusion of New Knowledge	Public; capital goods; some licensing; occupation	Public; some licensing; occupation	Public; extensive licensing; occupation	Capital goods; modest licensing; occupation	Capital goods; patent pool; occupation
Technology Author	11.4%	25.0%	25.0%	0.0%	0.0%

Sources*:* Ross Thomson, "The Making of the Mechanician: Science and Invention in Antebellum America." Paper presented to the Northwestern Economic History Workshop, Evanston, Ill., November, 2002. Biographies from Dumas Malone, ed. *Dictionary of American Biography* (New York, 1937). For patents, see Table 4.

However, there were even different sources of scientific education. For each innovation, 20 to 30 percent of innovators' highest educational attainment was in high schools or academies. Inventors could also acquire knowledge by self-study, involvement in mechanics' institutes or other extra-occupational means, achieving the knowledge of a "mechanician" in the process. Civil engineers and the telegraph had the highest share of mechanicians, who often acquired their knowledge in college and, in the case of electricity before the telegraph, could not have acquired the needed knowledge in the economy. Locomotive inventors commonly participated in mechanics' organizations: Baldwin and others were members of the Franklin Institute. Agricultural and sewing machinery had few mechanicians and few with college education, demonstrating that not all innovations required systematic knowledge learned off the job.[41]

Innovators also learned from their occupations. Occupations are listed at the time of the first major patent. Predictably, machinists predominated in mechanical technologies; they could gain systematic knowledge, not the knowledge of formal science, but a capacity to think conceptually about mechanical relations that involved formalization, by design and production training in machine shops. That seven reaper inventors were farmers and two sewing machine inventors were shoemakers (one of whom operated a sewing machine) attests to the significance of understanding the object of invention. Again, civil engineers and telegraph inventors differed. For the former, their most important inventions were bridges. Half of telegraph inventors had scientific or inventive occupations when they patented their first major invention, and others joined them later. The relatively high share of machinists reflects the role of instrument-makers such as Vail and Cornell; both later acquired electrical knowledge and developed telegraph inventions.

The importance of inventive institutions is not as clear as that of the machinery sector and scientific institutions. Many sources of learning contributed to forming an inventive community by focusing on new practical knowledge, including *Scientific American* and other journals, mechanics' institutes, industrial expositions, and many books, including the tens of thousands of copies of the Report of the Commissioner of Patents published annually. Mechanics' groups conveyed knowledge of inventive opportunities. Professions of patents agents, drafters, and model-builders facilitated invention and patenting, and in innovations such as the telegraph, these groups were active participants.[42] Prior

[41] Thomson, "The Making of the Mechanician."

[42] For a study of the role of the antebellum patenting system as a means of technological communication, see Ross Thomson, "Mediating the Public and the Private: The Patent System, Technological Learning, and Invention in the Antebellum U.S," Paper presented to the Economic History Association meetings, St. Louis, October, 2002.

inventing experience was also valuable in later invention. From 20 to 40 percent of major innovators had invented before their first major invention. Certainly, an essential role of the patent system was to provide incentives to invent and a mode for diffusion of invention. These incentives played a clear role within the dynamics of innovations.

Though not the best source for revealing the innovation process, biographies do show that however prolific, no innovator achieved practicality without the contributions of others. In each case, innovators following different learning paths were involved, sometimes cooperating, and often competing, and their interactions linked knowledge from various sources. Central to innovations was the establishment of networks through which learning was integrated. New useful knowledge was diffused in several ways. Much did not rely on the ability to privately appropriate useful ideas. Electrical knowledge was a public good diffused through scientific networks and publications. Much the same was true of civil engineering. The government trained engineers and helped diffuse this knowledge through this occupational medium with networks provided by the earlier development of canals and roads. Locomotives had a public quality because English innovations and some important American innovations were not patented in the United States but this knowledge was easiest to access from within emerging networks. Until basic patents expired, knowledge of sewing machines and reapers was public only to the extent that patent specifications were known and machines were demonstrated, but companies vigilantly tried to enforce patent rights. This is one reason that patent renewals were often hard-fought battles with wide press coverage. Publication was an increasingly important mode of diffusion. Innovators in areas with the most public knowledge, especially civil engineers and telegraph inventors, contributed by publishing technological treatises. This public knowledge was not free or universally available, but the access cost, to use Mokyr's term, declined with involvement in appropriate networks. Innovation in capitalism rested on knowledge that was not the property of any individual.

All technologies had private means of diffusion. Mechanical innovations all diffused as capital goods, protected by patents, and increasingly, by production and marketing capabilities. For some innovations, managerial firms began to develop, notably Singer, McCormick, Western Union, major railroads, and to an extent Baldwin. Though patent rights could stop diffusion, they often fostered it through licensing. This was fundamental in telegraphs, where most telegraph companies licensed patent rights, paid for by cash and shares. Morse preferred government ownership (and the purchase of his patent), which never materialized; the alternative of one company setting up all lines would have slowed diffusion. Though locomotive firms freely used the earliest practical technologies, they licensed some patents, including those that made the 4-4-0 practical.[43] Civil engineering improvements were typically public, though some bridge designs were licensed. Licensing in reapers and harvesters complemented in-house usage. McCormick stopped licensing rights by about 1848; Manny and others continued through the 1850s. Firms dominated by owner-inventors increasingly competed through superior products and marketing. Sewing machines represented the unique case where a patent pool governed diffusion, giving an advantage to pool organizers who received royalties, and probably more importantly, achieved economies of scale. At the same time large firms were arising in some sectors, patents enabled others to enter production or to gain revenues from assignments.

Although firms could appropriate returns from licensing or capital goods sales, leading techniques were spread through the externalities of trained workers who left for employment in other firms or to set up their own firms. Such mobility was a strong source of both the integration within sectors and new innovations. New firms rivaled older firms in harvesters, sewing machines, and locomotives, though they did not displace leading firms. Rather, new firms led in developing spin-off products in shoe machinery, buttonhole machines, and specialty telegraphs. After the war, workers such as Thomas Edison had much broader effects. Mobility of workers and new firm formation was an essential aspect of innovative networks and a source of positive externalities. The self-interest of innovators, the public character of knowledge, and positive externalities were each essential to the innovation process.

The very independence of innovative processes reinforced the importance of common institutions supporting innovation. Different people, in different regions, and with modest contact, developed railroads, telegraphs, reapers, and sewing machines. Though telegraphs occasionally followed railroad rights of way or were licensed to railroad firms, most telegraph business came from elsewhere. These conclusions are unaltered by the addition of petroleum production and refining, Corliss engines, and cylinder printing presses to our list of innovations. The rise of so many relatively independent innovations in this period may have been due to the presence of an effective machinery sector, an applied science community, and strong inventive institutions. Neither the railroad nor any other single

[43] The sale of patent rights occurred early in a product's life to enable others to produce outside the inventor's locality, when inventors could not feasibly introduce the product, such as many electrical improvements with significant infrastructural expenditure, and where overlapping patents required cross-licensing or pooling. On the market for patents later in the century, see Naomi R. Lamoreaux and Kenneth L. Sokoloff, "Inventors, Firms, and the Market for Technology in the Late Nineteenth and Early Twentieth Centuries," in *Learning by Doing in Markets, Firms, and Countries*, ed. Naomi Lamoreaux, Daniel M. G. Raff, and Peter Temin (Chicago, 1999), 19-57.

innovation drove antebellum development; the combination of innovations and the institutions that supported them had much greater impact.