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Understanding Machine Tool Development in the United States: Uniting Economic and Business History

Ross Thomson

The evolution of machine tools in the United States from 1820 through 1930 played an indispensable part in the development of mechanized production. But machine tool development can be understood in quite different ways. Economic historians often look at whole industries and at patents as quantitative measures of invention. Business historians frequently use firm records to relate inventions to the strategy, organization, and growth of the firm. I argue that both approaches are needed to understand how machine tools originated and spread, and that an evolutionary idea of firms and industries can integrate these approaches. Many types of firms produced, invented, and sold a wide range of machine tools, and firms were further differentiated by new methods or markets. Some particular firms and some types of firms ascended, but they never dominated and always found competition from new and different kinds of firms. To understand this process, patents and industry sources depict innovation as a whole. Firm records for the Brown and Sharpe Manufacturing Company and studies of ten other innovating firms demonstrate various ways in which firms made use of innovations and, in the process, educated others who would continue to innovate.

The evolution of machine tools in the United States from 1820 through 1930 played an indispensable part in the development of mechanized production. They were essential for mass production and for custom output. But their development can be understood in quite different ways. In studying innovation, economic historians, wary of generalizations from

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any firm, often look at whole industries and at patents as measures of invention. Business historians, doubtful that patents can measure invention and sensitive to differences among firms, frequently use company records to relate inventions to the firm's strategy, organization, and growth. Yet both approaches are needed to understand how machine tools originated and spread. Only when business and economic history are united can the machine tool revolution be understood.

An evolutionary idea of firms and industries will synthesize conceptions from both disciplines. Machine tools developed through an evolutionary process in which many types of firms innovated for quite different purposes. Some types of firms ascended. But the process had no end point; learning identified further problems and educated those who solved them, often in wholly new firms and even in new types of firms. To understand this process, patents and census data depict how overall usage related to invention over time; patents grew as mechanization advanced and where machinists and machine tool production concentrated. Firm records are needed to grasp how machine tools were used and developed. Records of the Brown and Sharpe Manufacturing Company demonstrate three ways that innovation related to production and sales: the company used its inventions to make sewing machines and machine tools, it sold capital goods, and it trained workers who set up their own inventive firms. A study of the modes of usage for lathe patents points to the diversity of agents, and a study of ten firms making and using machine tools illustrates how this variety directed innovation. Firms learned from each other, and their interaction helped structure machine tool development. If business history and economic history are in some sense opposites, looking at the firm's inner life and external context, then a unity of these opposites is needed to understand economy-shaping innovations.

Perspectives from Economic and Business History

Time and again economic history and business history have been declared mutually informing, and yet they often remain far apart. A quick history of the relationship will identify the problem. In 1934, N. S. B. Gras defined business history as the study of "how business has been organized and controlled through administration and management" as ascertained by case studies of firms using publications but especially company records. Business history could inform economic history, but the latter concerned more general developments.[1] Reflecting on the relation of business and economic history a dozen years later, Arthur H. Cole noted how the two disciplines were mutually enforcing. Business history contributes knowledge of the actual economic effects of business activity, which requires knowing the specific paths companies took. Economic history

[1] N. S. B. Gras, "Business History," *Economic History Review* 4 (April 1934): 385-98, quotation on p. 385.

supplies the data that conditions business choices. Cole hoped that, "in the history of entrepreneurship, business historians and economic historians could find an intellectual tract which both might cultivate in mutual good will."[2] Another dozen years later, Herman Krooss sounded a more skeptical tone. He noted that business historians have contributed hypotheses and information that have illuminated economic growth and the varied character of firms achieving that growth. But he also pointed to business history's growing divergence from economic theory, with its views that firms could maximize profits, that pure competition was optimal, and that a changeless, "typical" firm can characterize all firms. Worst yet, business history is "superbly vague," lacks a "unifying theme," fears generalization, and so conflicts with economic history's core pursuit of patterns and trends.[3]

Since then much has happened in both fields. Economic growth has become central to economic history, often examined over long time periods or among sets of countries. The inclusion of incomplete knowledge, market power, and externalities has added complexity to the economist's theoretical apparatus. Business history has changed just as greatly. Alfred Chandler developed a powerful interpretation of the rise, evolution, and significance of big business, which supplied a core theme for business history. Others extended his ideas to incorporate politics, professions, international business, and labor. Critics formed cogent alternatives that highlighted successful arrangements of smaller, net-worked firms producing a wide variety of goods in batches.[4] Yet the two

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[2] Arthur H. Cole, "Business History and Economic History," *Journal of Economic History* 5 (Dec., 1945): 45-53, quotation on p. 50. In later work, Cole turned his attention to firm-specific knowledge in reflecting on Edith Penrose's contention that the experience of teams in a firm generates knowledge that shapes the future performance of the firm. Arthur H. Cole, "What Is Business History?" *Business History Review* 36 (Spring 1962): 99.

[3] Herman E. Krooss, "Economic History and the New Business History," *Journal of Economic History* 18 (Dec. 1958): 467-80, quotations from p. 478. In a survey of the field eight years later, Harold Williamson came to much the same conclusions, though he noted progress in generalizing about the robber barons, the Horatio Alger myth, and the growth of big business. Williamson also noted that business history is often criticized for its neglect of economic theory. He renewed the call for cross-fertilization of business and economic history on empirical grounds; economic historians require knowledge coming from primary research, and in return can indicate the conditions for business success and the typical or atypical character of any firm. Harold F. Williamson, "Business History and Economic History," *Journal of Economic History* 26 (Dec. 1966): 407-17.

[4] Alfred D. Chandler, Jr., *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, Mass., 1977), and *Scale and Scope: The Dynamics of Industrial Capitalism* (Cambridge, Mass., 1990). On extensions to government-business relations, see Louis Galambos and Joseph Pratt, *The Rise of the Corporate Commonwealth: U.S. Business and Public Policy in the*

disciplines remain at odds, with much economic history following economics toward more abstract modeling and statistical testing to study markets and economies, whereas most business history uses company and similar sources to construct narratives about more qualitative developments.[5]

At the same time, scholars of very different types have developed ways to bridge the two disciplines. Chandler identified four concepts of the firm: a neoclassical theory in which a manager with full information maximizes profit, a principal-agent theory in which owners and managers have different knowledge and different interests, a transaction costs theory in which the firm, in a context of asymmetric information, organizes itself to minimize production and transaction costs, and an evolutionary theory, in which the firm, in a world of uncertainty and firm-specific capabilities, forms strategies and structures to best utilize its capabilities, often by developing new processes and products. Because of uncertainty, no strategy can be known to be best ex ante, so firms choose different strategies and modes of organization. Chandler concluded that the evolutionary notion best accounts for the history of the managerial firm.[6]

Others came to similar conceptualizations. Though he focused on different kinds of firms to develop a very different interpretation of the Second Industrial Revolution, Philip Scranton argued that firms took an enormously wide range of strategies, of which those of the managerial firm were but one type. In addition, firms settled into niches defined in part by the strategies of other firms, and often operated in communication networks where they coordinated their activity with other firms.[7] More recently, Naomi Lamoreaux, Daniel Raff, and Peter Temin interpreted broad sweeps of U.S. economic development through the various ways in which firms solved problems of imperfect and asymmetric information, highlighting the role of firms that formed long-term relations with other firms rather than simply responding to the invisible hand of markets or

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Twentieth Century (New York, 1988). On the role of labor, training, and interfirm cooperation, see William Lazonick, *Business Organization and the Myth of the Market Economy* (Cambridge, England, 1991). For one important critique and reconceptualization, see Philip Scranton, *Endless Novelty: Specialty Production and American Industrialization, 1865-1925* (Princeton, N.J., 1997).

[5] This is not to say that many scholars do not draw on and contribute to both disciplines; indeed, without their efforts, this essay could not have been written.

[6] Alfred D. Chandler, "Organizational Capabilities and the Economic History of the Industrial Enterprise," *Journal of Economic Perspectives* 6 (Summer 1992): 79-100. Chandler is referring to the theory of Richard Nelson and Sidney Winter. See Richard R. Nelson and Sidney G. Winter, *An Evolutionary Theory of Economic Change* (Cambridge, Mass., 1982) and Richard R. Nelson, "Why Do Firms Differ, and How Does It Matter?" *The Sources of Economic Growth* (Cambridge, Mass., 1996): 100-119.

[7] Scranton, *Endless Novelty*.

supplanting the market by the "visible hand" of hierarchical organization.[8] While different, these notions all find ways for the firm to shape development in an uncertain world.

Innovation, which by its nature does not take methods as given, strengthens the rationale for evolutionary perspectives. The prospects for solving technical problems, for developing solutions to practicality, and for commercializing practical solutions all are uncertain.[9] Because of the uneven distribution of knowledge, some may be better positioned to observe problems, others to find solutions, yet others to commercialize, which introduces coordination difficulties that can thwart innovation. The very nature of the agents can vary greatly, with independent inventors, firms using inventions, firms selling capital goods, and new firms all participating in the process. In such an environment, firms choose different strategies, leading some to ascend and others to descend. Success today need not continue tomorrow; continued innovation can change the agents and the sources of advantage. Moreover, individuals and firms learn from others, and such learning can accelerate change. Knowledge from successful innovation spreads unevenly, and those in communication networks have advantages in later innovation. Change involves cultural evolution, as Richard Nelson calls it, where differentiation and selection are linked to learning that can pass on evolutionary advantages to other individuals and firms.[10]

The case will be made in four steps. The first establishes the range of machine tool innovations from 1820 to 1930 and relates them to the advance of production. The second shows how a firm can shape innovation. The third identifies the range of innovating firms and their various innovative paths. The last examines how some firms passed advantages to others.[11]

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[8] Naomi R. Lamoreaux, Daniel M. G. Raff, and Peter Temin, "Beyond Markets and Hierarchies: Toward a New Synthesis of American Business History," *American Historical Review* 108 (April 2003): 404-33.

[9] Nathan Rosenberg, "Uncertainty and Technological Change," in *The Mosaic of Economic Growth,* ed. Ralph Landau, Timothy Taylor, and Gavin Wright (Stanford, Calif., 1996), 334-53.

[10] Richard R. Nelson, "Technical Change as Cultural Evolution," in *Learning and Technological Change*, ed. Ross Thomson (London, 1993), 9-23.

[11] One might argue that business and economic history are not enough. Technological history brings a distinct perspective similar to business history in sources, but often focusing on whole industries or regions. A political economy approach, in which government policies about patenting, regulation, and competition shape and are shaped by firms, can add important elements. For examples relating these approaches to business history, see Paul Uselding, "Business History and the History of Technology," *Business History Review* 54 (Winter 1980): 443-52, and Richard R. John, "Bringing Political Economy Back

Machine Tool Invention and Mechanization

Widening mechanization could have propelled machine tool invention for both demand and supply reasons. On the one hand, it increased the incentives to invent, and, on the other, it added to the knowledge that machine tool practitioners could use to invent. Economists often investigate these sources of innovation by examining the relation of usage and patenting quantitatively. Of course patents do not measure all inventive output, but, at least before research and development arose, they formed the best available measure of inventive activity.

Machine tool usage grew greatly from 1820 through 1930. In 1820, firms used virtually no machine tools. The engine lathe, invented by David Wilkinson in the United States and by Henry Maudslay in Britain, had little diffused in America. Wilkinson used some to make textile machines, and firearms armories had begun to adopt them, but machinists in Philadelphia knew nothing of them. Planers to cut flat surfaces, under development in Britain, were unknown in the United States. The milling machine was just being invented in firearms. The absence of machine tools severely limited metalworking capabilities, which slowed mechanization in textile and engines and prevented sophisticated machines from achieving practicality.[12]

By 1930, machine tools were widely used. The best estimates come from a survey of metalworking firms by the trade journal *American Machinist*. According to the survey, in 1930 the metalworking sector, defined to include machinery, transportation equipment, and objects such as screws, tools, and instruments, used about 1,390,000 metalworking machines. Other industries also used metalworking equipment, including the tool rooms of many factories. About 1,050,000 of these machines were machine tools; the rest forged, welded, riveted, bent, or pressed metal. Lathes were the largest group, with 300,000 machines in use. Grinding and drilling machines were next in importance, each with around 200,000, followed by 120,000 milling machines. In 1929, 280 firms in the machine tool industry employed 47,000 workers to make metalworking equipment, and their product included 24,000 lathes, 6,000 milling machines, and 19,000 grinding machines.[13]

In" and "Telecommunications," *Enterprise and Society* 9 (Sept. 2008): 487-90 and 507-20.

[12] Ross Thomson, *Structures of Change in the Mechanical Age: Technological Innovation in the United States, 1790-1865* (Baltimore, Md., 2009), 145-52 and passim.

[13] "40% of Metal-Working Equipment Is at Least 10 Years Old," *American Machinist* 74 (12 Feb. 1931): 285-88. Not all metalworking firms returned the surveys, and the journal attempted to estimate the machines of non-reporting firms by assuming they had the same machine-labor ratio as did reporting firms. For output in 1929, see U.S. Department of Commerce, Bureau of the Census,

Less systematic evidence indicates that engine lathes and planers had begun to penetrate many sectors by the Civil War. In the manufacturing census manuscripts in 1850, R. Hoe, the leading printing press firm, listed 43 lathes and 11 planers, and a prominent Patterson locomotive maker listed 250 lathes. Many machinery firms used lathes and planers by the 1850s, and major firearms firms mass produced using milling machines and turret lathes. But clearly the great growth of machine tools occurred after the Civil War, mirroring the expansion of mechanization.

Machine tool output grew with the extent of mechanization, and machine tool invention might have done so as well, but measures of such invention are hard to come by. Machine tools often were patented, though—especially early on—important machines such as the milling machine and turret lathe were not. Patent classifications do not identify machine tools per se; the various machine tools are spread among a dozen patent classes. However metalworking lathes can be identified. Lathes were invented early, and throughout the period they were the most common machine tool. Metalworking lathes were typically listed in three patent categories: "turning" (class 82), "metalworking" (class 29), and "threaded, headed fastener, or washer making: process and apparatus" (class 470). Each class included non-lathes, such as turning phonograph records in class 82, so I searched only for a patent's principal classification (and not secondary ones) in certain subclasses.[14] To get sufficient numbers of patents by period, I examined all years from 1836 through 1865, and then the first two years of each decade through 1921. The result was a consistent set of 773 metalworking lathe patents issued to U.S. residents throughout the period.

The lathe data set sheds light on several features of machine innovation. Lathe patents accelerated greatly over time, from under one patent annually in the 1836-1845 decade to over 90 around 1920 (see Table 1). The growth of patenting broadly paralleled the growth of mechanization, proxied here by employment in the machinery industry. After 1845, the two grew in close relation. Similarly, lathe numbers grew along with the occupation of machinists. Invention also varied with machine tool output. Consistent data on machine tool output do not exist, but by splicing an estimate based on census manuscripts for 1850 and 1860 with census estimates for 1900 and 1919, one can see clearly that

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Fifteenth Census of the United States, Manufactures, 1929, 3 vols. (Washington, D.C., 1933), 2: 1157-61.

[14] In particular, I examined subclasses 1.3 through 19 and 101 through 173 in class 82, subclasses 27 through 65 in class 29, and subclasses 57 through 86 in class 470. These groups included the large majority of patents with titles related to metalworking lathes, and frequently secondary classifications were also in the searched groups. I examined each patent individually to ensure that they were metalworking lathes.

patenting grew along with employment by machine tools firms, though patenting did not grow as rapidly.

Table 1
Metal-Cutting Lathe Patenting, Mechanization, and Machinists, 1836-1921

Period	Annual Patents	Machinery Workers (000s)	Machinists (000s)	Machine Tool Workers
1836-46	0.7	13.0		
1846-56	4.4	28.9	33.7	99
1856-65	8.8	54.4	52.9	983
1870-71	24.5	82.7	54.8	
1880-81	21.5	145.4	101.1	
1890-91	54.0	257.2	186.8	
1900-01	55.5	350.3	283.3	29,436
1910-11	70.0	710.8	479.0	
1920-21	91.5	772.8	839.6	53,111

Sources: Patent classifications came from the U.S. Patent and Trademark Office website. Patents were surveyed from the annual reports of the U.S. Commissioner of Patents, Google patents and Lexis-Nexis Academic. Most employment and occupational data came from U.S. censuses of manufacturing and population, respectively, for 1850, 1860, 1870, 1880, 1890, 1900, 1910, and 1920. Machine tool employment in 1850 and 1860 came from a study of census manuscripts in Thomson, *Structures of Change in the Mechanical Age*, 141-44.

Notes: Patents exclude those issued to foreign residents. Machinery workers are classified differently in various censuses, but typically include generic foundry and machine shop products, electrical machinery, and engines; they exclude sewing machines, agricultural machinery, and other special-purpose machinery enumerated separately. Machine tool employment in 1919 reflected wartime output and fell substantially in the 1920s. To get consistency over time, machinists include millwrights but exclude toolmakers. Machine tool workers for 1850 and 1860 include those machinery firms for which the census manuscripts listed machine tools as the most important machine.

Geographical data can illuminate the relation of output to invention. To sort out the sources of invention, economists often compare regions or states.[15] To get sufficient numbers of patents, Table 2 groups invention in

[15] Robert Higgs examines the relation of urbanization, manufacturing, employment, and patenting for the whole economy by a cross-sectional regression of states. Robert Higgs, "American Inventiveness, 1870-1920," *Journal of Political Economy* 79 (May-June 1971): 661-67. Kenneth Sokoloff used geographic

three broad periods, 1836-1865, 1870-1891, and 1900-1921. The regional distribution of patents can be compared to that of mechanization (as measured by employment in the machinery industry), machinists, and, when possible, machine tool industry workers. Regions that were high in machinery employment and machinists were also high in lathe patents; New England and the mid-Atlantic states were regularly high in all three, whereas the South and West were low.[16] The Midwest is interesting, because its ascendance as a center of mechanization was reflected in its rising share of patents.

The location of machine tool production was particularly important. New England typically had patent shares higher than its shares of machinery or machinists, perhaps, as data for the last period indicates, because its share of machine tool workers was higher than its share of machinery workers or machinists. Conversely, the mid-Atlantic states typically had a lower share of patents than machinery workers or machinists, and a share of machine tool workers below its share of machinists. The patent share in the Midwest, over time growing from below its share of machinery workers or machinists to above, correlates nicely with the region's emergence as the leader in machine tool production.

Comparing the four leading machine tool–producing states—Ohio, Massachusetts, Rhode Island, and Connecticut—to the rest of the country reinforces the point. In the 1900-1921 period, these states had 29 percent of machinery workers, 22 percent of machinists, and 59 percent of machine tool workers. Their 44 percent of patents suggests that factors related to proximity to machine tool production, and not merely usage,

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differences among patenting to argue that demand might have led invention. Kenneth L. Sokoloff, "Inventive Activity in Early Industrial America: Evidence from Patent Records, 1790-1846," *Journal of Economic History* 48 (Dec. 1988): 813-50. Other studies have examined the geographical structure of invention in particular industries to ascertain whether invention clustered near users or near groups of particularly skilled workers. See Naomi R. Lamoreaux and Kenneth L. Sokoloff, "The Geography of Invention in the American Glass Industry, 1870-1925," *Journal of Economic History* 60 (Sept. 2000): 700-729, and Ross Thomson, *The Path to Mechanized Shoe Production in the United States* (Chapel Hill, N.C., 1989). Geographic studies also derive conclusions by comparing industries, such as Dhanoos Sutthiphisal, "Learning-by-Producing and the Geographic Links between Invention and Production: Experience from the Second Industrial Revolution," *Journal of Economic History* 66 (Dec. 2006): 992-1025, and Thomson, *Structures of Change*.

[16] Larger population in inventive regions does not explain the correlation of mechanization and machine tool invention. In the middle period, for example, New England had 38% of patents but only 8% of the population, while, at the other extreme, the South had 30% of the population, but 3.5% of patents.

informed innovation. Learning from use and production is the most plausible factor.

Table 2
Regional Shares of Machine Tool Patents, Machinery, Machinists, and Machine Tool Workers
(%)

	New England	Mid-Atlantic	Midwest	South	West
1836-65					
Patent Share	51.1	40.3	7.2	0.7	0.7
Machinery Share	24.0	43.6	17.4	11.0	3.9
Machinist Share	31.7	42.7	13.5	8.4	3.6
1870-91					
Patent Share	37.5	33.0	21.0	3.5	5.0
Machinery Share	20.6	46.4	20.7	5.5	6.7
Machinist Share	23.4	38.6	20.6	7.6	9.8
1900-21					
Patent Share	25.8	26.0	37.6	3.7	6.9
Machinery Share	18.7	37.2	32.9	4.7	6.6
Machinist Share	14.9	33.4	30.0	8.8	13.0
Machine Tool Share	39.3	19.6	40.2	0.3	0.6

Sources: See Table 1.

Notes: Regional shares are based on data from 1860, 1880, and 1910 for the three periods. 1860 was chosen rather than 1850 because patents were heavily weighted toward the end of the period. Machine tool employment data for 1910 was not reported, so an average of data for 1900 and 1919 was used; about one percent of employees were not classified by state and are omitted from the regional shares.

For if markets were becoming national—as they were for many firms—and if firms sought good innovations wherever they developed, then people everywhere would face similar potential returns from inventing. The concentrated location of invention suggests that machine tool users, machine tool producers, and those they related to utilized their greater technological knowledge, knowledge of inventive opportunities, and access to potential users to invent more than others.

Correlations of course are not causation; at best they are consistent with interpretations of what might have caused innovation. But they do survey the universe of invention and usage. Moreover, the closer relation of machine tool patents to machine tool production suggests that machine tool firms had particular incentives and knowledge to invent machine tools. A study of a leading firm will help explain why.

Learning and Innovation: The Case of Brown and Sharpe

To understand innovation, business historians often examine particular firms to discern how invention fostered their goals and built on their capabilities. How did the firm make or acquire the invention? Presumably profit-making was its motive, but how did invention contribute to its profit? How did important inventions differ from others? How did some inventions relate to later inventions? Mere counts of patents answer none of these questions, but the study of a leading firm can.

The Brown and Sharpe Manufacturing Company was a key machine tool maker and innovator over much of the period. It and its antecedents spanned the period. Joseph R. Brown tried to specialize in machine tools in the 1830s but found the market too thin. He made clocks and then, along with his one-time apprentice Lucian Sharpe, entered precision metalworking and, in the late 1850s, sewing machines. To make sewing machines and firearms, Brown and Sharpe bought and developed mass production machine tools. It sold machine tools from early in the Civil War throughout the period, yet it continued to make sewing machines, clocks, and precision measurement devices. In an odd move, it also made hair clippers. After about 1880, its product line included screw machines/ turret lathes, milling machines, grinding machines, gear cutting machines, measurement devices, clocks, hair clippers, and sewing machines.[17]

Brown and Sharpe had innovated before it developed machine tools. Brown designed wire gauges that standardized wire sizes for Connecticut brass makers. He designed other measurement devices, such as a dividing engine, and developed a gear cutter. The company's reputation for precision metalworking helped secure a contract to mass produce the Willcox and Gibbs sewing machine. Brown and Sharpe's sewing machine work informed most of its major machine tool innovations.

Brown's four major inventions each emerged to solve a problem in production. Two originated from communication with Frederick Howe, one of the leading machinists of the era who had invented turret lathes at the Robbins and Lawrence armory. Brown's turret lathe originated when Howe, superintending Providence Tool Company's armory making Springfield rifles during the Civil War, asked Brown to make his turret lathes to be used in his armory and in Brown and Sharpe's sewing machine manufacture. Brown added "a self-revolving turret and later a feed device so a rod of metal could be fed and secured without stopping the machine."[18] Brown's universal milling machine came about when Howe, noting that

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[17] Joseph W. Roe, *English and American Tool Builders* (New Haven, Conn., 1916), 202-15; Henry Dexter Sharpe, *Joseph R. Brown, Mechanic, and the Beginnings of Brown & Sharpe* (New York, 1949); *A Brown & Sharpe Catalogue Collection* (Mendham, N.J., 1997).

[18] Quote from Luther Burlingame, July 6, 1929, Brown and Sharpe Manufacturing Company Records, box 16, Rhode Island Historical Society.

twist drills were made by hand, asked Brown to mechanize the operation. The result was one of the most versatile machine tools especially appropriate for toolroom use. Brown's third invention, the formed cutter, enabled milling machine cutters to be sharpened without losing their shape. Finally, the universal grinding machine originated in the mid-1870s when Henry Leland, who headed the sewing machine department, convinced Brown that a machine to grind straight and tapered work would find wide markets. After Brown's invention, which Leland made heavier and more rigid, the company sold universal grinding machines and plain grinding machines, the latter used more for manufacturing on a larger scale.[19] Each invention found dual uses; Brown and Sharpe both used and sold them. Brown patented each machine. In addition, Brown developed gear cutters and measurement devices, among which vernier and micrometer calipers were the most important.[20]

The company continued to develop each innovation. Through 1929 Brown and Sharpe received 198 assignments at the time of patent issuance.[21] They began slowly with five in each of the 1860s and 1870s, then increasing greatly through 1909 before decreasing in the next two decades. The company received 32 assignments for lathes, mostly for screw machines, 30 for milling machines, 25 for grinding machines, 20 for gear cutters, 10 for generic machine tools, 41 for micrometer calipers and other measuring devices, 21 for generic metalworking patents that applied to many machine tools and other machines, 9 for hair cutters, and a few for tools and steam generators.[22] Machines evolved in response to customer's needs to gain greater precision, speed, versatility, and rigidity. As patents document, lathe inventions positioned the cutting tool more accurately, diminished vibration, reduced the wear of parts, cut more evenly, changed feed speeds for light and heavy work, lowered time between turret operations, automatically indexed the turret, and increased the range of screws cut by the machine. Milling machine innovations reduced human measurement error, decreased set-up time, became more automatic for long runs of standardized pieces, added versatility in feed and types of metals cut, prevented damage to cutters and work, fed

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[19] Brown and Sharpe Records, box 10, folder 24.

[20] Roe, *English and American Tool Builders*, 205-15; David A. Hounshell, *From the American System to Mass Production, 1800-1932* (Baltimore, Md., 1984), 75-82.

[21] I have included two of Brown's patents not assigned but known to be used by the firm. In addition, Samuel Darling, who had formed a measurement instrument firm with Brown and Sharpe, had many patents not assigned at issuance but used by the firm.

[22] In addition, Brown and Sharpe bought or licensed dozens of other patents, including measuring instruments patents by nine inventors that it introduced to its product line. Kenneth L. Cope, *Makers of American Machinist Tools* (Mendham, N.J., 1994), 3-6.

coolants, added size for larger work, and gained durability. Novel grinding machines better removed chips and grit, added micrometer adjustments to the machine, ground interior surfaces, improved machine strength and cutting speeds, and cut a greater variety of shapes. The firm also improved its measuring devices and designed a measuring machine to ensure the accuracy of its micrometers, gauges, and other tools.[23]

Altogether sixty-three inventors assigned patents to the firm. Known employees made up 46 percent of these inventors, but assigned 75 percent of the patents, though some might have come after the workers left the firm's employment.[24] Typically the content of invention matched the worker's line of employment in the firm, though some workers crossed into other divisions. Innovation had become a regular, internal part of the company's activity.

Growing machine tool sales spread these innovations widely. Annual machine tools shipped rose from 54 during the 1860s to 78 in the 1870s, 288 in the 1880s, 904 in the 1890s, and 1,861 in first five years of the new century (See Chart 1). Sales grew in the late 1870s, the late 1880s, and especially from 1895 through 1903. The growth of sales had several sources. Certainly the surging demand for machine tools associated with mechanization in many industries contributed. Factors internal to the firm were needed to capture this demand. The company had excellent designs, which it regularly improved. Its machines had superb accuracy, in part because of its own innovations, patented and not. Finally, like other leading firms, Brown and Sharpe developed a sales system. It issued catalogs with drawing and technical specifications. Its 1868 catalog, with 15 pages on instruments and 29 pages on machine tools, included 68 testimonials and references for its universal miller and 35 for its screw machines. Its 1887 catalog grew to 155 pages.[25] The company employed numerous sales agents in U.S. cities and abroad. Agents sought out new business, with particular attention to growth sectors. Workers were sent out to set up machines, make tools, and train others. Agents spread sales geographically. Foreign sales reached a peak of 45 percent of units shipped in the late 1890s. Domestic sales spread among regions; whereas in 1867, 46 percent of machines sold domestically left New England, in 1902, 69 percent did so. The Midwest was a major beneficiary, increasing its share

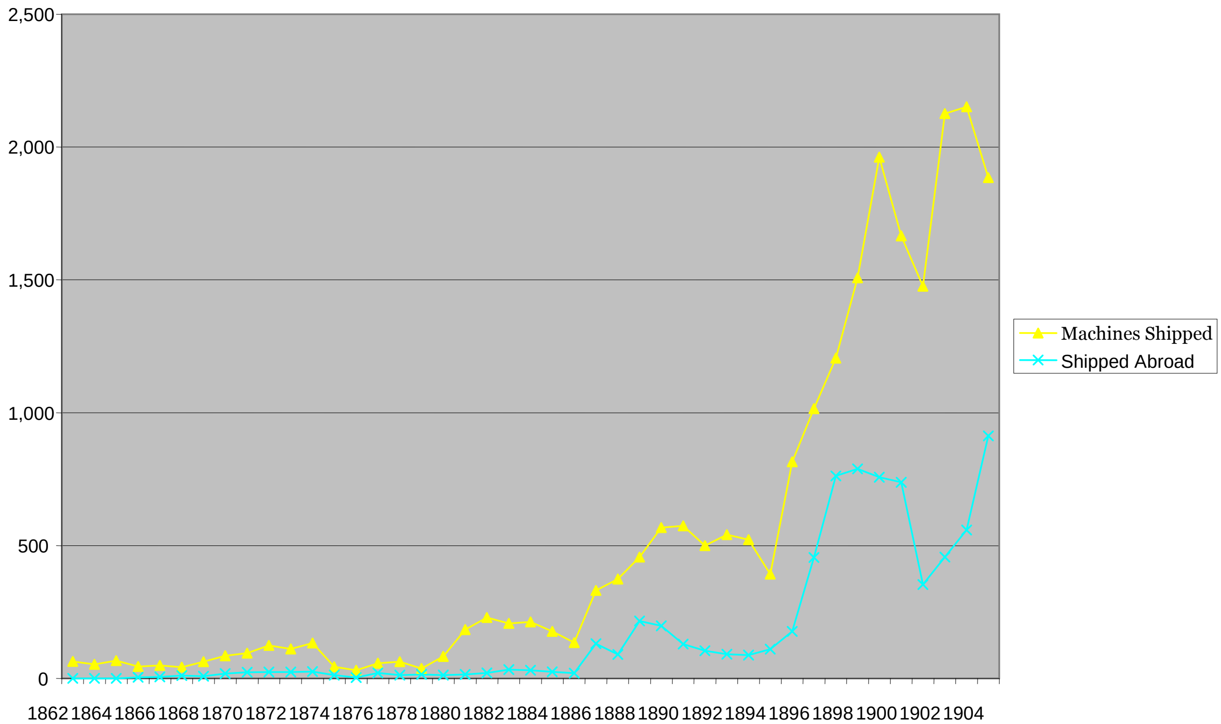
[23] "Accurate Measurements," *Scientific American* 75 (18 July 1896): 40.

[24] We do not know the contractual relations between Brown and Sharpe and its inventing employees. In principle, the inventors patented and owned the patent, and many firms paid their workers for their patents in addition to their wages or salaries. Naomi R. Lamoreaux and Kenneth 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 R. Lamoreaux, Daniel M. G. Raff, and Peter Temin (Chicago, 1999), 19-60.

[25] *A Brown & Sharpe Catalogue Collection*.

from 6 percent 1867 to 29 percent in 1902, nearly the region's share of machinery workers in the later year.[26]

Chart 1
Brown and Sharpe Machine Tools Shipped
(three-year moving average)



Source: Duncan M. McDougall, "Machine Tool Output, 1861-1910," in *Output, Employment, and Productivity in the United States after 1800*, ed. Dorothy S. Brady (NBER Studies in Income and Wealth, vol. 30) (New York, 1966), 497-522, at p. 517.

Brown and Sharpe's effects on machine tool development and mechanization were wider yet, because workers it trained brought the company's methods to other firms. At least in retrospect, the company prided itself on the firms its workers formed or led; in preparing for a company history, it listed 80 prominent workers, typically with leadership

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[26] Brown and Sharpe Records, Outgoing Correspondence, Letterbook no. 1, 1915-1919, letters of 15 April 1915 and 21 May 1915.

positions in the firm, and described their careers.[27] When added to sources, we can identify 106 prominent workers. Some spent decades at Brown and Sharpe; others spent only a year to two. Almost 70 percent of them left Brown and Sharpe and moved to other firms. Nine workers went to three or more companies after their departure. Of those leaving, 38 percent formed new firms, and virtually all of the rest found executive or sales positions including general managers, superintendents, chief draftsmen, or sales engineers. Two became engineering professors or deans. Several were leaders in the industrial mobilization for World War I, and one became a U.S. Senator.[28]

Migrating workers used machine production and design skills in their new jobs. They are known to have found employment at 91 firms (see Table 3). They entered 23 machine tool and related drop-forging firms. Three went to Pratt and Whitney, and several others moved to or formed leading shops in New England. Four brought Brown and Sharpe techniques to the emerging machine tool center of Cincinnati, and others moved to Cleveland, Detroit, and Milwaukee.[29] They also brought their techniques to other leading firms such as the press maker R. Hoe, the Willcox and Gibbs Sewing Machine Company, and the United Shoe Machinery Company. Many went to toolmaking firms, including those that made twist drills. Eleven entered the auto and tractor industries.[30]

The mobility was remarkably wide geographically. Only 19 percent of the firms located in Rhode Island and 38 percent in New England. The Midwest had 34 percent, particularly in Michigan and Ohio, and 21 percent located in the mid-Atlantic states, led by New York. Four were in other countries. A somewhat higher share of new firms remained in New England (45 percent), but 38 percent were formed in the Midwest. The national and international markets for Brown and Sharpe products was paralleled by the mobility of its workers.

Workers took inventive skills to their new firms or used them to form firms. Sixty-eight percent of surveyed workers (including the company's principals) received patents through 1929, and they received 872 patents

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[27] This is not to say that the company appreciated the mobility at the time. The company frequently complained about other firms hiring away its workers. Brown and Sharpe Records, Outgoing Correspondence, 1915.

[28] Brown and Sharpe Records, several different boxes.

[29] Of course, Brown and Sharpe was hardly solely responsible for the success of companies to which Brown and Sharpe workers migrated. The four workers moving to Cincinnati machine tool firms were far less important for the rise of Cincinnati as a machine tool center than were developments in Cincinnati itself. Roe, *English and American Tool Builders*; Scranton, *Endless Novelty*, 193-219.

[30] Workers leaving did have one benefit for Brown and Sharpe; they often became good customers. In a survey of most 1902 shipments, the company sold 91 machine tools to 22 U.S. companies to which their former workers went, 8% of its domestic sales.

Table 3
Mobility of Brown and Sharpe Workers

Industry	Firms	Examples
Machine Tools	25	New England: Pratt & Whitney (3), Norton Grinding, Jones & Lamson Cincinnati: Lodge & Shipley, LeBlond, Bickford, Cincinnati Milling Cleveland and Detroit: Warner & Swasey (2); Leland & Faulconer Multiple locations: Niles-Bement-Pond
Machinery: Printing	1	R. Hoe
Engines & boilers	6	Babcock & Wilcox
Sewing & Shoe Machines	3	Willcox & Gibbs (2); United Shoe Machinery
Machinery: Other	9	
Tools & Screws	11	Morse Twist Drill, Union Twist Drill
Instruments	2	
Autos & parts	10	Cadillac (3); Packard
Tractors	1	Allis
Electrical equipment	4	Shaw Electric Crane
Firearms	3	Remington
Metal products	3	Gorham
Other	5	
Engineering	5	
Unknown	3	
All	91	

after coming to Brown and Sharpe (and another 12 earlier). Only 26 percent had patents used by Brown and Sharpe (see Table 4). Yet 55 percent had other patents, and these patents made up 80 percent of all patents issued to one-time Brown and Sharpe workers. As expected, those who worked only at Brown and Sharpe had most of their patents used by the firm, though one-third of their patents were not used by their employer and some were assigned to other firms. But Brown and Sharpe used only 10 percent of the patents of workers leaving the firm.[31] Those

[31] Workers typically did not patent for other firms while employed at Brown and Sharpe. Samuel Darling patented but did not assign many patents while a partner at Darling, Brown and Sharpe. Charles Norton did assign patents to another firm in between periods of employment at Brown and Sharpe, but not during his employment. One inventor assigned to Willcox and Gibbs, whose machine Brown and Sharpe made. One other inventor did not assign one patent amid several Brown and Sharpe assignments. One patentee assigned two patents to Gorham Manufacturing, a Providence firm and Brown and Sharpe customer, while also

who formed new firms were especially prolific; 89 percent patented, and their firms used 78 percent of their patents not issued to Brown and Sharpe. Among those who secured employment in established firms, 54 percent had non-Brown and Sharpe patents, and their employer used 72 percent of them. However another 16 percent were used by firms for which they were not known to have worked.

Table 4
Invention by Brown and Sharpe Workers, by Later Employment

	All	Only Brown and Sharpe	New Firm	Other Established Firm
Workers	106	33	27	46
Share with Patents	67.9%	63.6%	88.9%	58.7%
Total Patents	872	166	456	250
Patents to B & S				
Share of Workers	26.4%	48.5%	14.8%	17.4%
Total Patents to B&S	177	109	23	45
Share of All Patents	20.3%	65.7%	5.0%	18.0%
Other Patents				
Share of Workers	54.7%	27.3%	88.9%	54.3%
Patents	695	57	433	205
Patent Shares, other patents				
To Own Firms, New	48.8%	0.0	78.3%	0.0
To Own Firms, Estab.	18.7%	0.0	1.6%	72.2%
To Other Firms	14.1%	21.1%	6.5%	16.1%
Unknown	18.4%	78.9%	13.6%	11.7%

Notes: Workers are categorized by their type of employment after leaving Brown and Sharpe. Workers without other employment are called "only Brown and Sharpe." Those who found employment in a new firm are listed as such; a few also found employment in established firms. Only patents at or after employment at Brown and Sharpe are included; the twelve patents received by workers before employment at Brown and Sharpe are omitted.

Such patents were central to their working life after Brown and Sharpe. Inventors like Frank Mossberg or Charles H. Norton assigned dozens of patents to their own firms. These patents often built closely on work they had done at Brown and Sharpe. Norton, for example, developed Brown and Sharpe's grinding machine line before forming his own grinding machine firm. His activities were essential to the transition from

assigning to Brown and Sharpe. In the case of Brown and Sharpe, workers concentrated on invention for the firm during their employment, but not after.

the relatively small-scale grinding Brown and Sharpe had undertaken to the heavy production grinding used in automobile production.[32] The transition came in part when Norton formed a Detroit partnership with another Brown and Sharpe worker, Henry Leland, to make heavier grinding machines. Leland went on to become president of Cadillac Motor and Norton president of Norton Grinding Company. Many joining machine tool and other metalworking firms patented for their new employers; for example, Henry Norris became a leading designer for the Cincinnati Bickford Tool Company. Other workers assigned to independent firms. Carl Sundstrom assigned patents to three firms while maintaining his own engineering practice. Others both formed their own firms and assigned patents to other firms. Through these channels, inventive capabilities nurtured at Brown and Sharpe had much wider effects.

As a leading firm, Brown and Sharpe's experience was hardly representative of all machine tool innovation. In part that is the point. The idea of a representative firm, one that describes all firms in an industry, is inconsistent with the conditions in which innovation occurred. Firms were not maximizing profits in well-defined markets with perfect knowledge. Machine tool firms had to discover potential demands, decide whether to innovate, and identify how to market their products, each step subject to incomplete knowledge. Brown and Sharpe chose one strategy—to produce a variety of precision products using innovative techniques. But it could have chosen to remain an instrument-maker, to confine its growth activities to mass producing sewing machines, or to specialize only on machine tools. The company structured it activities to accomplish its strategy, dividing attention in the firm among units making instruments, sewing machines, and machine tools and forming an apprenticeship system to train workers for each. In the process, it formed capabilities enabling it to innovate and remain a leader. The distinctive strategy, structure, and capabilities of the firm mattered for industry development, and other firms could not simply copy its success. Using firm-specific knowledge, Brown and Sharpe chose a particularly effective way to navigate in an uncertain world.

Innovation and Organizational Variety

If firms developing machine tools followed different paths, then an understanding of machine tool innovation as a whole must identify these paths. Brown and Sharpe made less than three percent of the country's machine tools in 1900 and received only one percent of sampled lathe patents after 1870. Other firms may have been organized very differently;

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[32] For example, Norton's crankshaft grinder is said to have performed in 15 minutes operations that skilled handworkers had previously done in five hours. James J. Flink, *The Automobile Age* (Cambridge, Mass., 1988), 46.

indeed, they might not even have sold machine tools. Independent inventors might not have had firms at all.

The sample of lathe patents can illuminate these issues if more can be learned about lathe inventors and the ways they gained usage. Successful invention required knowledge of machining methods and their limits, and machinists and related professions were best positioned to hold this knowledge. In the lathe sample, these occupations dominated invention. Occupations could be determined for inventors of about three-quarters of the patents. Technological occupations regularly received four-fifths of such patents, and the share rose to nine-tenths for twentieth-century inventors. Machinists held far and away the most prolific technological occupation, but mechanical engineers, draftsmen, and designers became important after 1900. Other manufacturing occupations dominated the rest, with agriculture, trade, and services taking out a tiny share. Inventors with technological occupations overwhelmingly concentrated in the East and Midwest, corroborating the conjecture that inventors learned from occupational practice centering in these regions.

Patents do not identify whether the invention was used, but inventors often owned, worked for, or assigned to firms that could have used their lathe inventions, including inventors of about half the patents in the sample. These patents need not have been actually used, but, as Brown and Sharpe's experience made clear, firms actively attempted to bring their patents into use. One basic difference was whether firms used lathes to make their own product (called self-usage) or sold their lathes as capital goods. For over half of surveyed patents (and all but seven patents positioned to be used), city directories, historical biographies, journals, and records of the National Machine Tool Builders Association were sufficient to identify whether the firm sold machine tools. Over the whole period, 42 percent of surveyed lathe patents with known usage were self-used. The three patents known to be used before 1845 were self-used by the inventor's firm or assignees. The share of lathe patents that machine tool firms received increased from 26 percent from 1846 through 1865 to 46 percent from 1870 through 1881, 66 percent from 1890 through 1901, and 69 percent from 1910 through 1921.

The kinds of firms represent a broad cross-section of lathe producers and users. Machine tool firms included many of the largest, led by Pratt and Whitney (24 patents in the sample), Niles-Bement-Pond (13 patents), Lodge & Shipley (13), R. K. LeBlond (9), William Sellers (11), and Jones and Lamson (8). Each of these had more sampled patents than did Brown and Sharpe. Several dozen other machine tool firms also patented. Lathe-using firms also patented, including such major firms as General Electric, Singer, McCormick Harvester, and Westinghouse Air Brake. Many screw companies patented extensively; firearms firms, watch firms, steel firms, and one automobile firm also invented lathes.

The kind of lathe usage affected how inventors directed other patenting, and so how they affected innovation more broadly. The issue can be explored through a study of all patenting by 313 inventors from the metal lathe sample who invented through 1910, together with 19 earlier lathe inventors, who collectively received 3,951 patents through 1929. Inventors are grouped into periods by their first surveyed lathe patent. Over the whole period, inventors averaged 11.9 patents. Average patenting grew from 8.3 for inventors first patenting lathes by 1865 to 13.7 for inventors beginning from 1870 through 1890 and 14.9 for inventors beginning in 1900 or 1910.[33] Over time, inventors concentrated more on machine tools, increasing average machine tool patents over the three periods from 2.0 to 5.0 to 9.0. A clear pattern emerges: many more inventors patented lathes over time, and those inventors concentrated more on machine tools.

The kind of usage for lathe patents differentiated patenting by lathe inventors. The usage of lathe patents could be ascertained for 53 percent of inventors, who took out 81 percent of metalworking lathe patents in the sample.[34] Inventors whose firms or assignees used their lathe patents to produce other commodities consistently received over half of their patents for inventions outside machine tools and related inventive objects (see Table 5). Their lathes helped to make machines, hardware, or metal products, and most of their inventive efforts concentrated on those products. By contrast, inventors whose firms sold machine tools received under one-quarter of their patents outside machine tools and related generic machine patents. This share fell greatly over time. Before 1866, such inventors received half of their patents outside machine tools and related patents, reflecting the fact that most firms sold machine tools along with other products. That share fell to 14 percent in the last period.

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[33] The sample includes all metalworking lathe inventors before 1866 and in 1870, 1880, 1890, 1900, and 1910. Inventors from 1920 were not examined, because many patented well into the 1930s, and those patents would be omitted. By considering only lathe inventors through 1910, each inventor is investigated for at least nineteen years after their lathe patent. Partly because 1920 inventors were omitted, the share of self-used inventors is higher than in the full lathe sample. The growth of average patents over time in part an artifact of selecting all inventors before 1866 but only those every ten years for later years. This procedure does not capture those inventing only outside the selected years after 1865 but does include patents outside those years for those who invented in sampled years, whereas it includes all patentees—including those receiving only one lathe patent outside census years—for earlier inventors.

[34] In addition, inventors who did not own lathe-making or -using firms could have gained usage by assigning rights after the issuance of the patent, sometimes for particular territories. According to Patent Office assignment records, several lathe inventors gained use in this way before 1866, but because I did not conduct the same study for later inventors, such inventors were not counted as having usage. Thomson, *Structures of Change*, 149-52.

Hence the growing share of machine tool patents over time resulted from the growing share of inventors with commodity usage and the growing concentration of those with commodity usage on machine tools, increasing the machine tool share of their patents from 30 percent in the first period to 70 percent in the last. Lathe inventors fostered mechanization both through their machine tool inventions and, particularly for those with self-usage, through inventions in products their machine tools made.

Table 5
Total Patenting by Kind of Use and Period

	All	Before 1866	1870-1890	1900-1910	Brown & Sharpe
Self-Usage					
Inventors	88	46	24	18	15
Self-usage/All with Usage	49.7%	71.9%	58.5%	25.0%	46.9%
Average Patents	13.2	13.1	14.4	11.7	16.2
Machine Tool Share	23.0%	19.7%	27.5%	25.2%	30.0%
Related Patent Share	19.3%	20.6%	19.7%	15.2%	21.4%
Other Patent Share	57.6%	59.7%	52.9%	59.5%	48.6%
Commodity Usage					
Inventors	89	18	17	54	17
Average Patents	22.8	11.7	33.3	23.1	15.6
Machine Tool Share	58.3%	30.0%	43.6%	69.7%	74.8%
Related Patent Share	18.2%	20.0%	21.6%	16.3%	16.9%
Other Patent Share	23.5%	50.0%	34.8%	13.9%	8.3%
Other Inventors					
Inventors	155	71	46	38	12
Average Patents	4.9	4.3	6.0	4.8	11.0
Machine Tool Share	32.7%	30.3%	32.9%	36.6%	43.9%
Related Patent Share	11.3%	10.4%	7.2%	19.1%	25.8%
Other Patent Share	55.9%	59.3%	59.9%	44.3%	30.3%

Note: Usage is determined from the character of the firm with which the inventor or assignee is associated. If the firm sells machine tools, the patent is assumed to have commodity usage, in that the firm could embody the invention in its product. If the firm uses but does not sell machine tools, the patent is assumed to be self-used.

A comparison with Brown and Sharpe workers illustrates some similarities and differences. To maintain comparability with the lathe sample, only Brown and Sharpe workers who patented machine tools after 1870 are examined. Workers are classified by whether they left Brown and Sharpe for companies that used their own lathes, left for those that sold machine tools, or did not leave at all. Among workers leaving, the 47 percent who found employment in self-using firms was higher than the 37 percent of all lathe inventors from 1870 on. Like other inventors, Brown and Sharpe workers who self-used lathe inventions at later firms took out almost half of their patents outside machine tools and related patents, typically related to the product of the firm. Again like other lathe inventors, Brown and Sharpe workers who later worked for machine tool firms overwhelmingly focused on machine tools and related patents.

In addition to differing from self-using firms, machine tool firms also differed from each other. In an environment characterized by firm-specific knowledge and innovative uncertainty, firms followed different strategies toward innovation with different effects on others. The very multiplicity of innovators, operating in different contexts, requires a closer look at the variety of firm strategies and their effects on innovation.

Machine tool producers differed in markets and specialization, as a survey of seven prominent lathe-making and lathe-inventing firms demonstrates. Pratt and Whitney was the closest to Brown and Sharpe. Both began to sell machine tools during the Civil War with links to Civil War armories. Both sold wide ranges of machine tools. Pratt and Whitney specialized more on firearms, for which it made whole lines of machinery, but its products included grain scales and envelope-making machines. Other lathe manufacturers had narrower product lines. Under James Hartness's leadership, Jones and Lamson of Springfield, Vermont concentrated on flat turret lathes, in which they led the nation and world. Two Cincinnati machine tool firms, Lodge and Shipley and R. K. LeBlond, also concentrated on lathes. Philadelphia's William Sellers and Company concentrated on heavy machine tools for railroads, marine engines, and similar work, while also producing railroad equipment. Sellers formed Edgemoor Iron Company and Midvale Steel Company for his metallurgical and heavy mechanical engineering operations. Niles Tool Works of Cincinnati and later Hamilton, Ohio also concentrated on heavier lathes for railroad and similar work. Its 1899 merger with firms formed by William Bement and Lucius Pond formed Niles-Bement-Pond, the largest machine tool firm in the United States, which then bought out Pratt and Whitney (though the latter continued to operate under its own name).[35]

Each of these firms innovated and patented regularly. Each began slowly, but accelerated its patenting over time (see Table 6). Except for Niles-Bement-Pond, firms typically started with patents from their

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35 Roe, *English and American Tool Builders*; *Descriptive and Illustrated Catalogue of the Pratt & Whitney Co.* (Hartford, Conn., 1888); Pratt & Whitney Company, *Accuracy for Seventy Years: 1860-1930* (Hartford, Conn., 1930); Wayne G. Broehl, Jr., *Precision Valley* (New York, 1976); Scranton, *Endless Novelty;* Domenic Vitiello, "Engineering the Metropolis: The Sellers Family and Industrial Philadelphia" (Ph. D. diss., University of Pennsylvania, 2004); Rick Stager, "History of the Niles-Bement-Pond Tool Company: The Story of the World's Biggest Machine Tool Business" (Birchrunville, Pa., unpub. MS). Using Niles-Bement-Pond connections, Pratt and Whitney moved into airplane engines.

principals, who in the firm's first two decades received from half the patents for Pratt and Whitney to nine-tenths for Sellers and all for LeBlond. Over time, each firm involved others in their patenting, though principals remained central in more specialized lathe firms. With total patents ranging from 65 through 641, innovation and patenting had become integral to the strategies of these firms.

Table 6
Patents Issued to Major Machine Tool Firms by Date

Decade	Brown & Sharpe	Pratt & Whitney	Sellers	Niles-Bement-Pond	Jones & Lamson	Lodge & Shipley	LeBlond
1850-1859			9				
1860-1869	5	11	20	1			
1870-1879	5	15	41	1	1		
1880-1889	21	74	27	23	3	4	
1890-1899	56	71	34	20	29	4	1
1900-1909	59	121	26	73	32	30	17
1910-1919	25	119	6	76	30	16	24
1920-1929	28	230	10	134	16	11	32
All	199	641	173	328	111	65	74

Notes: Patents include those assigned to the firm and those in the firm's product line issued to principals.

Firms' inventions typically paralleled their product lines. Each invented machine tools, though they varied greatly from 33 percent of all patents to 88 percent (see Table 7). Like Brown and Sharpe, Pratt and Whitney patented wide ranges of machine tools, which enabled it to equip whole government armories in Europe. It also made machine tools for sewing machines, bicycles, and automobiles. It and Brown and Sharpe advanced precision instruments in machine tool work. Pratt and Whitney developed a number of precision measuring devices in its gauge division, including the Bond-Rogers comparator, which helped measure the standard inch. It also developed an enormous range of products, including an envelope machine for which it received 24 patents and a grain weighing machine with 49 patents assigned to the firm.[36]

William Sellers and Company, which first specialized on machine tools around 1850, patented the widest range of machinery. Its machine tools concentrated more on heavy uses such as locomotives, marine engines, and construction. Related to Sellers' other interests in the Edgemoor Iron

[36] Roe, *English and American Tool Builders*; Pratt & Whitney Company, *Accuracy for Seventy Years*.

Company and Midvale Steel Company, his machine tool company also patented metalworking machines to roll, press, bend, punch, and hammer

Table 7
Patents Issued to Major Machine Tool Firms by Type
(%)

Type	Brown & Sharpe	Pratt & Whitney	Sellers	Niles-Bement-Pond	Jones & Lamson	Lodge & Shipley	LeBlond
Machine Tools	59.1	66.0	32.9	75.9	82.0	87.7	86.5
Machine: Generic	10.6	6.7	7.5	8.2	5.4	10.8	12.2
Measurement	20.7	5.6	0.6	0.0	0.9	0.0	0.0
Other Metalworking	0.0	5.8	19.1	8.2	8.1	0.0	0.0
Tools	3.5	0.8	1.2	0.0	0.9	1.5	0.0
Other Concentrations	4.5	11.4	28.3	5.2	0.0	0.0	0.0
Other Patents	1.5	3.7	10.4	2.4	2.7	0.0	1.4
Other Concentrations	Hair Clippers	Envelope Machines	Basic Metals	Electric Motors			
		Grain Weighing	Boilers & Injectors				
Railroad-Related	0.0	0.0	25.4	15.2	0.0	0.0	0.0

metal, together with puddling and annealing furnaces, casting apparatus, railroad equipment, and bridge designs. Before the Civil War, Sellers had sold the Gifford injector for locomotives, and the firm patented a series of locomotive boilers and injectors. Sellers adopted a strategy of integrating many metalworking operations for large-scale industry, and one-quarter of its patents aimed at railroad uses.

Niles-Bement-Pond also concentrated on heavy machine tools, as had the three companies that united to form it. The consolidated firm invented extensively among a wide variety of heavy machine tools, but with a focus on railroad equipment such as car-wheel lathes. Early on it sought ways to use electric motors to drive machine tools, and it patented many electric motor control devices to apply the motor to its heavy tools. More specialized lathe firms invented more narrowly. Jones and Lamson focused on the Hartness flat turret lathe; virtually all its patents had that object directly or indirectly. Two Cincinnati firms also narrowly targeted patenting. Lodge and Shipley patented lathes and related generic machine inventions, and R. K. LeBlond concentrated even more on lathes. They and many other narrowly focused companies would make Cincinnati the leading machine tool center in the early twentieth century.

A wide array of firms used their own lathe inventions to craft their products throughout the period. Many of the earliest inventors adapted lathes to manufacture screws and bolts. Some of them sold both screw products and machine tools. Screw making remained a central object of invention through the whole period, including firms that made the first automatic lathes and the first multi-spindle automatics. Firearms producers also invented widely. The federal Springfield Armory innovated extensively, but patented little. Private firms patented firearm designs and machine tools to make them. Robbins and Lawrence and Colt Manufacturing led antebellum innovation; both developed systems of mass production that approached interchangeability.[37] In addition, firms making harvesters, electrical equipment, and automobiles found the need to invent lathes. McCormick Harvester received a patent for a "vertical gang lathe" to turn varying numbers of shafts simultaneously, which saved labor. George Corliss patented a lathe to finish the ends of steam engine cylinders. American Waltham Watch invented a machine for turning watch pinions. Edgemoor Iron patented a machine for facing the heads of boilers.[38]

Two inventions by very different firms had particular importance in the twentieth century. Frederick Taylor, working for Bethlehem Steel, undertook a research effort that yielded harder alloys used to make high-speed steel cutting tools; when developed, such tools made heavier cuts at double the speed without losing their shape. Taylor had worked at Midvale Steel, where Sellers authorized an extensive series of experiments on optimal machine tool usage using Midvale's special steels. He renewed his interest at Bethlehem, and, when evaluating steels for use in Bethlehem's machine shops, developed the new alloys. The resulting patents proclaimed that their tool would "run at a higher cutting speed" and at "higher temperatures" than existing tools. The patent, sold to Bethlehem, added to the firm's product line. A prolonged process of machine tool redesign was needed to realize the potential of higher speeds.[39]

A second change came from the introduction of the electric motor to drive machine tools. Firms developing electric motors targeted machine tool use, led by General Electric (GE). It developed motor-driven machine

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[37] Hounshell, *From the American System to Mass Production*; Thomson, *Structures of Change*.

[38] U.S. Patents 420,064; 432,791; 450,398; 961,542.

[39] U.S. Patents 688,269 and 688,270; Roe, *English and American Tool Builders*, 250; Charles D. Wrege and Ronald G. Greenwood, *Frederick W. Taylor: The Father of Scientific Management, Myth and Reality* (Homewood, Ill., 1991), 125-48; Harless D. Wagoner, *The U.S. Machine Tool Industry from 1900 to 1950* (Cambridge, Mass., 1966), 9-10. Bethlehem's patents were annulled when it sued Niles-Bement-Pond for infringement and lost.

tools from the 1890s and entered into extensive discussion with leading firms. For example, in 1899 Brown and Sharpe corresponded about how GE motors would handle speed variation, gearing changes, and changes in direction of motion. GE designed motors attached to individual machines, which it successfully applied to milling machines in 1901 and grinding machines in 1904.[40] This "unit-drive" system spread widely in the 1920s. GE also designed machine tools to use its motors. John Riddell, the mechanical superintendent at GE's Schenectady plant, designed portable machine tools, each to cut large parts secured to floor plates. Though agents new to machine tool invention initiated the effort to apply this general purpose technology to machining, machine tool firms such as Sellers, Pratt and Whitney, and especially Niles-Bement-Pond quickly followed suit.[41]

Machine Tool Networks and Cross-Firm Learning

Firms inventing, making, and using lathes clearly evolved through myriad paths, but these paths were not independent. For all their diversity, such firms learned from each other. Machine tool users and producers were linked through networks that communicated knowledge widely among practitioners. Sale of machine tools spread knowledge to machinery producers of all types and to other metalworking industries. Express knowledge sharing linked many machine tool producers and users. Inter-firm learning flowed through these networks. Labor markets linked machinists and related engineers who moved through the mechanical industries in search of jobs and entrepreneurial opportunities. Such learning diffused knowledge, including that needed to invent.

Two kinds of learning were linked to the product market. Machine tool firms and their customers learned from each other. They communicated about more than price, because customers could not readily assess the quality of the product and often required instruction on how to use or service it. U.S. firms developed detailed catalogs with extensive drawings; in the words of an English observer, an American machine tool maker "takes the prospective purchaser into his confidence, giving him in his catalogues information which would enable any builder, if he were so

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[40] Brown and Sharpe Records, Outgoing Correspondence, 6 Sept. 1899, 9 Sept. 1899, 1 Dec. 1899; Historical Data, vol. 3. It was recognized quite early that the motor made it much easier to change machine speeds, and the elimination of shafting and belting enabled machines to be located more effectively. "A Direct-connected Motor and Lathe," *Scientific American* 74 (15 Feb. 1896): 104.

[41] Frederick A. Halsey, *Methods of Machine Shop Work for Apprentices and Students in Technical and Trade Schools* (New York, 1914), 191-99; John Riddell, "Portable Versus Stationary Machine Tools," *Transactions of the American Society of Mechanical Engineers* 22 (1901): 588-98; Wagoner, *The U.S. Machine Tool Industry*, 11-19.

disposed, to make the machine."[42] User-producer learning could be indirect; because machine tools were used by many firms and industries, machine tool firms passed on learning from one user to users across the economy. Unlike most industries, where firms bought little from each other, machine tool firms rarely produced all types of machine tools they needed and so purchased extensively from one another. By the mid-1860s, Sellers and Bement each purchased universal milling machines from Brown and Sharpe, and Sellers added two screw machines. A survey of most of its shipments in 1902 shows that Brown and Sharpe sold 118 machine tools to 41 U.S. machine tool firms, about 8 percent of its domestic sales that year. Sales efforts, demonstrations, training, and servicing all spread knowledge from machine tool firms to their customers.[43]

Other learning had competitive motives. Firms studied each other's machines. In one study of grinding machines, Brown and Sharpe dismissed two competitors but was concerned about a third whose machine was heavier and cheaper than its own. Patents offered some protection domestically, but less internationally. The firm's correspondence regularly identified foreign firms copying its machines, including one Danish firm that copied its milling machine and "in their advertising matter, have also copied the description of the machine verbatim."[44]

Firms shared knowledge more publicly. Principals of firms published some of their findings, and the *American Machinist, Iron Age,* and *Transactions of the American Society of Mechanical Engineers* widely reported on machine tools. For example, at the American Society of Mechanical Engineers meeting in which James Hartness became president, one session included four papers and about two dozen recorded participants, including workers for Brown and Sharpe, Lodge and Shipley, Cincinnati Milling Machine, General Electric, iron and steel firms, machine tool users, and the managing editor of *American Machinist*. The discussion, ranging over gearing, motors, standardization, and the merits of cast iron or steel parts, touched on many of the key issues of the day. Moreover, visitors toured machine tool factories. Hundreds who signed Sellers' visitors register from the 1860s, including Joseph Brown, Lucian

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[42] The author contrasted American methods with the more secretive policies of English firms, whose catalogs are "drawn up rather with a view to conceal as much as possible from rival makers than with the object of affording lucid descriptions to the purchaser." "American vs. English Machine Tools," *Scientific American* 82 (21 April 1900): 242.

[43] Brown and Sharpe Records, box 6, vol. 2; *A Brown and Sharpe Catalogue Collection*, 20-30.

[44] Brown and Sharpe Records, box 10; folder 23, and Outgoing Correspondence, folders 2 and 3.

Sharpe, and many of the country's leading machinists.[45] In a world where imperfect knowledge reigned, such presentations and tours added to the reputation of the firm.

At times firms shared contracts with other firms. When William Lodge decided to specialize on engine lathes but his partner wanted to sell whole ranges of machines, they contracted out to have other firms make other machine tools and parts; R. K. LeBlond and many other Cincinnati machine tool makers got their start in this way. Cincinnati firms coordinated marketing efforts abroad or when visitors came to town. At times firms rented space in other firms' buildings. Facing common local labor markets, firms collectively supported training in technical high schools, with notable success. Now the biggest machine tool center in the country, Cincinnati firms initiated a national organization, the National Machine Tool Builders Association, in which Cincinnati firms far outnumbered those of any other city.[46]

Firms were also linked genetically; they inherited knowledge from earlier firms and passed on their own skills to their descendents. Here Brown and Sharpe's experience was common: those trained in leading firms were essential to the wider progress of the industry. Such mobility formed the two largest machine tool firms before 1860 when William Sellers left Fairbanks and Bancroft in Providence and William Bement left Lowell Machine Shop to form their Philadelphia firms. Workers also spread mass production techniques from firearms to other sectors. The extent of this mobility was extraordinarily wide. Of twenty-nine leading managers and workers of two leading antebellum firearms firms, Robbins and Lawrence and Colt Patent Firearms, all but Samuel Colt and his successor Elisha Root found work with other firms. Some worked for many firms. Ten moved to other firearms manufacturers, including Remington, Spencer, Smith and Wesson, and the Springfield Armory. Another ten formed or joined machine tool firms specializing in mass production equipment; they helped give rise to leading machine tool firms. Francis Pratt and Amos Whitney had been inside contractors at Colt, then worked in an early firm selling milling machines before offering a line of machine tools. Frederick Howe prompted Joseph Brown's inventions; others joined Bement and Jones and Lamson. Some workers applied and developed firearms methods to make drop forgings, screws, and tools. Such firms brought mass production techniques to sewing machines, bicycles, textile machinery, engines, mining machinery, and much else. In this way, the

[45] "The Session on Machine Shop Topics." *Iron Age* 92 (11 Dec. 1913): 1340-42; William Sellers and Co., "Visitor's Book" (Hagley Library, Wilmington, Del.). No doubt some Sellers visitors were customers.

[46] Scranton, *Endless Novelty*, 208-18. I thank Ralf Richter for supplying me a complete list of all National Machine Tool Builders Association members.

dynamics of self-usage helped form new industries or improve production methods in existing industries.[47]

Invention was integral to the process. Five-sixths of the twenty-nine workers at these two firms patented. They averaged 22 patents, 81 percent of which were issued after 1865. To take one prominent case, after leaving Colt, Christopher Spencer invented a silk-winding machine, which three other Robbins and Lawrence or Colt workers improved and produced. Spencer then moved to firearms, where his repeating rifle became a weapon of choice by the Civil War's end. To make it he collaborated with Charles Billings, the principal drop forging contractor at Colt, to develop broad-drop forging methods. Billings and Spencer then formed a firm to make drop forgings in the 1870s, which led the way in precision forging methods. Stimulated by another one-time Colt contractor, Spencer developed a turret lathe to make sewing machine bobbins, which he later recognized to embody the core principle of the automatic turret lathe, a basic advance in machine tool design.[48]

Machine tool firms had similar spinoffs. Pratt and Whitney trained a dozen leading machine tool producers, who often had been inside contractors. William Gleason and E. P. Bullard went on to form important machine tool firms specializing in gear cutters and boring machines in Rochester and Bridgeport, respectively. Cleveland's Worcester Warner and Ambrose Swasey, of Warner and Swasey, Reinholdt Hakewessel of National Acme, George Bardens of Oliver and Bardens, and A. F. Foote all learned their skills at Pratt and Whitney. So did others moving to Pawtucket, Chicago, and Beloit, Wisconsin. Two Sellers workers formed a machine tool firm in Wilmington. William Sellers trained Frederick Taylor and supported his experiments, which would lead to high-speed tools at Bethlehem Steel (and affected Taylor's more famous organizational innovation, Scientific Management). Coleman Sellers had been a foreman at Niles and Company before becoming chief engineer at William Sellers & Company, and George Gray had been a Niles superintendent before forming a leading Cincinnati machine tool firm. Jones and Lamson, itself the beneficiary of workers trained at Robbins and Lawrence and at Brown and Sharpe, employed a series of workers who invented and formed their own firms, including Edwin Fellows, William Bryant, and George Gridley, who developed, respectively, a gear shaper, a chucking grinder, and an automatic multiple-spindle lathe. Hartness supported the development of

[47] Roe, *English and American Tool Builders;* Thomson, *Structures of Change,* 268-69.

[48] Roe, *English and American Tool Builders*; Ross Thomson, "The Continuity of Innovation: The Civil War Experience," *Enterprise and Society* 11 (March 2010): 128-65.

each firm with endorsements and investments.[49] Firms in Cincinnati typically gave rise to other firms, each specializing in a narrow range of products. In his various firms, William Lodge had nine known workers leave to form other firms, and contracted with at least six others whose firms turned to machine tools.[50]

Educated in making and designing machine tools, the workers continued to do so in their new firms. Of 35 workers leaving the six machine tool firms (not including Brown and Sharpe) for which sufficient information exists, 32 received patents. Eleven patented surveyed lathes, including Taylor and several automatic lathe inventors, and another 15 surveyed lathe inventors assigned patents to the new firms of these workers. Most others made and patented machine tools, but a few spread patenting into firearms, precision devices, and telescopes.

Of course, the seven surveyed machine tools hardly dominated machine tool innovation. But they were important; they and the firms their workers formed received 18 percent of all surveyed lathe patents from 1870 on, 38 percent of the patents with known usage, and 55 percent of the patents issued to machine tool firms. They also represented a more general pattern. Machine tool firms typically were innovators. In a study of 128 members of the National Machine Tool Builders Association in the early twentieth century, 86 percent were assigned patents. Moreover, just as machine tool firms trained machinists, draftsmen, and engineers, so did machinery and other machine tool–using firms, and these occupations dominated all lathe invention. By training workers to use and make machine tools, firms also provided information about how to invent and bring inventions into use. Through relations to customers, knowledge sharing, and worker training, machine tool users and producers had formed organized but open-ended networks that spread knowledge

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[49] Roe, *English and American Tool Builders*; Joseph Wickham Roe, *James Hartness, a Representative of the Machine Age at Its Best* (New York, 1937); Pratt & Whitney, *Accuracy for Seventy Years*; Broehl, *Precision Valley*. Hartness's support for his workers in setting up their own firms around Springfield was similar to the experience of Brush Electric Company and the White Sewing Machine Company in Cleveland. Workers from Brown and Sharpe and Pratt and Whitney differed in that they moved greater distances than did Hartness's workers. Naomi R. Lamoreaux, Margaret Levenstein, and Kenneth L. Sokoloff, "Financing Invention during the Second Industrial Revolution: Cleveland, Ohio, 1870-1920," in *Financing Innovation in the United States, 1870 to the Present,* ed. Naomi R. Lamoreaux and Kenneth L. Sokoloff (Cambridge, Mass., 2007), 46-61.

[50] Roe, *English and American Tool Builders*; Scranton, *Endless Novelty*. Many fewer firms are known to have spun off from Sellers and Niles-Bement-Pond than from the other five firms. This may be a result of the anecdotal character of sources, or of the capital and information costs of establishing firms making heavy machine tools.

readily, and this knowledge informed later inventors and their paths to commercialization.

Conclusion

How then should the remarkable development of machine tools in the United States be understood? This essay has tried to answer the question by uniting approaches of economic history and business history. An economic history approach pointed to the economy-wide growth of machine tool use, machine tool production, and machine tool patenting. Because regions strong in machine tool use and production were also strong in patenting, invention arguably was the outcome of experience making and using machine tools. A business history approach explored this claim by looking at a leading firm, the Brown and Sharpe Manufacturing Company. Its sales were linked to learning and invention through use of its machine tools in making sewing machines, through sales of its machine tools, and through sales by firms formed by workers it trained. In each of these dimensions, problems arose that directed further invention. Through this evolutionary problem-solving activity, Brown and Sharpe grew and the firms it spawned multiplied. Yet as an industry leader, it may have been highly exceptional.

To explore the diversity of innovating firms requires returning to the whole. Inventive firms used their new lathes in quite different ways. Some used them to manufacture other products, while others sold machine tools. Some did both, while other firms sold complements to machine tools such as steel or electric motors. The patent portfolios of inventors for these firms varied accordingly. The trend was toward greater invention by machine tool firms, though self-usage always was important. Machine tool firms differed greatly in the range of their product lines. They typically invented, but the content and breadth of their invention varied with the kinds of products they made. As machine tool firms increased their share of lathe patents, they also increased their share of basic innovations, such as automatic lathes and lathes for heavy mass production work. Yet new innovators from the steel and electrical industries made basic innovations that reshaped machine tools and their usage in the twentieth century. Machine tool innovation, hence, was the product of many kinds of firms, and the relative growth of some firms and types of firms always found competition from other firms and new kinds of innovators. The firms also learned from each other through sale, competition, publications, meetings, and spinoff firms. This learning, part of Nelson's "cultural evolution," gave structure to the whole and supported a dynamic far stronger than a simple competitive selection mechanism could have sustained.

As the argument developed, the perspectives of business and economic history became interfused. The study of industry trends and of a single firm followed perspectives that would be recognized, respectively, as economic history and business history. The perspectives joined when knowledge of particular firms was used to identify the diversity of innovating firms in the whole economy and when learning among these firms integrated machine tool development, helping to understand its aggregate trends. Likewise, the sources used—census and patent records common in economic history, and firm records and trade publications central to business history—each contributed to the understanding of machine tool development. Much as Arthur Cole had hoped, uniting business and economic history has provided more insight into innovation than either discipline could have provided by itself.