# Eras of Technological Convergence: Machine Tools and Mechanization in the United States, 1820-1929

Ross Thomson

University of Vermont

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Abstract: Following up on the seminal insights of Nathan Rosenberg, this paper explores how, and how widely, technology converged among U.S. machine-tool using industries from 1815 through 1930. Convergence involved the invention and spread of machine tools, and both occurred in a variety of ways. Through the study of Brown and Sharpe company records, census data, and patenting by metalworking lathe inventors and machine tool firms, I argue that machine tools evolved through three stages of progressively wider convergence and different organizational forms. Through 1865, firms often made their own machine tools and used inventions in their own firms. Convergence was narrow, occurring through diversification by machinery firms, incipient sale of general purpose machine tools, and some worker mobility. From 1865 through the 1890s, machine tool firms became more central to the invention and dissemination of machine tools among industries. Widening mobility and new firm formation by workers trained by machine tool firms, along with some diversification, added to the convergence. After 1900, machine tool firms and their workers remained central to invention and diffusion for established industries and autos and other new sectors. But major innovations also emerged and spread from new sources making complements to machine tools, notably the steel and electrical industries, so that materials science and electrification had come to contribute to metalworking industries.

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The United States was widely recognized for its breadth of mechanization, a breadth that by the 1920s led the world in autos, electrical equipment, and machines to reap, mine, print, spin, sew, type, and make machines. The widespread mechanization rested on U.S. market size and structure, but also on American machine-making prowess. How this prowess grew and spread among so many kinds of machines has formed a classic question. In a classic answer, Nathan Rosenberg highlighted the importance of technological spillovers among industries. All mechanized production shared certain problems and solutions, and the rate of technological change depended on the pace of diffusion of the common knowledge among sectors and the capacity to solve problems that could transform production elsewhere. In this view, industrialization across industries involved a relatively small number of broadly similar production processes. Because of this technological convergence, as Rosenberg terms it, a development in one industry could benefit others.[1]

In Rosenberg's conception, technological convergence structured a process involving invention and diffusion that reshaped much of the economy. Invention solved production problems in particular industries, generating products that were cheaper or higher in quality. Innovations in metalworking machines, which made machines for all industries, could spread to production processes in other industries. Machine tools were at the core of this metalworking evolution. The machine tool industry was a center of learning that improved products in many industries, including machine tools. The industry functioned as a transmission center of the new techniques, spreading them across machine-using sectors. Rosenberg demonstrates that, from

[1] Nathan Rosenberg, "Technological Change in the Machine Tool Industry, 1840-1910", in *Perspectives on Technology* (Cambridge: Cambridge Univ. Press, 1976), pp. 9-31.

1840 through 1910, solutions to problems arising in firearms and then in sewing machines, bicycles, and automobiles fostered development across wide ranges of industries. The sector using machine tools, he suggests, played a unique, strategic role in diffusing and generating techniques that accelerated technological change for the whole economy.[2]

This paper explores how, and how widely, technology converged among industries in the case of U.S. machine tools from their first significant usage around 1820 through their widespread utilization in 1930. The paper reinforces Rosenberg's basic contention about the growing cross-industry impact of machine tool innovation. Both machine tools themselves and the knowledge of their users and producers contributed to this impact. Moreover, the key innovators that accomplished this convergence changed over time, defining distinct eras of machine tool development and technological convergence.

## Issues and Approach

Because technological convergence involves invention that spills over among industries, it would be expected to have greater economic effects when 1) the range of convergent uses was greater, 2) when capabilities to solve potentially convergent problems was greater, and 3) when artifacts and knowledge spread more readily between potential uses. Convergence involved knowledge that applies to many industries. Two kinds of convergence should be distinguished. Production converged when machine tools developed for one industry transform others. In this case, some knowledge was embedded in machines, but knowledge also was required to use these machines. Production convergence was more extensive when the range of metalworking uses was broader. At the same time, broader production convergence increased the potential returns

[2] Ibid., pp. 10-11, 17.

to machine tool invention. A positive feedback system could form in which invention fostered mechanization, which increased incentives to invent.

In addition, knowledge of machines and their usage may have helped solve problems in product design that pertained to many industries. This design convergence implied that those holding such knowledge were better able to solve problems of cross-industry impact. Design convergence pertained both to machine tools and to the products they fabricated. If, as Rosenberg suggests, all industrialization involved a few processes, design convergence could have spanned mechanized production. However, the distinct problems in designing machine tools, as opposed to machines to sew, reap, or weave suggests that differences in convergence was a matter of degree, with all machine designs having some affinity, but with some machines sharing more features than others. Agents of innovation varied accordingly.[3]

Finally, techniques developed in some sectors require means to spread to others. Several types of diffusion and associated agents could have transmitted techniques. Rosenberg emphasizes the machine tool industry as the key means of transmission, as firms specialized in narrower range of products that they sold in many industries. He also notes the role of machinery firms more broadly, which used machine tools and had knowledge of principles of mechanical production. Such firms might diversify to sell new machine tools in addition to the products made with these tools. In addition, the movement of workers diffused knowledge even when machine tools were not sold, and new firms could make or use new machine tools.

The role of each kind of agent can be expected to vary over the course of capitalist development. Rosenberg identifies a process in which plants first made the machine tools they used, firms then came to sell machines as an added product line, and some firms vertically

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[3] On the two forms of convergence, see Ross Thomson, *Structures of Change in the Mechanical Age: Technological Innovation in the United States, 1790-1865* (Baltimore, 2009), pp. 144-157 and passim.

disintegrated to specialize in machine tools.[4] This suggests a historical progression. It also points to limits to diffusion when firms were using their own tools. The complementary character of innovations in a multi-industry technology also helps grasp the dynamics of machine tools. Metal cutting could be considered a general purpose technology in that it had the potential to have effects on many industries, required considerable time to develop, and developed through innovational complementarities, in which the development in the core technology depends and is affected by development in its application sectors. These complementarities might slow the initial technological development of the technology, because the limited development of machine tools and their users each constrained the development of the other. On the other hand, the widening use of machine tools could accelerate change by bringing in new sectors and new knowledge that could reshape machine tools and their users.[5]

Rosenberg explored convergence largely by looking at four industries, firearms, sewing machines, bicycles, and automobiles, though he points out that machine tools were used far more widely. I address the issue with a more quantitative study of diffusion and patenting throughout the sector using machine tools. In particular, an inventory of machine tools identifies how widely machine tools were used in 1930 and helps define the extent of potential convergence over time. A data set of lathe patentees from 1816 through 1921 documents invention and its characteristics. Studies of the sales, workers, and patenting of the machine tool firm Brown and

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[4] Rosenberg, "Technological Change in the Machine Tool Industry, pp. 12-17.

[5] On the idea of a general-purpose technology, see T. Bresnahan and M. Trajtenberg, "General Purpose Technologies: 'Engines of Growth,'" *Journal of Econometrics* 65 (1995), pp. 83-108 and the essays in Elhanan Helpman, ed., *General Purpose Technologies and Economic Growth* (Cambridge, Mass: MIT Press, 1996). Machine tools have been called a "near GPT" as distinct from GPTs such as steam engines and electrical machinery. Richard G. Lipsey, Cliff Bekar, Kenneth Carlaw, "What Requires Explanation?" *General Purpose Technologies and Economic Growth* ed. Elhanan Helpman (Cambridge, Mass, 1998), pp. 15-54. Rosenberg has written on chemical process technologies and the steam engines as GPTs in "Chemical Engineering as a General Purpose Technology," in Elhanan Helpman, ed., *General Purpose Technologies and Economic Growth* (Cambridge, Mass., 1996), pp. 167-192, and Nathan Rosenberg and Manuel Trajtenberg, "A General-Purpose Technology at Work: The Corliss Steam Engine in the Late-Nineteenth-Century United States," *Journal of Economic History* (March, 2004), pp. 61-99.

Sharpe Manufacturing Company, firearms producers Robbins and Lawrence and Colt Manufacturing, and of several later machine tool innovators provide firm-level detail of convergence and its mechanisms. An examination of all patents for a set of metal-lathe inventors, when contrasted with patents of wood-lathe inventors, provides evidence of the convergent direction of invention of both types of inventors.

After considering the potential for convergence and invention to meet it, the paper argues that machine tools evolved through three stages of progressively wider convergence and different organizational forms. Through 1865, firms often made their own machine tools and used inventions in their own firms. Yet convergence did occur through diversification by machinery firms, incipient sale of machine tools, and some worker mobility, and machine tool inventors also invented in application sectors. From 1865 through the 1890s, machine tool firms became more central to the invention and dissemination of machine tools among industries. Widening mobility and new firm formation by workers trained by machine tool firms, along with some diversification, added to the convergence, and machine tool inventors continued to invent in application sectors. After 1900, machine tool firms and their workers remained central to invention and diffusion for established industries and autos and other new sectors. But major innovations also emerged and spread from new sources making complements to machine tools, notably the steel and electrical industries, so that materials science and electrification had come to contribute to metalworking industries.

## Trends of Usage and Invention

Several trends in machine tool usage and invention point to the potential for convergence over time and the agents who might realize it. The range of convergent uses was first estimated systematically in 1925, when *American Machinist* conducted its first surveys of metalworking machinery usage. The more complete 1930 survey revealed the usage of 129 kinds of metalworking machinery for 20 industrial sectors, which totaled 1,390,000 metalworking machines, including 1,050,000 machine tools, and over 300,000 machines to press, weld, rivet, bend, hammer and forge metal (see Table 1). Given that some sectors were omitted, including machine tools and industries using machine tools in their toolrooms, machine tool usage was greater yet. Every machinery sector used them. Among sectors that had begun to mechanize before the Civil War, engines, railroads, and textiles remained important users, and agricultural, woodworking, printing, and sewing machinery used smaller numbers of machine tools. Sectors that ascended after the war, including mining, oil extraction, and pumping machinery, electrical machinery, and a variety of new machines for typing letters and making food, shoes, and steel added to the usage. Automobiles, aircraft, and other 20$^{th}$ century innovations used rapidly growing shares of machine tools. In addition to machines, over a quarter of machine tools were used to make an enormous variety of metal products such as tools, screws, steam fittings, wirework, hardware, stoves, firearms, and clocks.[6] The products formed by machine tools in turn shaped commodity production throughout the economy. Machine tools were used to mass produce but also to produce in small batches or singly. The latter remained important; engine, bench and tool room lathes comprised more than two-fifths of all lathes in use.

Moreover, these uses were convergent; machine tools that made one kind of product also made many others, as evidenced by the similarity of composition of various types of machine tools by sector. The four most common types of machine tools—lathes including those that made screws, milling machines, grinding machines, and drilling machines—together made up 78

[6] The survey contains one major problem: the sum of the 20 sectors contains about 10 percent more machine tools than do the totals. By comparing the survey with that of 1935, it appears that the principal problem is in the textile machinery totals, which include over ten times as many machines as in 1935. The composition by type of machine is roughly equal between the two periods. I have not attempted to adjust for this discrepancy.

percent of all machine tools; machines to plane, shape, bore, polish, and cut gears and threads made up the rest. The four major types of machine tools formed from 66 to 82 percent of the inventories of listed sectors. Lathes were the most common, and their share varied from 26 to 33 percent of machine tools. Each other machine tool was used by every sector. Naturally, sectors varied in usage; the railroad sector used relatively fewer milling machines and considerably higher shares of boring, planing, and shaping machines. Smaller pieces such as watches and instruments needed different equipment than those making large engines and dynamos, and mass production sectors had more automatic machines than those making small batches. Still, even when looking the narrowest categories, machine tools were used by many industries.[7]

Table 1. Machine Tool Usage, 1930

| Type of Use | Machine Tools (000s) | Lathes and Screw | Milling Machines | Grinding Machines | Drilling Machines | Other |
|---|---|---|---|---|---|---|
| All | 1178 | 29.5% | 12.1% | 17.3% | 19.0% | 22.1% |
| RR and Engine | 139 | 27.6% | 5.2% | 15.7% | 17.4% | 34.1% |
| Resource Extraction, Conveyance | 54 | 30.7% | 8.3% | 14.7% | 21.5% | 24.7% |
| Electrical | 96 | 32.9% | 10.1% | 13.8% | 24.8% | 18.5% |
| Autos and Aircraft | 178 | 25.6% | 13.1% | 16.6% | 27.3% | 17.4% |
| Other Machines | 392 | 30.1% | 14.3% | 18.7% | 17.5% | 19.4% |
| Other Metal Products | 318 | 30.4% | 13.0% | 18.2% | 14.8% | 23.6% |

*Source:* Totals are given in "40% of Metal-Working Equipment Is at Least 10 Years Old," *American Machinist* 74 (February 12, 1931), pp. 285-288; 24 earlier reports in 1930 and 1931 detailed machine tool usage by industry.

*Notes:* The 1930 survey was based on questionnaires sent to machine-tool using firms; the response rate was reportedly high. An attempt was made to estimate the output of nonreporting firms based o the assumption that they had the same machine-worker ratio as reporting firms. The sum of 1.18 million machine tools is greater than the published totals of 1.05 million for unknown reasons.

The identification of sectors using machine tools in 1930 can be used to indicate the

[7] The only exceptions were railroad axle and wheel lathes, used only in the railroad sector. Yet even here the core technological principles were applied more broadly.

potential for technological convergence in earlier periods. A machine tool that made engines, textile machines, and screws in 1930 could have done so in earlier years. Hence the size and diversity of industries that might have used machine tools provides an indicator of the potential for convergence. Of course, this potential need not have been realized, but if potential usage existed but had not been actualized, then other factors must have been at work.

The 1930 census provides a snapshot most closely related to the 1930 machine tool inventory. For each of the 20 categories of machine tool users, the corresponding industries were determined; their wage earners comprised the potential users of machine tools.[8] Machine-tool using industries were significant, including almost 30 percent of workers in all manufacturing (see Table 2). Moreover, users were arrayed over many industries, so that technologies developed for some could have spilled over into others. Among nonelectrical machines, 30 industries sold products valued at over $25 million, and another 25 had products exceeding $5 million. Electrical machinery targeted lighting, power, communication, locomotives, and home appliances. Aircraft, automobiles, motorcycles, and trucks added to the breadth. Fabricated metal products added a great variety of other products.

A similar procedure can determine the size of potential machine-tool using sectors in earlier census years. Several trends are apparent. Most evidently, the number of potential machine tool users grew greatly over time, from about 95,000 workers in 1850 through 2.5 million in 1930.[9] These workers also grew as a share of the whole manufacturing sector, almost

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[8] Of course not all workers used machine tools; total machine tools were about half of total. Workers were differentially equipped; those in agricultural implements and railroads averaged half as many as the whole group. Still, machine tool usage in each sector was considerable.

[9] The identification of potential machine tool users is rough for two reasons. Some kind of threshold level of usage must be imposed, otherwise sectors such as rolling mills, blast furnaces, and even textiles would be included. I tried to stick to the sectors in the 1930 machine tool survey. Varying census definitions complicated the calculations; for example, I included wirework but excluded wire-making, but the census of 1850 listed these together. However because core machine tool users were identifiable over the period, I have confidence in the broad sweep of patterns in potential machine tool usage.

tripling their share over these 80 years, at a time when manufacturing was growing relative to the whole economy. This growth was accomplished overwhelmingly by the growth of machinery production; employment in fabricated metal products using machine tools fell from 59 to 20 percent of the total over the period. Furthermore, the range of potential spillovers grew over time. Key macro-trends extended the range of machine tool use, notably the growth of automobiles and aircraft in the 20th century and electrical machinery after 1880, which together employed one-third of machine-tool users in 1930. Many post-Civil War changes were only smaller by comparison, such as the development of typewriters, cash registers, calculators and other office machinery, mining and petroleum machinery, food-processing methods, household machinery, shoe and leather machinery, and a wide array of construction equipment.

Table 2. Potential Usage of Machine Tools

| Year | Potential Users (000s) | Share of Manuf. Workers | Non-elec. Machines/ Users | Metal Products/ Users | Electrical Machines/ Users | Auto, Air/ Users | Machinists/ Blacksmiths |
|---|---|---|---|---|---|---|---|
| 1930 | 2536 | 28.7% | 46.5% | 20.5% | 14.7% | 18.4% | 4.63 |
| 1920 | 2509 | 27.9% | 53.1% | 21.8% | 10.9% | 14.3% | 3.79 |
| 1910 | 1477 | 22.3% | 65.3% | 21.6% | 8.0% | 5.1% | 1.99 |
| 1900 | 1014 | 19.1% | 63.2% | 32.0% | 4.7% | 0.0% | 1.22 |
| 1890 | 671 | 15.8% | 64.1% | 34.3% | 1.6% | 0.0% | 0.86 |
| 1880 | 348 | 12.7% | 61.7% | 37.9% | 0.4% | 0.0% | 0.59 |
| 1870 | 288 | 14.0% | 47.3% | 52.7% | 0.0% | 0.0% | 0.39 |
| 1860 | 146 | 11.1% | 48.5% | 51.5% | 0.0% | 0.0% | 0.47 |
| 1850 | 95 | 9.9% | 41.0% | 59.0% | 0.0% | 0.0% | 0.34 |

Still, there was ample scope for convergence in the mid-19th century. The census of 1850 lists a dozen potential machine-tool using sectors with over 1000 workers, including an omnibus category of machinists and millwrights with 28,000 workers. That sector included industries such as steam engines, textile machinery, printing presses, and woodworking machinery. The range of industries narrowed earlier in the century, as did the scale of those industries, but even in 1820 potential machine tool users made engines, textile machines, printing presses, wood lathes, screws, tools, firearms, and clocks. Convergence in early periods certainly was possible.

Potential clearly was not reality. Many potential usages in earlier periods were not achieved; earlier craft methods did the job, however inadequately. No direct measure of machine tool utilization exists, but one trend demonstrates the trajectory. Blacksmiths had typically transformed iron into products in the craft era, and machinists multiplied as mechanization advanced. The relative sizes of these occupations hence provides an indicator of the extent of machine tool usage, though only a rough one because other occupations also worked metal, and later machinists relied on machine tools more than earlier ones did. While machinists (listed with millwrights for consistency across census years) were as third as numerous as blacksmiths in 1850, they were 4.6 times as common in 1930. Blacksmiths were about as numerous in 1870 as they were in 1930, but machinists had multiplied a dozen fold. Moving backward from 1850, machinists must have fallen in proportion to blacksmiths, and machine tools declined even faster, because the earliest machinists made machines without engine lathes or planers.

For machine tools to gain usage, best practice methods had to spread but also to improve; the few, simple, inaccurate machines tools of 1820 could hardly manufacture the Corliss engines and sewing machines of 1860, much less the dynamos and automobiles of a half-century later. Invention grew over time, but because machine tools were spread over a dozen patent classifications, that growth is hard to measure. I have constructed a data set of metalworking lathe patents based on a survey of patents in three patent office classifications. [10] These do not

[10] Metalworking lathes were typically listed in “turning” (class 82), “metalworking” (class 29), and “threaded, headed fastener, or washer making: process and apparatus” (class 470). For details about the data set and its limitations, see Ross Thomson, “Understanding Machine Tool Development in the United States: Uniting Economic and Business History,” *Business and Economic History On-Line,* forthcoming.

include all lathe innovations, since some were not patented, and certainly not all machine tool innovation. But as the most common machine tool throughout the period, lathes were essential. To get sufficient numbers of patents I examined all years from 1836 through 1865, and then the first two years of each decade through 1921. I added nine patents that were clearly metalworking lathes from 1816 through 1835. The result was a consistent set of 782 metalworking lathe patents issued to U.S. residents throughout the period.

Lathe patenting grew greatly over the period. From about 0.5 patent per year before 1845, annual lathe patenting grew to 7 from 1846 through 1865, 23 from 1870 to 1881, 55 from 1890 to 1901, and 81 from 1910 to 1921 (see Table 3). The growth of lathe patents roughly paralleled the growth of machinists, the principal users of metalworking lathes. The relationship was no coincidence, because machinists were the principal lathe inventors throughout the period. They were ideally positioned to invent. As the principal users of machine tools, they best understood the limits of existing methods. As the producers and designers of machine tools, they understood the technological principles that could overcome the limits of machines. City directories and the census of population provided occupational data for inventors of 74 percent of the patents in the sample. Among these inventors, machinists typically received three-quarters of all patents. The next largest group of inventors was engineers and applied scientists (especially mechanical engineers) and occupations associated with innovation (especially draftsmen and designers). These inventors shared machinists' knowledge of mechanical principles, and were often employed by machinery firms. The importance of these inventors grew over time from a few percent of all patents through 1881 to 17 percent from 1890 through 1911 and 35 percent in 1920 and 1921. The share of other inventors, predominantly with manufacturing jobs, never exceeded about a quarter of patents and fell to about a tenth after 1890.

Table 3. Metalworking Lathe Invention, 1816-1921

| Period | Annual Patents | Machinists (000s) | Machinist Share | Science & Inventive Share | Others, Share | Commodity Usage Share |
|---|---|---|---|---|---|---|
| 1816-25 | 0.4 | | 0.0% | 0.0% | 100.0% | 0.0% |
| 1826-35 | 0.5 | | 100.0% | 0.0% | 0.0% | 0.0% |
| 1836-45 | 0.7 | | 75.0% | 0.0% | 25.0% | 0.0% |
| 1846-55 | 4.4 | 33.7 | 79.7% | 1.4% | 18.9% | 24.1% |
| 1856-65 | 8.8 | 52.9 | 73.8% | 6.3% | 19.8% | 27.9% |
| 1870-71 | 24.5 | 54.8 | 78.1% | 0.0% | 21.9% | 29.4% |
| 1880-81 | 21.5 | 101.1 | 69.4% | 3.2% | 27.4% | 60.0% |
| 1890-91 | 54 | 186.8 | 71.9% | 19.3% | 8.8% | 55.8% |
| 1900-01 | 55.5 | 283.3 | 72.4% | 13.5% | 14.1% | 75.0% |
| 1910-11 | 70 | 479.0 | 76.9% | 18.0% | 5.2% | 79.1% |
| 1920-21 | 91.5 | 839.6 | 54.4% | 34.7% | 10.9% | 58.8% |

*Notes and sources:* Patents classifications came from the U.S.P.T.O. website. Patents were surveyed from the annual reports of the U.S. Commissioner of Patents, google patents and lexis-nexis academic. Occupational data came from U.S. censuses for 1850, 1860, 1870, 1880, 1890, 1900, 1910, and 1920.

The incentives for inventions and the mode of their diffusion depended upon how inventions were used. Lathe inventions gained use in two principal ways. Some inventors (or their assignees) used lathes to manufacture other goods, while others sold lathes embodying their invention; I term these self-usage and commodity usage respectively. Inventors could also gain returns by assigning or licensing patents to those who used or sold lathes. The kind of usage could be ascertained for 53 percent of patents. A clear trend exists: about three-quarters of lathes with known usage were self-used through the Civil War, about one-half were so used for the remainder of the 19th century, but only about three-tenths were self-used used in the 20th century. Because the prospects for convergence were greater when machine tools were sold as capital goods, the growing share of self-usage could structure eras of convergence.

For lathe inventions to spill over from one industry to others, they had to solve shared problems. It is imaginable that lathe inventions pertained to only one industry, precluding convergent applications. As a study of the content of lathe patents shows, this was only exceptionally the case. Lathes are classified by their stated use and the industry to which that use pertains. The largest category of patents were generic; they solved a problem that was not specific to any industry or group of industries, such a producing more quickly, more accurately, or for a wider range of operations. Such generic patents applied to a wide range of industries. The share of generic patents rose from about one-third to three-fifths of patents over time (see Table 4).[11] The largest specific use was making screws and such threaded products as nuts, bolts, and threaded pipe. Because threaded products were among the most common of machine parts and were used widely in metalworking, woodworking, and elsewhere, screw advances were widely applicable. Lathes for turning watch parts and small objects such as jewelry, pinions, dental equipment, ball bearings, keys, and wire shared features with each other. The production of firearms shared principles with many other objects, including mass-produced metalwork. As the archetypal GPT, the engine, together with boilers, valves, and mechanisms to convert the form of energy (especially crankshafts), applied to many industries. Engine patents rose over time, including ten targeting improvements in automobiles late in the period. Railroad patents were among the most industry-specific, including car wheel lathes and locomotive-crankshaft lathes, though these too overlapped with other large objects and engines. Lathes had a wide variety of other objects. They made tubes, textile machines, umbrella parts, bells, locks, and oil well apparatus. Seven turned large electrical parts. Few of these lathes were specific to a particular product. Much the same was true of machine tools to plane, bore, mill, grind, and cut gears. Lathe inventions had the potential to reach multiple industries.

[11] The large share in generic patents in part reflects efforts by inventors and patent agents to depict their inventions in the widest possible terms; because the art of patent writing and the use of patent agents increased over time, this factor by itself would have increased the share of generic patents.

Table 4. Lathe Patents by Type and Period

| Type of Lathe | 1816-1865 | 1870-1891 | 1900-1921 |
|---|---|---|---|
| Generic | 35.1% | 48.0% | 60.8% |
| Screw and other Threaded | 29.1% | 21.5% | 19.8% |
| Clock and Small | 12.8% | 8.5% | 1.4% |
| Firearms | 10.8% | 0.5% | 0.2% |
| Railroad | 4.1% | 7.5% | 6.7% |
| Engines and Related | 2.7% | 6.0% | 8.5% |
| Other | 5.4% | 8.0% | 2.5% |

Hence prospects for technological convergence existed from 1820 but broadened with the formation of new industries over time. Growing machine tool invention might have contributed to the convergence. But how widely was the convergence realized? The small number of machinists, relatively modest output, and self-used inventions might have blocked convergence before the Civil War. Without convergent uses, incentives to invent might have weakened. These barriers were surmounted in different ways, by different agents, and to different degrees over time, initiated by an era of self-used innovation yet considerable convergence.

## Beginnings: Self-Usage, Diversification, and Worker Mobility

In 1820, the United States faced several interrelated limits to mechanization. Machine tools were few and primitive. Engine lathes had been invented by 1800 and planers were under development, and the milling machine was invented around 1820. But they were little used, and in 1820 Philadelphia and New York machinists used none of them. The absence of machine tools imposed severe limits on the precision, durability and speed of machinery. Indeed, limited machine tool capabilities prevented sophisticated machines, such as cylinder printing presses, from achieving practicality. Design capabilities also were weak, reflecting the scarcity of machinists and mechanical engineers. In this context, mechanization had begun in textiles, steam engines, printing, clockmaking, and screwmaking and was on its way in firearms and woodworking. But these industries advanced through largely independent processes. Their distinct technological problems—forming thread, boring engines, printing paper, working wood, and fabricating firearms—limited cross-fertilization.[12] Machine tool inventors targeted the needs of specific industries, such as making screws, firearm barrels, looms, clock parts, and engine valves. Firms typically used the inventions they or their assignees developed. Though self-usage would remain the dominant way to utilize machine tool innovations, machine tools and mechanization spread widely over the manufacturing sector by 1865.

When machine tools were built in house and improvements were self-used, did they spread among industries and how? Three paths were most important. Some firms diversified into products from other industries. Born to make textile machinery and regulate water power for the Lowell mills, Locks and Canals and its successor the Lowell Machine shop added locomotives and machine tools to its product line, and assigned machinists to design products to secure wide markets. It imported a British planer and then sold one to a leading Providence steam engine firm, which then itself sold planers. Other textile machinery and enginemaking firms did the same. This diversification did not always work out—the Lowell Machine Shop dropped its machine tool line after its chief designer left—but others entered the competition. Many firms innovated for their own use and then sold machine tools as part of their product line, while retaining their previous products. At times the sales were unanticipated; in the single largest documented machine tool sale before the Civil War, the British government bought a whole line of machine tools to make firearms from Robbins and Lawrence after a Parliamentary delegation to the 1853 New York exhibition visited the firm. By adding machine tools to their

[12] Thomson, *Structures of Change*, pp. 15-65, 145-152 and passim.

product lines, firms benefited from the use of innovations in their core industries and also from selling the innovation to other sectors, one clear rationale for technological convergence.[13]

Most self-used machine tool innovations did not spread in this manner. In some cases, innovators consciously prevented such diffusion. For example, the steam engine innovator George Corliss, hoping to control his innovation, refused to sell his patented gear-cutting machine, but did sell cut gears. Even such self-used innovations could diffuse technology across industries, as Corliss's gears and—far more importantly—his steam engines illustrate. These were important cross-industry sources of innovation even in the absence of the spread of machine tools, and by contributing to mechanization, they advanced the scope of potential convergences.[14] Still, the self-usage of innovations such as Corliss's gear cutter, potentially applicable to many industries, limited the spread of technological change.

Worker mobility spread machine tools from tool users even without sale. Such mobility, long key to the spread of techniques within industries, was equally essential—perhaps even more central—to the spread of techniques between industries. Such movement was common among machinists, and it often originated from firms that spread knowledge within industries.[15] Many examples exist, but more systematic evidence is hard to find. Evidence for 29 leading managers and workers of two prominent firearms firms of the 1850s, Robbins and Lawrence and Colt Patent Firearms, helps to fill the gap. These firms led in the use of milling machines, turret lathes, and other mass production machine tools and forging methods that had been pioneered by the Springfield Armory and government contractors.[16] All but Samuel Colt and his successor Elisha Root found work with other firms. Over the next half-century, their workers moved to 56

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[13] Ibid, pp. 145-152; Nathan Rosenberg, ed., *The American System of Manufactures* (Edinburgh, 1969), pp. 180-192.
[14] Louis C. Hunter, *A History of Industrial Power in the United States, 1780-1930. Vol. 2: Steam Power* (Charlottesville, Virginia, 1985), pp. 275-294; Rosenberg and Trajtenberg, "A General-Purpose Technology at Work."
[15] David R. Meyer, Networked Machinists Forge America's First High Technology Industries (Baltimore, 2006).
[16] Merritt Roe Smith, *Harpers Ferry Armory and the New Technology* (Ithaca, 1977).

different firms as skilled workers, foremen, or superintendents or as proprietors of new firms. Some worked for many firms. Two Robbins and Lawrence workers moved to Colt, and ten workers of these firms moved to eleven other firearms companies (see Table 5). Others found convergent uses. Ten formed or joined a total of 17 machine tool firms, including industry leaders. Francis Pratt and Amos Whitney had been inside contractors at Colt, then worked in an early firm selling milling machines before offering systems of firearms equipment and a line of machine tools during the Civil War. Two other Colt workers moved to Pratt and Whitney before forming their own firms after the war. Some workers developed firearms methods to drop forge screws and tools, including the leading postbellum drop forging firm, Billings and Spencer. Three adapted firearms techniques to mass produce Wheeler and Wilson sewing machines during the war. Others brought mass production techniques to bicycles, textile machinery, engines, mining machinery, and even automobiles. The breadth of this mobility was remarkable.

Table 5. The Mobility of Robbins and Lawrence and Colt Workers

| Industries | People | Firms | Firms: Examples |
|---|---|---|---|
| Firearms | 10 | 11 | Sharps (5), Remington, Spencer, Smith and Wesson, Springfield |
| Machine tools | 10 | 17 | Pratt and Whitney (4); Brown and Sharpe (2); Bement; Bullard; Gleason; Cushman; Jones and Lamson |
| Drop forging | 2 | 1 | Billings and Spencer (2) |
| Screws and tools | 3 | 2 | Hartford Machine Screw (2), Providence Tool |
| Sewing machines | 8 | 4 | Wheeler and Wilson (3); Willcox & Gibbs; Weed (2) |
| Textiles and its machines | 5 | 5 | Crompton Loom; Draper Loom, Conant Thread |
| Steam engineering | 5 | 5 | Porter; Southwark (2); Chicago, Burlington and Quincy Railroad |
| Bicycles and autos | 2 | 3 | Pope (bicycles); Cadillac, Lincoln (autos) |
| Other | 7 | 8 | mining machinery, general machinery, metal products, engineers |

*Sources:* Roe, *English and American Tool Builders*, pp. 173-201; Guy Hubbard, "Development of Machine Tools in New England," *American Machinist* 59 (1923): 1-4, 139-42, 241-44, 311-15, 389-92, 463-67, 541-44, 579-81, 919-22; 60 (1924): 129-32, 171-73, 205-9, 255-58, 271-74, 437-41, 617-20, 875-78, 951-54; 61 (1924): 65-69, 195-98, 269-72, 313-16, 453-55; Hounshell, *From the American System to Mass Production*, pp. 68-82; *Dictionary of American Biography*; *Mechanical Engineers in America Born Prior to 1861: A Biographical Dictionary* (New York, 1980); Thomson, *Structures of Change*, pp. 268-269.

Invention was essential to the process. Five-sixths of the 29 managers and workers patented. They averaged 22 patents, 81 percent of which were issued after 1865 (see Table 6). To take one prominent case, Christopher Spencer had trained in textile machinery, tool building, and locomotives before joining Colt. Upon leaving Colt, he worked for the Cheney Brothers and invented a highly important silk-winding machine. Hezekiah Conant, a Robbins and Lawrence machinist who had taught Spencer drafting in Hartford, improved the Spencer machine, and Pratt and Whitney made it. Spencer then moved to firearms, where his repeating rifle became a weapon of choice by the Civil War's end. To make it he developed the broad-drop forging methods based on Colt's die-forging techniques. In this he collaborated with Charles Billings, the principle drop forging contractor at Colt. Sometimes the effects were indirect, such as when Frederick Howe, A Robbins and Lawrence alum superintending the armory at the Providence Tool Company, suggested to Joseph Brown that he design turret lathes and milling machines.

Table 6. Patenting by Robbins and Lawrence and Colt Workers

| | All Inventors | | Two Firearms Firms | | Inventors' Firms | | Other and unknown | |
|---|---|---|---|---|---|---|---|---|
| | Inventors | Patents | Inventors | Patents | Inventors | Patents | Inventors | Patents |
| All | 24 | 531 | 7 | 55 | 21 | 360 | 14 | 116 |
| Patent Type | | | | | | | | |
| Firearms | 13 | 34.7% | 6 | 89.1% | 7 | 27.2% | 3 | 31.9% |
| Machine tools | 15 | 17.1% | 2 | 3.6% | 14 | 20.8% | 3 | 12.1% |
| Related metalworking | 16 | 12.4% | 2 | 5.5% | 12 | 13.9% | 6 | 11.2% |
| Sewing | 7 | 3.8% | | | 3 | 3.6% | 4 | 6.0% |
| Textiles | 5 | 20.3% | | | 3 | 27.8% | 2 | 6.9% |
| Steam Engineering | 6 | 2.8% | | | 3 | 1.4% | 4 | 8.6% |
| Other | 15 | 8.9% | 1 | 1.8% | 8 | 5.3% | 12 | 23.3% |
| All after 1865 | 23 | 429 | 3 | 28 | 19 | 313 | 14 | 88 |

Robbins and Lawrence and Colt received only 55 of these patents, overwhelmingly for firearms designs and production methods. Workers invented heavily when they left the two firms. Sixty-eight percent of their patents were used by the firms they formed or came to work for. These were predominantly new firms in which the inventors had proprietary interests; such firms received 46 percent of patents. Others worked as superintendents, master mechanics, and contractors for established firms such as Winchester, Wheeler and Wilson, and Weed Sewing Machine, receiving 22 percent of total patents. Another 22 percent were used outside the inventor's firms or were unused.

The content of their invention differed from that of their parent firms, but frequently converged with it. Nine inventors patented firearms outside the parent firms, seven associated with their own firms. The revolvers and breechloaders of the parent firms were important innovations, and later firms continued such innovation by developing repeating rifles and revolvers. But the new firms concentrated less on firearms, which received 27 percent of patents to firms associated with inventors. More inventors built on the production methods of the parent firms. Sixteen invented machine tools, 14 using or selling them in their own firms. Trained in firms that led in machine tool methods, inventors advanced such methods in many directions. Pratt and Whitney lathes led in tool-room use and their mass-production machine tools found wide markets. Pratt took out eleven machine-tool patents and Whitney another seven for milling, drilling, planning, and turning improvements. Some machine tool inventors used their machines in their own production, including inventors for Colt, Remington, and Wheeler and Wilson. Here knowledge of their innovations spread through the patents themselves and the movement of workers, although these firms on occasion sold machine tools. Most sold their machines as capital goods beginning on the eve of the Civil War, thereby providing an incentive to expand sales by realizing convergences. About the same number patented related inventions to work metal, measure, and change forms of motion, including generic machine motions, tool fabrication and design, forging and stamping operations, and measurement required for accurate production. Forging had been central to firearms manufacture, and methods deepened through the exploration of firearms fabrication in the Civil War and after.

Workers also patented in application sectors other than firearms, including machines to sew, weave, and generate power. Here the convergence with firearms was more distant; sewing and textile machines used generic design principles learned by making firearms or engines or looms, but had no unique relation to firearms. Such lesser-order convergences operated across much of the machinery sector, and knowledge of how to produce precise, complex parts certainly facilitated invention that might otherwise have been discouraged because production was so challenging. Yet the number of inventors in these more distant fields was fewer. Textile machines, sewing machines, and steam engineering each had at least five patentees, and for each of these patent groups, three used (or were positioned to use) these patents in firms for which they worked. Two patentees used machine design capabilities to perfect loom and winding technologies, including the industry leader George Crompton.[17]

Machine tool firms constituted a third way to realize technological convergences. They were often formed by mobility from other machinery firms. Such mobility formed the two largest antebellum machine tool firms when William Bement, who designed machine tools at the Lowell Machine Shop, and William Sellers, who worked for Fairbanks and Bancroft in Providence, left to form their Philadelphia firms. These firms designed and sold machine tools

[17] The image of the pure inventor, with little concentration in production, was best captured by Rollin White and William Hicks, who depended on patent sale or licensing for their returns. Yet they were exceptions; far more typical were those who formed new firms or accepted managerial positions in established firms, applied production capabilities acquired in firearms manufacturing, and often invented to improved production or the product.

to a wide range of industries from the late 1840s. Both Sellers and Bement concentrated on larger, general purpose machine tools used in railroads, locomotives, engines, construction, and shipbuilding, and they sold such machines widely. According to his order books, in his first six years Sellers sold some forty lathes to firms making or repairing engines, sugar machinery, iron-making equipment, woodworking machines, railroad equipment, railroad car wheels, pipes and other fabricated metal products, and chemicals. During the war, hundreds visited his works, including railroad, locomotive, firearms, machine tools, engine, locomotive, textile machine, sewing machine, clock, stove, and woodworking machine firms. Sellers was particularly innovative, taking out 21 patents through 1865, including nine for machine tools, three for regulating mechanical motion, and six for metalworking improvements. He would take out nearly seventy more patents over the course of the century. Bement received one machine tool patent and two mechanical motion patents. Like other firms, their workers left to set up their own shops. Crossley and Allen left Sellers to form a Wilmington, Delaware firm concentrating on machinist's tools, noting in an ad that they had both headed departments at Sellers. After William Bement had induced George Hubbard, initially trained at Robbins and Lawrence, to leave Amoskeag to join his firm, Hubbard and another Bement-trained worker formed Cresson and Hubbard, which made gunmaking machinery during the Civil War.[18]

Specialized machine tool firms, originating in the late 1840s, had expanded greatly by 1860. The census of 1860 lists 17 machine tool firms with 455 workers, but census manuscripts in major machine-making counties reveal 28 firms for which machine tools was the most important type of machine, employing nearly one thousand workers. Another dozen firms sold machine tools as a secondary product line. But such firms rarely concentrated on machine tools

[18] Roe, *English and American Tool Builders*, pp. 257-255 and passim; Guy Hubbard, "Development of Machine Tools in New England," *American Machinist* 60 (June 12, 1924), pp. 875-876; Thomson, *Structures of Change*, pp. 146-152.

alone. The most important machine tool firm, William Sellers and Company, made machine tools valued at $80,000, but added $75,000 in shafting and gearing, and $50,000 in railroad turntables and other products. Others combined machine tools with steam engines, boilers, sewing machines, textile machines, castings, and a variety of other products, thus integrating metalworking and its applications. Invention was common; the principals of over half of 42 machine tool firms listed in city directories and census manuscripts for at least a four year period received patents, averaging 4.7 through 1865, and others patented after the war.[19]

Through these mechanisms, machine tools spread greatly within and between industries. General purpose machine tools spread with remarkable rapidity. David Wilkinson's engine lathe spread to firearms and screwmaking by 1820, but no wider. Philadelphia and New York machinists found many uses for Henry Maudslay's slide rest after they discovered it in the early 1820s. Diffusion sped after the mid-1830s. Within a decade of its first importation, the planer was used to make textile machinery, engines, locomotives, printing presses, generic machinery, and machine tools. Diffusion followed machinists' movements. Because they moved across industries, so did machine tools, but their movement was more constrained geographically, limiting access of whole regions to the new technology. In the 1850 census manuscripts, R. Hoe, the leading printing press firm, listed 43 lathes and 11 planers, and a leading Patterson New Jersey locomotive maker listed 250 lathes. As inventories of machinery firms indicate, lathes and planers were common. By the Civil War, most leading machine shops used planers and engine lathes; firms outside leading locations were less well equipped. More specialized turret

[19] Thomson, *Structures of Change,* pp. 135-141,151. Knowledge also spread through publications and meetings. From the time the *Journal of the Franklin Institute* praised Maudslay's slide rest in 1826, it and other journals spread knowledge about engine lathes, planers, and their uses. The *Scientific American* was the most widely read; its machine tool articles and advertisements numbered in the dozens annually. Philadelphia's Franklin Institute, like other mechanics' institutes, spread knowledge, including examples of machines working, in their classes and exhibitions. Published patents and the efforts of patent owners to secure usage were important means to spread knowledge widely. These means to diffuse knowledge operated throughout the period. But they typically complemented the first three modes of diffusion.

lathes and milling machines had begun to move outside firearms, though with much less consequence by 1865 than the movement of planers and engine lathes. The diffusion of machine tools was one contribution to mechanization in many industries, and by overcoming production bottlenecks, greater mechanization was one result.

Rapid mechanization surely stimulated machine tool invention. Lathe patenting was modest through 1845, and had not grown relative to population since before 1810. Invention was limited by the pool of machinists, by complementarities among machine tools—most importantly that accurate machines to turn metal required accurate machines to plane it—and the mutual limitations of inadequate machine tools and weak application sectors. Invention surged over the next two decades, reflecting a growth of markets, expanded inventive capabilities of the increasingly numerous and sophisticated machinists, and innovative complementarities with a growing variety of application sectors. Though self-used inventions predominated, machine tool firms expanded their share of patenting, and machinists spread the innovations. These inventions had major effects. Though using basic principles established by 1840, engine lathes and planers improved in design, attachments, and precision, increasing their usefulness. Turret lathes and much specialized screwmaking equipment had not existed in 1840. Improved machine tools constituted a second contribution of machine tool users to mechanization in many sectors.

Machine tool inventors further extended their impact by inventing extensively in machine-tool using sectors, and by so doing extended the use of machine tools. Though complements to machine tools, the products of application sectors entailed knowledge of machine design that machine tool inventors, three quarters of whom were machinists, typically possessed. Machine tool inventors included many important applications inventors, including James S. Brown in textiles, Thomas Harvey and Thomas Sloan in screwmaking, Ethan Allen and

Elisha Root in firearms, Hiram Hayden in brassmaking, and George Corliss in steam engines.

This cross-industry invention can be explored for lathe inventors by identifying all of their patents through 1929. To get sufficient numbers across time, I examine all metalworking inventors from 1816 through 1865, and those in census years through 1910, omitting 1920 inventors to be able to survey at least 19 years after their lathe patent. Inventors of metalworking lathes from 1816 through 1865 averaged 8.5 patents in total (see Table 7). Forty percent were received through 1865; the rest extended into the next period. Only a quarter of their patents were machine tools, with relatively modest movement out of lathes. Related generic machine, metalworking, and measurement patents made up another 18 percent, but 57 percent of patents had other objects. Most were within the machine-tool using sector. Over a tenth targeted fabricated metal products, led by clocks and firearms. Over a quarter were machines to make steam engines and textile, sewing, railroad, and the gamut of antebellum machines. Hence four-fifths of all patents fell within the machine tool using sector; many others categorized as carriages, agricultural equipment or construction incorporated metallic parts. Inventors within the machine-tool using sector internalized the complementarity of machine tools and their application sectors by inventing both. Success in machine tool innovation enabled them to make products more rapidly or of higher quality, and product innovations increased the need for machine tools. Shared principles of metal manipulation in making machine tools and their products enabled innovators to make use of design convergences.

Of course, machinists using but not inventing machine tools contributed far more to the development of machine-tool using sectors than did machine tool inventors, whose machine tools comprised a tiny share of all patents. For many inventors, knowledge of machine design in some industries aided the development of others. New industries developed rapidly by building on the capabilities of old.  The railroad developed so quickly in the United States because engine-makers and textile machinery makers applied their knowledge to building locomotives and equipment.  The sewing machine developed when textile machinists used knowledge of thread manipulation and machine fabrication.  Convergences among established sectors, such as cam designs in textiles that spread widely, likewise advanced mechanization.

Table 7.  All Patents, Metalworking Lathe Inventors

| | 1816-1865 | 1870-1890 | 1900-1910 |
|---|---|---|---|
| Inventor | 130 | 87 | 110 |
| Average Patents | 8.5 | 13.7 | 14.9 |
| Patent Shares | | | |
| Metalworking Lathe | 21.4% | 27.6% | 31.7% |
| Other Machine Tools | 3.0% | 9.0% | 28.7% |
| Machine Tool Related | 18.4% | 17.3% | 16.6% |
| Application:  Metal | 10.8% | 9.4% | 4.1% |
| Application: Machine | 26.2% | 23.7% | 15.8% |
| Machine Tool Sector | 79.8% | 87.1% | 96.9% |
| Other | 20.2% | 12.9% | 3.1% |

Inventors in application sectors benefited from improved knowledge of machine tools and their usage.  George Crompton, for example, did not invent machine tools, but gained exceptional proficiency in them through his work at the Colt Armory.  The point is not that machine tool inventors led mechanization, or even that machine tool usage did so.  The practitioners in application sectors were essential to the process, and they induced, and often undertook, machine tool innovation.  Rather the point is that developments within a variety of application sectors—including machine tools themselves—led to machine tool development, which in turn enabled existing application sectors to grow more rapidly and other such sectors to emerge, adding to the supply of machinists.  Over time, machinists spread among sectors, machine tool invention grew, and machine tool firms came to spread their products more readily than machinist mobility by itself would have allowed.

As a result, machine tool usage in 1865 was much different from that of 1835, and even more from that of 1815. Many sectors had not realized their potential machine tool usage; agricultural implements and many other industries were still largely the domain of blacksmiths, and foundry machinery was primitive. But the machinery industries in 1860, employing four times as many workers as in 1840 with more and better machine tools, were fundamentally different than their predecessors. Convergent inventions were essential to the change. A trajectory had formed, and its momentum would shape an era of greater machine tool convergence in which capital goods firms play a more central role.

## Commodity Usage and Extensive Convergence

Over the last third of the 19th century, machine tool usage grew greatly. Potential machine tool users multiplied seven fold from 1860 through 1900. Established industries realized more of this potential, and machine tools extended to new sectors. Expanded mechanization led this growth; machinery industries grew from 48 to 68 percent of potential machine tool users. Machinists multiplied over five fold. Annual lathe patents grew over six fold from the 1856-1865 decade to 1900. Machine tool firms increased their role in spreading and inventing metalworking equipment.

Technological convergence was integral to this process. New products by diversifying firms, machine tool sale, and movement of workers each continued to realize convergences. Indeed, as the case of the Brown and Sharpe Manufacturing Company illustrates, a single firm could engage in all three. Brown and Sharpe’s history nicely encapsulates the difference of the pre-1865 era from what followed. Joseph R. Brown tried to specialize in machine tools in the 1830s but, finding the market too thin in even so advanced a city as Providence, he turned to clocks. In the 1850s, with his apprentice and then partner Lucian Sharpe, he moved into precision metalworking and, late in the decade, contracted to manufacture the Willcox and Gibbs sewing machine. To make sewing machines, the firm bought and developed machine tools. Purchased machine tools were inadequate to precision work, so Brown designed a production gear cutter in the mid-1850s and, during the war, a turret lathe, a universal milling machine, and formed milling cutters. The immediate targets for the latter three innovations were Brown's own sewing machine production and the needs of Frederick Howe's armory at Providence Tool Company. Yet Brown and Sharpe virtually immediately secured a much wider body of users. It sold machine tools from early in the Civil War throughout the period, yet it continued to make sewing machines, precision measurement devices, and clocks. After Brown invented a universal grinding machine in the 1870s, the company's product line included screw machines/turret lathes, milling machines, grinding machines, gear cutting machines, vernier and micrometer calipers, along with clocks, hair clippers and sewing machines. After the war, the company invested heavily in invention, and it received nearly 200 patent assignments to develop each of its machine tools and precision devices. It also found its revenues coming increasingly coming from the sale of machine tools rather than sewing machines; the machine tool share rose from 21 percent of its sales in 1866 to 88 percent in 1891.[20]

Brown and Sharpe fostered convergence most directly through the breadth of its machine tool sales. These sales grew greatly from annual averages of 54 machine tools in the 1860s to 78 in the 1870s, 288 in the 1880s, 904 in the 1890s, and 1,861 in the first five years of the 20th century (see Table 8). The range of purchasing industries widened. Brown and Sharpe records can be categorized users by industry for five-eighths of its shipments. Firearms comprised two

[20] Brown and Sharpe Manufacturing Company, "Sales, 1866-1891," Records (Rhode Island Historical Society, Providence, Rhode Island) New Box 11, folder 9; Roe, *English and American Tool Builders*, pp. 202-215; Brown & Sharpe, *A Brown and Sharpe Catalogue Collection* (Mendham, New Jersey, 1997).

thirds of its shipments during the Civil War, like other machine tool firms. But other purchasers added to demand, led by sewing machine and shoe machinery firms and machine tool firms. The share of firearms fell dramatically after the war, though large sales to government arsenals—particularly outside the U.S.—periodically added to demand. Sewing and shoe machinery declined in importance, but new industries made up the gap, led by electrical equipment, cash registers and other business equipment, bicycles, and automobiles. Use of convergent technology enabled such industries to produce adequate equipment virtually from their inception. Brown and Sharpe also sold to machinery firms making printing presses, engines, agricultural machinery, mining equipment, cranes, and elevators, and to firms making tools, screws, textiles, meters, steel, pumps, gas, paper, chemicals, musical instruments, and rubber.[21]

Table 8. Brown and Sharpe Machine Tool Shipments by Industry, 1861-1904

| | 1861-69 | 1870-79 | 1880-89 | 1890-99 | 1900-04 |
|---|---|---|---|---|---|
| Annual Machines Shipped | 53.9 | 77.8 | 287.5 | 903.5 | 1861.0 |
| Shares by Industry | | | | | |
| Firearms: Private | 35.6% | 11.0% | 0.9% | 2.8% | 4.1% |
| Government Arsenals | 5.4% | 3.2% | 23.6% | 9.8% | 9.6% |
| Sewing & Shoe Machines | 26.9% | 36.7% | 12.8% | 4.4% | 4.1% |
| Machine Tools | 12.2% | 5.2% | 9.4% | 11.9% | 10.4% |
| Railroad | 4.2% | 6.5% | 8.6% | 4.0% | 2.9% |
| Scientific Instruments | 3.2% | 3.2% | 4.0% | 3.9% | 4.5% |
| Electrical Equipment | 0.0% | 0.6% | 6.7% | 13.1% | 12.8% |
| Business Equipment | 0.0% | 0.0% | 1.3% | 5.3% | 11.5% |
| Bicycles | 0.0% | 0.0% | 1.7% | 5.6% | 1.2% |
| Automobiles | 0.0% | 0.0% | 0.0% | 1.0% | 4.3% |
| Other | 12.5% | 33.5% | 31.1% | 38.2% | 34.6% |

*Sources:* Duncan McDougall, “Machine Tool Output, 1861-1910,” in *Output, Employment, and Productivity in the United States After 1800. Studies in Income and Wealth, vol. 30* (New York, 1966): 505, 516.

[21] Brown and Sharpe, “Sales Book 1900-1903,” Records, New Box 11, vol. 2.

Sales to many industries would not indicate technological convergence if each industry specialized in a single, distinct type of machine. But this was not the case; each kind of machine was sold to many industries, and many industries purchased several kinds of machines. For example, in 1867, five years after its invention, the universal milling machine was sold to 31 machinery firms including those specializing in machines to reap, sew, print, pump, work wood, make textiles and shoes, engines, locomotives, and machine tools, as well as 27 other firms making products as diverse as clocks, tools, brassware, screws, jewelry, textiles, and ammunition.[22] The cross-industry character of demand increased the scale of potential demand for any machine tool, and hence added incentives to invent.

To some extent, the company realized convergences by diversifying. Its product line grew in ways that internalized convergent technologies. It not only sold machines to many industries, it used production convergences to make sewing machines, a variety of machine tools, and measurement devices using machines and instruments of its own construction. The requirements of production were not the same: the interchangeable parts production of 10,000 Willcox and Gibbs sewing machines differed greatly from the fabrication of a hundred machine tools with different details and attachments. But each used methods of precision metalworking. Moreover the designs of the various machine tools converged, so that forming excellent screw machines eased the task of designing grinding or gear cutting machines. Indeed, many of the firm's patents were for machine tools in general, indicating that designs of the machines converged. Brown and Sharpe did not diversify far; aside from sewing machines and several kinds of sewing machines, it left the vast majority of metalworking to its customers.

Brown and Sharpe also spread technologies across industry lines through the mobility of its workers. Largely through the efforts of Brown and Sharpe to write a company history, the

[22] Brown & Sharpe, *A Brown and Sharpe Catalogue Collection*, pp. 20-23.

employment experience of 106 leading workers can be determined. Most had been leaders within the firm, and learned how to make, use, and develop machine tools and precision devices. Almost 70 percent of them moved from Brown and Sharpe to other firms. Most formed their own firms or became general managers or superintendents.[23] Migrating workers used their production and design skills in 91 known firms in a wide range of industries. They entered 25 machine tool and related drop-forging firms (see Table 9). Three went to Pratt and Whitney. Several 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.[24] They also brought their techniques to other leading firms such as the pressmaker R. Hoe and the United Shoe Machinery Company. Many went to toolmaking firms, including those that made twist drills. Eleven entered the auto and tractor industries, including three going to Cadillac. This mobility utilized capabilities to design new machines learned at Brown and Sharpe. Even worker who went far afield, such as Alton Shaw who formed the Shaw Electric Crane Company, used design knowledge mechanisms formed at Brown and Sharpe.

Table 9. Mobility by Brown and Sharpe Workers

| Industry | Firms | Examples |
|---|---|---|
| Machine Tools | 25 | New England (Pratt & Whitney (3), Norton Grinding, Jones & Lamson)<br>Philadelphia (Edward Harrington)<br>Cincinnati (Lodge & Shipley, LeBlond, Bickford, Cincinnati Milling)<br>Cleveland and Detroit (Warner & Swasey (2); Leland & Faulconer)<br>multiple locations (Niles-Bement-Pond) |
| Machinery: Printing | 1 | R. Hoe (New York) |
| Engines & boilers | 6 | Babcock & Wilcox |

[23] Brown and Sharpe, Records, several different boxes.
[24] Of course, Brown and Sharpe was hardly solely responsible for the success of companies to which Brown and Sharpe workers migrated. The three 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, though one became the chief designer at Cincinnati-Bickford. Roe, *English and American Tool Builders;* Philip Scranton, *Endless Novelty: Specialty Production and American Industrialization, 1865-1925* (Princeton, New Jersey, 1997), pp. 192-219.

| | | |
|---|---|---|
| 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 | |

*Sources:* Brown and Sharpe, "Various Company Histories," Records, New Box 20; Roe, *English and American Tool Builders*; "Personals," *American Machinist*, weekly, selected years 1896-1926.

Workers took inventive skills to their new firms or used them to form firms. Seventy percent of those who went to other firms had patents. Only one-tenth of their patents were assigned to Brown and Sharpe. Invention was central to their work after Brown and Sharpe. Seventy percent of their patents were used by their later firms. They made use of knowledge learned at Brown and Sharpe in later invention, as evidenced by comparing patents they assigned to Brown and Sharpe to those received after leaving. At Brown and Sharpe, they concentrated on machine tool patents; such patents and related generic operations concerning mechanical movements and gearing made up 85 percent of such patents (see Table 10). Measurement patents and hair clippers made up the rest. Workers often followed similar lines after leaving Brown and Sharpe. Machine tool and related patents made up half of their patents, with the latter now including a large share of other metalworking machines to cut screws and files, swage, forge, and move materials. Measurement devices and sewing machines were clearly related to work at Brown and Sharpe. They also used more general machine design skills in inventing a great variety of machinery and fabricated metal products, all the while remaining within the machine-tool using nexus. Particularly when inventing for their own firms, workers used knowledge acquired at Brown and Sharpe to undertake inventions with convergent design principles; their share of patents outside the machine-tool using sector was only four percent for those working for established firms and one percent for those forming their own firms. Workers' other patents were less closely related to Brown and Sharpe's patenting composition, with one-quarter outside the machine-tool using sector, largely reflecting the greater role of consulting engineers among such inventors.

Table 10. Composition of Patents at Brown and Sharpe and After Leaving

| Type of Patent | Brown & Sharpe | Other | Later Estab. Firms | Later New Firms | Other Firms and Unknown |
|---|---|---|---|---|---|
| All | 68 | 634 | 155 | 333 | 146 |
| Machine Tool | 73.5% | 34.4% | 29.0% | 41.7% | 23.3% |
| Related | 11.8% | 16.6% | 15.5% | 18.3% | 13.7% |
| Measurement | 4.4% | 4.1% | 8.4% | 1.8% | 4.8% |
| Sewing & Shoe Machine | 0.0% | 4.4% | 9.0% | 0.6% | 8.2% |
| Other Machine | 0.0% | 27.9% | 30.3% | 30.9% | 18.5% |
| Fabricated Metal | 0.0% | 5.2% | 3.9% | 5.7% | 5.5% |
| Other | 10.3% | 7.4% | 3.9% | 0.9% | 26.0% |

Brown and Sharpe's experience was linked to technological convergence in several ways. Its sale spread the same machines among a wide, and widening, set of industries. Its machine-tool and sewing machine production converged with the production of its customers, so that inventions to make its products also generated machine tool sales. Its universal milling machine and formed cutting tools were basic advances in machine tools used in toolrooms across the economy, and its grinding machines were just as important. Making sewing machines involved mass production with interchangeable parts, and machines it designed for this purpose found markets among other mass producers. Multi-industry markets led it to rely on convergences to increase its market size, augmenting incentives to innovate. This recognition did not come easily. Brown first worked on grinding on lathes to manufacture sewing machine parts, sold some machines, and then began to build a machine specially for grinding. Leland had to convince him that the market was wide enough to invest in developing a truly universal grinding machine. The resulting machine was a technical and commercial success in lighter uses. Brown and Sharpe could not internalize all convergences, which it learned when its workers took its production and design knowledge to many industries and used it to innovate. Yet the effects of this mobility were entirely negative for Brown and Sharpe, because they added to its reputation and firms of its one-time workers bought its machine tools and measurement devices.[25]

Other machine tool firms also sold machine tools widely, invented extensively, and trained workers who left the firm and invented elsewhere. Firms sold to wide ranges of industries. Like Brown and Sharpe, Bullard Machine Tool Company sold extensively to machine tool firms, who bought 16 percent of its machines from 1880 through 1904, compared to 11 percent for Brown and Sharpe. Both firms sold extensively to electrical machinery firms. But Bullard's 24 percent of machines sold to the railroad sector was far above Brown and Sharpe's 4 percent, and Bullard's 11 percent of machines going to iron and steel firms exceeded Brown and Sharpe's modest share. Firms such as Bement, Sellers, and the Niles Tool Works resembled Bullard's orientation to railroads and heavy machine tool uses. Pratt and Whitney was, like Brown and Sharpe, more oriented to lighter uses making screws, sewing machines, and firearms. But most machine tool firms sold to customers from many industries.

Likewise machine tool firms typically invented. Five lathe firms in business since the 1870s received between 33 and 171 patents through 1899, led by Pratt and Whitney. For all but Sellers, who patented extensively in metallurgy and railroad equipment, firms took out most of

[25] Brown and Sharpe, Records, New Box 10, folder 24; Robert S. Woodbury, "History of the Grinding Machine:" 58-71 in *Studies in the History of Machine Tools* (Cambridge, Mass., 1972); Hounshell, *From the American System to Mass Production*: 80-81.

their patents for machine tools, though Pratt and Whitney mirrored Brown and Sharpe in patenting and producing other goods. Like Sellers, Niles and Bement targeted railroads for some of its patents, but all firms had large numbers of patents that applied to many industries.

Worker mobility spread knowledge from many companies. Pratt and Whitney rivaled Brown and Sharpe in the importance of its workers. Of 24 known workers who left the firm through the 1920s, over half formed or joined machine tool firms. Others set up machine shops, made metal-pressing, electrical, and business machines, set up generic machine shops, made screw products and screw machines, and worked in metal fabrication. Over four-fifths of them received patents after leaving Pratt and Whitney. Nineteen workers were known to have left Lodge and Shipley; most populated the Cincinnati machine tool industry and about four-fifths patented after leaving. The number of firms making machine tools and accessories had grown to 400 by 1900, with about 150 of them selling machine tools, and many were graduates of older firms.[26] Other workers brought knowledge to industries using machine tools.

Most later firms were more specialized than Brown and Sharpe, and hence lost the possibility of both selling machine tools and the goods they produced. Most specialized on a narrower range of machine tools, and so could not apply learning from some machines to improve others. On the other hand, firms came to anticipate that they could sell their machine to many industries, thus taking account of technological convergences in their decisions to invest in innovation. Lathe innovations proliferated, and machine tool firms took out a larger share of them. Led by machine tool firms, inventors took out a larger share of patents for generic lathes and for other lathes that solved problems for wide ranges of industries.

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[26] Mobility is determined from a variety of sources of which the most important are Roe, *English and American Tool* Builders and the "Personals" weekly listings of the *American Machinist.* On the number of producers, see U.S. Census Office, *Twelfth Census of the United States: 1900*. *Manufactures*. Pt. 4 (Washington, 1902), p. 381; *American Machinist* 25 (November 6, 1902), p. 1635.

Self-using firms continued to generate convergent machine tools and metalworking techniques. Three Colt workers illustrate the widespread effects of moving from firearms to a convergent industry. After working together to make firearms, Billings and Spencer, together with their associate George Fairfield, used their skills to make sewing machines. Spencer developed a turret lathe to make sewing machine bobbins, which, as he recognized, embodied the core principle of the automatic turret lathe. This machine, developed the machine at the Weed Sewing Machine Company, "ranks with Maudslay's slide-rest and the turret tool-holder" as a fundamental machine tool innovation. The machine could be used to make screws and many other products, and on this basis he and Fairfield formed the Hartford Machine Screw Company. Spencer did not sell the machine but licensed the patent to Pratt and Whitney. A number of Pratt and Whitney workers developed the screw machine, including multispindle versions.[27]

In another line of wide influence, Charles Billings reshaped drop forging methods. Prompted by firearms work at Colt and Spencer and his work forging sewing machine shuttles, he and Spencer formed Billings and Spencer to make drop forgings in 1869. The firm produced a great variety of forgings, capturing the convergence of the technology among products. He also developed products made with his forging methods. When Billings toured an Edison plant and observed the inefficient design of the commutator brushes, he used his forging prowess to design durable L-shaped forged parts, which he patented in 1888. This was a mechanical patent, but one that was readily adopted to increase electrical generating capabilities.[28]

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[27] Roe, *English and American Tool Builders*, pp. 175-177, quote from p. 176; Ross Thomson, "The Continuity of Innovation: The Civil War Experience," *Enterprise and Society* 11:1 (March, 2010), pp. 128-165; Donald E. Wood, *From Archimedes to Automation: The History of the Screw Machine* (Cleveland, 1973?), p. 10.

[28] Samuel Hart, *Encyclopedia of Connecticut Biography* (New York: American Historical Society, 1917), pp. 183-186. Self-used inventions continued to generate machine tools firms, such as the Cincinnati screw and tap firm whose superintendent, Frederick Holz, designed a milling machine for grooving its taps that became to so widely useful that the Cincinnati Milling Machine Company was formed to sell it.

Just as the sewing machine benefited from earlier innovations yet posed problems requiring further innovation, so did other innovations. The bicycle directly benefited from prior machine tool developments. Albert Pope, the most important entrepreneur, contracted to have his bicycles made by Fairfield at the Weed Sewing Machine Company plant. Fairfield and his successors used sewing machine methods and even the same equipment to mass produce the bicycle. A number of production problems brought innovations that affected other sectors. The extensive use of ball bearings led to developments in grinding methods; both ball bearings and their manufacturing methods ramified widely. The combination of formed cutters and oil-tube drills used to make bicycle hubs had implications for much of industry.[29]

The last third of the 19th century marked an era in which technological convergence was increasingly quick and affected a growing share of the economy. The growth of machine tool firms and the decline of firms making their own machine tools implied that sale could spread innovations. The movement of workers was in part an alternative path of convergence, and machinery and metal fabricating firms did make their own tools, jigs, fixtures and some specialized machines. But much of the workers' movement led to the formation of firms making or using machine tools, and both types of firms bought machine tools.

The increasing number of application sectors posed new problems whose solutions affected other sectors. Toolroom methods advanced with the universal milling machine, tool grinders, and precision measurement devices. More durable, heavier engine lathes and planers spread to meet the growing demand of electrical machinery producers and others. The milling machine spread to a much wider range of metalworking operations. Turret lathes because increasingly automatic; some were designed for heavier work. The grinding machine was

[29] *Twelfth Census Manufactures*. Pt. 4: 386-387; Rosenberg, "Technological Change in the Machine Tool Industry," pp. 24-25, 29; Hounshell, *From the American System to Mass Production*, pp. 189-208.

adopted for many finishing operations. Lubrication methods and friction-reducing mechanisms such as ball bearings improved cutting speed and accuracy. Design capability grew greatly; even if the special-purpose machines for mass producing sewing machines, business machines, and bicycles did not apply elsewhere, their design principles did.

When machine tool firms ascended as centers of metalworking machines and knowledge, so too lathe inventors became more specialized. Whereas metalworking lathe inventors before 1866 received 24 percent of their patents in machine tools, lathe inventors in the last third of the century received 37 percent of their patents for machine tools. Shares of related measurement and metalworking patents fell slightly, and shares of other patents fell from 57 to 46 percent (see Table 7). Most of the other patents continued to be directed to machine tool application sectors, some, like textiles, engines, railroads, sewing machines and clocks continuing from the previous period, and others, such as business equipment, bicycles, shoemaking, and electrical machinery largely new to the period. Hence the share of patents outside the machine-tool using sector fell from 20 percent through the war to 13 percent after. The specialization of invention had two clear causes. First, inventors from firms using their own machine tool innovations—including notable clock and firearms inventors—often also patented in those industries. Among lathe patents with identifiable usage, the share issued to such self-using firms fell from 76 percent before 1866 to 49 percent after. Second, machinery firms specialized, so that while earlier firms might have made and invented machine tools and their products, later firms were less likely to do so. This specialization did lose the potential design convergences shared among machine tools and metal products. But convergence benefited from the wider markets for machine tool firms. In the next century the Smithian dynamic toward specialization would be disrupted by a more Schumpeterian one of major innovation.

## Interfused Development: Innovation from Inside and Outside

The trajectory formed over the 19th century, in which machine tool diffusion and invention expanded and increasingly became the domain of machine tool firms, continued into the new century. But this internal dynamic would change in basic ways. The major growth industries of the early 20th century, automobiles and electrical machinery, would reshape machine tools. Metallurgical advances would increase the speed of cutting tools. Electrification would modify machine tools that had developed in an age of steam. These external factors deepened the technological convergence within the machinery sector, and introduced convergences with chemical and electrical technology.

The factors realizing convergences among machine-tool users in the 19th century continued and in ways deepened in the 20th. Machine tool firms continued to sell their machines to firms across the economy to make machinery and fabricated metal products. Following the path of Brown and Sharpe and Bullard, many firms sold across the metalworking sector, and the breadth of the sector allowed some firms to specialized on a few, or even a single, machine tool. Convergence broadened as new industries arose; electrical machinery and automobiles employed two percent of workers in industries using machine tools in 1890 but 33 percent in 1920, and other new industries ascended at the same time. Firms making and using machine tools continued to train workers whose mobility spread knowledge among industries. Many leaving Brown and Sharpe found jobs elsewhere after 1900, including all who went to automobiles and many who moved into machine tools. Dozens of workers moved from other machine tool firms into positions of responsibility throughout the metalworking sector. Moreover workers from elsewhere in the sector moved to machine tool firms. Extensive mobility and new firm formation consolidated Cincinnati's position as the leading machine tool center.[30]

As employment in sectors potentially using machine tools nearly quadrupled from 1890 through 1920, incentives to invent grew, and because machinists more than quadrupled in the same period, those with capabilities to invent grew commensurately. Patenting grew as well. Annual lathe patents expanded from 33 in the 1870-1891 period to 72 in the new century, and patents probably grew faster for machine tools just coming into widespread use such as grinding machines and gear cutters. Two factors suggest that these patents were used more widely. The share of generic patents grew from 50 to 61 percent between the periods, while the share dedicated to particular sets of industries fell with the exception of patents to make engines, now led by internal combustion engines. Moreover, the share of lathe patents taken out by or assigned to machine tool firms grew from 51 to 70 percent of patents, easing their diffusion among industries. Firms from newer industries began to patent lathes, including firms making electrical machinery and automobiles, and the trend in the 1920s toward self-usage might have signaled an upcoming change. But overall machine tool firms grew in invention and diffusion.

As machine tool sales grew and machine tool firms invented more, lathe inventors specialized more on machine tools. Inventors first patenting lathes in the 20th century received 60 percent of their total patents for machine tools, far above the 37 percent for 1870-1890 lathe inventors (see Table 7). Lathes patents increased somewhat, but the big change was the growth from 9 to 29 percent of patents for other machine tools or which pertained to whole groups of machine tools. Application sectors patents fell from 33 to 20 percent, and those outside the machine tool using sector declined to an insignificant 3 percent of patents.

To a considerable extent, the trajectory of the content of patents persisted: machine tools became more automatic, more accurate, faster, heavier, and more rigid. Automatic and

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[30] Roe, *English and American Tool* Builders; "Personals" weekly listings of the *American Machinist.*

semiautomatic machines were developed to work forgings fed separately in addition to bar iron or wire. Precision standards improved significantly, aided by the use of grinding machines. Many machine tools cut more metal per minute, and added weight and rigidity supported speed and accuracy. Though the 19th century had exhibited each of these tendencies, quite distinct 20th century developments advanced them. Firms hired designers and mechanical engineers to improve the quality their products and expanded their drafting departments. Though organized research labs had little existence, systematic experimentation grew, and published results by such engineers as A. L. deLeeuw of Cincinnati Milling Machine led to machine redesign and productivity growth.[31]

Yet new sectors and innovators from outside the industry strongly shaped the trajectory of technological change, particularly automobiles, metallurgical innovations, and electrical motors. The automobile industry became the biggest new machine tool user. It became a mass production industry, like firearms, sewing machines, and bicycles before it, and like them utilized the machine tools it found and posed new problems for innovators. But the automobile was much larger and heavier and so required different machine tools, and its demand for machine tools was much greater than earlier mass production sectors. Its scale of operations soon became large enough that mass production machine tools could be used, machines capable of producing on a much larger scale than locomotives, railroad car wheels, or other heavy, machined products. Firms and inventors quickly responded. For example, in 1902 Brown and Sharpe sold 29 milling, grinding and gear cutting machines to 21 different automobile and parts companies, including Dodge and Packard. By 1910, many machine tool firms had Detroit

[31] Roe, *English and American Tool* Builders, pp. 273, 277. DeLeeuw was an engineer at Cincinnati Milling Co. and later at Singer. A series of his widely discussed experiments on milling machine cutters identified cutting methods that increased metal cut relative to horsepower consumed. A. L. DeLeeuw, "Milling Cutters and Their Efficiency," *Journal of the American Society of Mechanical Engineers* 33 (April, 1911), pp. 995-1004.

offices, including Brown and Sharpe, Pratt and Whitney, and Niles-Bement-Pond.[32]

Workers trained in machine tool firms also contributed. After learning at the Springfield Armory, Colt, and then Brown and Sharpe, Henry Leland, along with another Brown and Sharpe worker, Charles Norton, formed Leland, Faulconer, and Norton in 1890, which made grinding machines, woodworking machines, and other machinery in Detroit. As part of its efforts, it patented grinding machines and an important gear-feed milling machine that allowed greater control over feeds and speeds. After Norton left, Leland and Faulconer ground bevel gears for bicycles for which Leland patented a bevel gear generator. Leland also made gas engines for boats. The firm became a recognized leader in precision machining, which led to contracts to make transmissions for the first Oldsmobile and then make engines for that car. Leland designed a superior engine and, when asked about the prospects of a failing company with which Henry Ford had been associated, convinced the investors to form a new company, Cadillac. The company merged with Leland and Faulconer and used its capabilities to produce interchangeable parts cars. Nine other Brown and Sharpe workers made autos or auto parts. Other firms contributed as well; Walter Flanders made sewing machines at Singer, machine tools at the Landis Tool Company, and sold machine tools before coming to Ford Motor Company, where his contributions were essential to Ford's mass production success.[33]

Invention was needed to realize the potential for mass production of heavy objects. Auto firms only exceptionally patented machine tools, and machine tool firms received few auto design patents. But auto firms played several critical roles in mechanization. They conceived of mass production of interchangeable parts and laid out the flow of work to accomplish it,

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[32] Brown and Sharpe, "Sales Book;" Detroit Business Directory, 1910.

[33] U.S. Patents 548,167 and 624,508; Robert S. Woodbury, "History of the Gear-Cutting Machine:" 84, 122 in *Studies in the History of Machine Tools* (Cambridge, Mass., 1972); Robert S. Woodbury, "History of the Milling Machine," 64 in *Studies in the History of Machine Tools* (Cambridge, Mass., 1972). *From the American System to Mass Production*, pp. 80-82, 220-221.

including—after interchangeable parts production had been achieved—the moving assembly line. They designed and produced jigs and fixtures. They not only purchased machine tools, they also designed special- and single-purpose machines which they produced or contracted with machine tool firms to build; Ford claimed—too sweepingly—to have designed every special purpose machine in their plant. They maintained and at times built the tools for such machines.[34] But machine tool firms played equally important roles. They designed a series of vitally important machines, often building on developments that preceded the automobile. Perhaps the most important change was the development of production grinding. Charles Norton, the central innovator, had designed and patented grinding machines at Brown and Sharpe but was frustrated in his attempts to use grinding not simply for narrow, slow finishing cuts but for much deeper, wider cuts on heavier machines. In 1900 he formed the Norton Grinding Company, which was closely linked to the Norton Emery Wheel Company, a firm making grinding wheels. Sold first to make printing presses, electrical machinery, and machine tools, his machine's biggest early success came in grinding crankshafts on contract for automobile firms, reducing to fifteen minutes operations that had taken five hours. In 1905 he sold several machines to auto companies and later sold 35 to Ford. Norton, the Landis Tool Company (which had trained Flanders), and others designed specialized machines for camshafts, transmissions, brakes, and engines. Automobiles remained the largest market, but aircraft, railroads, armaments, and machinery throughout the economy accounted for nearly half of Norton's sales, and Norton's inventions targeted railroads, rolling mill, papermaking, and

[34] Hounshell, *From the American System to Mass Production*, pp. 217-261. Hounshell makes clear that the moving assembly line was an innovation in its own right with different roots than interchangeable parts. Here too the machine tool using sector benefited from a wider range of convergences emanating from meatpacking, flour milling, brewing, and foundries.

crushing rolls.[35]

Other machine tool innovations had similar effects. In the 1880s, the Bullard Machine Tool Company had developed a vertical boring machine capable of more precise work than earlier boring machines, and after 1900 it developed this machine into a turret lathe that could drill, bore, or turn simultaneously, thus combining the operations of separate machine tools. Bullard developed this machine to extend its product line into automobiles, and his machine greatly reduced the time to make Ford's flywheels before being applied more generally. Other firms developed special crankshaft lathes, gang drill presses, and gear cutters. They multiplied simultaneous operations in machines to mill 30 cylinders or drill 45 holes. Many of these changes were anticipated before the auto and undertaken by inventors and firms such as Norton, Bullard, and Landis who had been active in the 19th century. Indeed automobile manufacturing could develop so rapidly only by using tools and capabilities developed for other purposes.[36]

Changes in the auto industry spilled over into other sectors. The use of grinding for production, not simply finishing purposes, had widespread effects. New machine tools spread among many kinds of mass produced products, but were also applied to goods produced in smaller batches. Ball bearings, refined in auto production, were applied widely. Forced lubrication of machine tools, centralization of controls in one place, and standardization of small parts also spread. Machine tools were also beneficiaries, as machine tools adopted the antifriction bearings, gearing, and self-lubricating mechanisms perfected on automobiles. One of the beneficiaries was machine tools. The effects were wider yet; vanadium steel developed for

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[35] Woodbury, "History of the Grinding Machine, pp. 97-133; Charles W. Cheape, *Family Firm to Modern Multinational: Norton Company, A New England Enterprise* (Cambridge, Mass., 1985), pp. 58-74. The modest number of patents targeting automobiles greatly underestimates the impact of the industry, because many of the patents say nothing about the use to which the innovation will be put. The dozens of articles on automobile production in *American Machinist* forms a better guide to the impact of the auto.
[36] Wood, *From Archimedes to Automation*, pp. 31-32.

autos came into wider use and initiated a search for other alloy steels.[37]

Fundamental sources of machine tool development utilized knowledge not typically held by machine tool producers or users. Norton's grinding machine was made much more useful by the simultaneous development of artificial abrasives. Norton's partner firm, Norton Emery Wheel, later renamed the Norton Company, led in developing artificial aluminum oxide (called Alundum) cutting tools. To do so, it purchased an exclusive license for an Alundum-making patent, mastered electric furnace technology, developed bonding methods, and undertook years of experimentation that led to furnace improvements. Success came around 1906, when a new electrochemical technology increased the cutting power of a new machine tool. The various Norton firms concentrated patenting around their complementary needs. On its machine tools side, they received 86 patents for grinding machines, some with targets in many industries, one casting patent, and one machine measurement patent. Their abrasive side patented more broadly, with 17 chemical patents for abrasive compounds and their manufacture, 12 electrical furnace patents, 19 patents to design and form grinding wheels, and another 19 for new products such as anti-slipping stair treads.[38]

High speed steels had more general impact on machine tools. The introduction of high-speed steel cutters involved metallurgical knowledge foreign to the machinists' training. Such cutters are often attributed to the work of Frederick Taylor and Maunsel White at Bethlehem Steel, but as is typically the case others undertook much pertinent innovation. Taylor had long been interested in discovering the best steel for cutting edges. With William Sellers's approval, he had undertaken a series of experiments at Midvale Steel, where he was a shop superintendent

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[37] *American Machinist* 38 (Jan 16, 1913), p. 119; 38 (January 23, 1913), p. 161; 38 (April 3, 1913), pp. 9; 38 (May 8, 1913), p. 759. Rosenberg, "Technological Change in the Machine Tool Industry," pp. 27-28; Sol Eisenstein, "Machine Tool Milestones, Past and Future," *Mechanical Engineering* 52 (November, 1930), p. 961.

[38] Cheape, Family Firm to Modern Multinational, pp. 74-84. Patents were determined from a google patent search and then individually consulted.

and later the chief engineer of the machine shop, which concentrated on heavy military ordnance. Sellers was the only major machine tool firm that patented heavily in metallurgical fields. In the late 1890s, now heading Bethlehem Steel's largest machine shop, Taylor and the metallurgist White conducted a careful series of experiments to identify the best tool steel. They compared existing steels and developed a new steel alloy formed at much higher temperatures, dubbed high-speed steel because its cutters could cut two to three times as rapidly as existing cutters. Bethlehem Steel used the steel to cut its costs greatly and—until its patents were invalidated in a suit with Niles-Bement-Pond—also licensed or sold patent rights in the U.S. and abroad.[39]

The new cutter created opportunities that could not be realized on existing machine tools. Designers noted the need to alter their machines, led by two leading lathe makers. Noting in 1902 that its existing lathes "were incapable of utilizing the new steels to their full advantage" and that "radical departures would have to be made in the general design," Bullard developed a new lathe twice as heavy as its existing machines with better lubricating systems and power devices to substitute for hand action. Lodge and Shipley designed a lathe of greater power and weight. Increased power required the gearing to be redesigned. By the end of the decade, high-speed cutting tools used on heavier, more powerful, often more automated machines were common, though more in roughing than in finishing operations. The effects were wider yet, since the methods used to discover and spread the new knowledge—systematic experimentation and careful measurements of temperatures—applied to technological change in metallurgy and

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[39] Thomas J. Misa, *A Nation of Steel: The Making of Modern America, 1865-1925* (Baltimore, 1995), pp. 173-200; U.S. Patents 688,269 and 688,270; Roe, *English and American Tool Builders*, p. 250; Charles D. Wrege and Ronald G. Greenwood, *Frederick W. Taylor: The Father of Scientific Management, Myth and Reality* (Homewood, Ill., 1991), pp. 125-148; Harless D. Wagoner, *The U.S. Machine Tool Industry from 1900 to 1950* (Cambridge, Mass., 1966), pp. 9-10. In addition to the high-speed steel patents, Taylor and Henry Gantt assigned Bethlehem patents for a means to heat and cool metal cutting tools and a pyrometer. After the Taylor-White patents, Bethlehem Steel contributed little to machine tool development directly, though they did receive a number of machine tool patents in the 1920s, including milling machines to remove surface faults from billets of rolling mills.

more widely, unlike the craft-like methods typical of earlier firms making crucible steel cutters.[40]

Finally, the electric motor replaced the steam engine in driving machine tools, and did so largely by individual motors linked to each machine. Electrical machinery firms were the principal innovators. The innovation was suggested seriously in the mid-1890s, diffused slowly at first, but accelerated around World War I and particularly in the 1920s, though grinding machines were holdouts. General Electric, concerned both to sell motors and to produce electrical machinery, was essential to the process. The key technological issues were complex—variable versus constant speed motors, AC vs DC motors, group drive of machines using shafting versus individual drives—but GE and others explored them and patented improvements.

GE and its predecessors were initially interested in machine tools to manufacture electrical machinery. John Riddell, who would become mechanical superintendent at GE's Schenectady plant, assigned six machine tool patents to Thomson-Houston over the 1890s to make the armatures, commutators, and magnets of dynamos. GE continued with another 38 patents to make electrical apparatus, particularly dynamo coils and turbines. These were special purpose machines designed for self-usage. GE knew that machine tools were not just a means to make their equipment, but that machine tool firms could be a market for their electrical products. From Riddell's first patent in 1900 for an "electrically-operated machine tool," GE received 36 patents for motors or electrical devices to run machine tools (in addition to many more for motors more generally). A number of these designed reversing mechanisms for reciprocating machines such as planers. Some motor patents targeted printing presses, type-setting machines, and sewing machines in addition to machine tools. GE also received 14 generic patents for machine tools, four patents regulating machine motion, and one patent for an alternative to high-

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[40] *American Machinist* 25 (Nov. 6, 1902), pp. 1635-36 (quote from p. 1635); 38 (May 8, 1913), p. 772; Misa, *A Nation of Steel*, pp. 200-205. Rosenberg points out the importance of artificial abrasives and high-speed steel in "Technological Change in the Machine Tool Industry," pp. 25, 29-30.

speed steel designed for machine tool cutters. Finally, it moved in a quite different direction when it patented portable machine tools to bring the machine tools to fixed work, often involved in making electrical equipment. Machine tool firms joined the innovation, led by Niles-Bement-Pond, which received 26 electric motor patents from 1903 through 1929.[41]

Electricity had many effects on a wide variety of machine tools, and hence on much of the economy. The cost of shafting was greatly reduced, except in group drive applications. Machines could be located more flexibly, and electric cranes readily moved material. Portable machine tools added to the flexibility. Greater power could be brought to machines, particularly important for rapid, rough cuts using high-speed steel. Moreover, costs fell because friction losses from the shafting were eliminated and machines used no power when not in use. Motors did away with the need for belt shifting under different loads, and hence permitted quicker adjustments to achieve the desired machine speed. They allowed greater control, such as quicker return strokes on planers. Finally, they provided better knowledge of power requirements and the stresses of machine operation, which led to the redesign of many machines.

These internal and external factors combined to reshape the machine tool dynamic. The linkages began in the preceding period, when Taylor experimented in Seller's Midvale machine shop, and when machine shops bought new forms of British steel. Electrical machinery firms were already major machine tool customers, and incandescent lighting already illuminated factories. Norton Emery Wheel already sold to machine tool firms, giving it pause to finance Charles Norton and risk alienating one of its best customers, Brown and Sharpe. Machine tool and bicycle producers were involved in automobile production and design from the 1890s.

Still, mass-produced automobiles, high-speed steel, motor-driven machinery, and

[41] Riddell patent 660,801; *American Machinist* 37 (December 19, 1912), pp. 1009-1011; 41 (August 6, 1914), pp. 225-227; 44 (January 20, 1916), p. 126; *Twelfth Census of the United States: 1900. Manufactures* Part 4 (Washington, 1902), pp. 386-387. Harless D. Wagoner, *The U.S. Machine Tool Industry*, pp. 11-19.

artificial abrasives were fundamental new technologies. The interfusion of their development with machine tool evolution formed a new era of technological convergence. In this stage, the auto became the biggest growth market for machine tools, and heavy, mass production machine tools were designed for this market. Production grinders responded early, and artificial abrasives added to their utility. High-speed steel and electric motors diffused rapidly to autos, to growing sectors, and to new factories. Both required major redesign of machine tools, and motors enabled measurement needed to direct design. Based in part on its more systematic technical studies, the machine tool industry brought out new machines to make use of the new metallurgy and new energy sources. The results spread to many industries. By the 1920s, electric motors running individual machines and traveling cranes were common in firms making and using machine tools. Special purpose machine tools, already used to make textile machinery, firearms, sewing machines and bicycles by 1900, developed to make automobiles, electrical machinery, aircraft, and many consumer durables. While machines were targeted at particular uses, the capabilities to design them applied more widely.

Now the convergence extended beyond metalworking. Machine tools depended on advances in metallurgy, and the new alloys found other uses. Grinder cutters rested on the chemistry of aluminum and silicon and the technology of electric furnaces. Factories lit by incandescent lamps used motor-driven machine tools and electric hoists and assembly lines. The evolution of mechanical technology had become intertwined with those of electricity and chemistry. The interfusion formed a new era of technological convergence that linked general purpose technologies.

## Technological Convergence, Machine Tools, and Mechanization

The epochal transition from the initial mechanization efforts of 1820 to the widespread mechanization of 1830 was equally a transition from little technological convergence among machine tool using sectors to widespread convergence among dozens of industries. Convergence contributed to the change in two ways. Production methods developed in some sectors enabled others to mechanize more easily. Moreover knowledge of mechanical principles in some sectors enables advances in others. As Rosenberg insightfully notes, learning within the machinery sector formed a "highly developed facility in the designing and production of specialized machinery [that] is, perhaps, the most important single characteristic of a well-developed capital goods industry and constitutes an external economy of enormous importance."[42] This design convergence could improve machine tools and the products they made. Improved application sectors, in turn, demanded more machine tools but also formed knowledge that might foster further design improvements across application sectors.

How is this convergence to be explained? Three factors were at work: means to spread knowledge of machine tool techniques, growing ranges of potential machine tool users, and growing inventive capability. Changes in the means to spread knowledge and hence to realize convergences delineated eras of technological convergence. In a first, extending through the Civil War, convergence emerged out of the common needs and capabilities of separate metalworking developments, in which firms developed machine tools for use in their own production processes. Self-used lathe (and presumably other machine tool) inventions spread when some firms diversified into machine tools, but more importantly, when machinists spread machine tools to other firms and other industries, commonly through new firms formed to make machines or machine tools. Convergence was rapid among leading firms using engine lathes and planers, but less rapid outside leading regions and among mass production machine tools.

[42] Rosenberg, "Technological Change in the Machine Tool Industry," p. 17.

A second stage evolved out of the first. The emerging machine tool firms increased their importance in spreading machine tools among industries, and—given machine tool markets enlarged by convergences—inventing. As invention by machine tool firms rose, self-used inventions fell relatively but continued even in machine tool firms meeting their own production needs. Workers continued to spread techniques and inventive capabilities. Convergence spread into mass production sectors making sewing machines, bicycles, and office machinery, but had only begun to penetrate agricultural machinery.[43] A 20th century stage continued the trend toward diffusion and invention by machine tool firms and the movement of machinists, but fundamentally reshaped machine tools by innovations in products, materials, and power sources. New innovators invented for self-usage in making heavy armaments at Bethlehem and electrical equipment at GE, but then discovered markets for steel and motors among machine tool producers. Norton Emery Wheel funded grinding machine development and found markets for abrasives for these machines. Convergence extended

The progress toward diffusion and invention by machine tool firms rested on growing markets for machine tools and hence on the extension of mechanization and fabricated metal products. Invention in metalworking sectors was needed to develop the machines and products that would require machine tools in their own construction. Machine tool producers and inventors contributed to this invention in two ways. First, machine tools enabled developments that would have been much more difficult without them; that electrical machinery and automobile producers found machine tools at hand allowed them to make precise-enough products at acceptable costs. Machine tool invention often solved new problems, creating machine tools that applied elsewhere. Second, machine tool producers and inventors used their design knowledge outside machine tools. At least for lathe inventors, invention in application

[43] Hounshell, *From the American System to Mass Production*, pp. 153-187.

sectors was common before 1865, but declined over time. The machine tool sector had to rely on the inventiveness of others in its application sectors.

How, then, did invention in the machine tool sector relate to invention in application sectors? In particular, did technological convergence not simply connect application sectors through common use of machine tools but also link them directly to each other? Machine tools and their application sectors both worked metal, unlike, say, textiles machines, which worked on cotton or wool. Hence machine tools may have had greater design convergence with application sectors then these sectors had with each other. On the other hand, all machines shared design convergences, so that inventors from one application sector might move into others.

A comparison with another turning machine, the woodworking lathe, can explore these issues.[44] Analogous to the study metalworking lathe inventors, USPTO data identified woodworking lathe inventors from each year before 1866 and then from census years through 1910, and all patents through 1929 were determined. Because woodworking lathes applied to woodworking industries, its inventors might have concentrated their other inventions on wood products. Yet because the lathe shared design features with other machines, inventors might have moved within the machinery sector.

The comparisons demonstrate a clear contrast of two parts of the machinery sector. Though average patents differed little between inventors of metalworking and woodworking lathes, the distribution of patent types differed meaningfully (see Table 11). Patents are separated into five types: machine tool and related, machine tool applications, woodworking

[44] Lathes that cut wood were highly significant in shaping what was once a universal construction material. It was central to mass production in firearms; around 1820, when the milling machine was invented to shape lock pieces, Blanchard's pattern lathe transformed gunstock production. By the Civil War, the lathe shaped shoe lasts, oars, hat blocks, and many other irregularly shaped parts.

machines and related, woodworking applications, and other patents.[45] Machine tool inventors concentrated on machine tool and related patents, and, analogously, woodworking lathe patentees concentrated on woodworking machines. The concentration grew over time for each lathe type, though it was never as high for wood lathe inventors.[46] But machine tool inventors patented a much larger share in its own applications than woodworking inventors, who never received more than nine percent of patents in wood products. The striking difference between the two kinds of lathe inventors is that whereas metalworking lathe inventors had few patents for wood machines and applications, woodworking lathe inventors patented extensively in machine tools and its applications outside woodworking. In the three periods, they received, respectively, 39, 52, and 27 percent of their patents in the machine tool using sectors, in addition to wood machines and related patents.

Table 11. Patent Types, Metalworking and Woodworking Lathe Inventors

| | *Metalworking Lathe Inventors* | | | *Woodworking Lathe Inventors* | | |
|---|---|---|---|---|---|---|
| | 1816-1865 | 1870-1890 | 1900-1910 | 1816-1865 | 1870-1890 | 1900-1910 |
| *All Inventors* | 130 | 87 | 110 | 50 | 38 | 23 |
| Average Patents | 8.5 | 13.7 | 14.9 | 7.3 | 13.0 | 9.8 |
| Patent Shares | | | | | | |
| Machine Tools & Related | 42.8% | 54.0% | 77.0% | 15.6% | 5.7% | 8.4% |
| Machine Tool Application | 34.9% | 31.4% | 19.3% | 23.6% | 46.4% | 18.7% |
| Wood Machines & Related | 2.2% | 1.8% | 0.5% | 36.2% | 34.8% | 53.3% |
| Wood Application | 3.5% | 4.5% | 0.4% | 11.5% | 4.5% | 12.0% |
| Other | 16.6% | 8.3% | 2.7% | 13.2% | 8.7% | 7.6% |
| *Technological Occupations* | 61 | 49 | 89 | 13 | 6 | 12 |
| Average Patents | 12.8 | 19.8 | 16.3 | 17.5 | 43.0 | 12.8 |
| Inventor Share, Known Occ. | 73.5% | 80.3% | 90.8% | 40.6% | 31.6% | 66.7% |
| Patent Shares, Known Occ. | 81.6% | 87.3% | 93.6% | 69.7% | 76.6% | 77.3% |

[45] To link each patent to one category, all woodworking machine and related patents for metalworking and woodworking inventors have been grouped in that category, even though they were also in the application sectors of machine tools. This reduces the share in the application sector noted in Table 7.
[46] Though part of the correlation comes from the simple fact that each inventor had at least one surveyed patent of the appropriate kind, inventors also received many other patents of the same type, and would retain the same concentration even if surveyed patents were omitted.

| | | | | | | |
|---|---|---|---|---|---|---|
| Machine Tools & Related | 88.8% | 92.9% | 95.0% | 98.2% | 5.3% | 88.9% |
| Machine Tool Application | 79.9% | 81.9% | 88.3% | 75.0% | 95.5% | 76.5% |
| Wood Machines & Related | 95.0% | 100.0% | 77.8% | 60.4% | 44.0% | 86.8% |
| Wood Application | 100.0% | 65.1% | 100.0% | 51.3% | 71.4% | 34.6% |
| Other | 62.5% | 79.8% | 92.9% | 63.0% | 80.0% | 71.4% |

Hence the application sectors for machine tools—industries using machine tools to make machinery and fabricated metal products—grew at least in part from design convergences with other application sectors. Application sectors not only complemented machine tools, as the GPT literature argues, they also converged with one another, including machine tools, so that the development of one created knowledge relevant to others. Thus the automobile industry could develop so fast not only because machine tools were available but also because other machinery sectors generated knowledge that developed the automobile itself.

The comparison of metalworking and woodworking lathe inventors helps identify the source of inventive capabilities and of their cross-industry application. For both types of lathes, technological occupations—machinists supplemented by designers, draftsmen, and mechanical engineers—dominated patenting. These occupations made up a lower share of inventors with known occupations for wood lathe inventors; carpenters, cabinetmakers, and last makers were relatively more important. The greater share of nontechnological occupations among wood lathe inventors makes sense because whereas the producers and the users of machine tools were machinists, the users of wood lathes typically were not. But technological occupations received from 70 to 77 percent of all patents issued to wood lathe inventors with known occupations. They concentrated their patents within the machine tool using sector. Their share of wood application patents was beneath their share of all patents, but they dominated patenting in other machine tool application sectors, with between 75 and 95 percent of such patents.[47]

Machinists were central to convergence before a machine tool industry had come into being, and remained central throughout the period. They helped invent and spread the first engine lathes and planers. Their machine-making knowledge enabled them to enter new industries, as textile machine and steam engine producers came to make locomotives. Their design knowledge enabled them to develop new commodities, as the textile machinist Elias Howe did when inventing the sewing machine. They trained workers who moved between sectors, setting up new firms in the process, as Sellers, Bement, Pratt, and Whitney did in the machine tool industry. As markets grew, they built machinery firms that displaced much machinery built in-plant, firms making textile machines, engines, presses and, as a relative latecomer, machine tools.[48] Their role would deepen in later periods. Henry Leland spanned the three eras. He went from a Civil War Springfield Armory contractor and worker to Colt, to Brown and Sharpe to head its screw and sewing machine departments, to Leland and Faulconer making grinders, bicycle gears and boat engines, and finally to Cadillac. Machinists also came to autos from other application sectors making bicycles, machine tools, sewing machines, and engines. Their invention was typically mechanical; for the most part, they left chemical and electrical inventions to other technological occupations.

The three factors underlying technological convergence in the machine-tool using

[47] The one apparent exception was the 5.3 percent share of machine tool and related patents technological occupations received in the middle period. This was largely because one inventor, a Warren Ohio carpenter when he patented a lathe, moved to a metalworking firm in nearby Youngstown, where he received many metalworking patents. One of the problems of the small number with technological occupations in the middle period has the opposite bias. One machinist, Rudolf Eickemeyer, received 187 patents, and is the sole reason why average patenting was so high for technological occupations in that period. He patented a hat-block turning lathe as part of his successful efforts to mechanize hat-making. He then turned his attention to electrical machinery, where in addition to his 76 patents for motors, locomotives, and other electrical devices, he supplied Charles Steinmetz his first job in the United States.

[48] On the distinctive role of machinists and their cross-industry significance before 1865, see Thomson, *Structures of Change.*

sector—the capability to invent, the generation of application sectors, and the means to diffuse knowledge among these sectors—were hence interlinked. Mechanization trained machinists who improved machine tools and other machines, developed application sectors, and spread knowledge through their movement among industries. Machine tools played a central role, because they enabled production convergence among sectors and because machinists trained to use them also developed design capabilities of wide application. The developing mode of dissemination distinguished eras of technological convergence based on the extent of self-used invention. A third era added to the diffusion patterns of the second new innovators grounded in nonmechanical technologies. Of course, the distinctive 20th century dynamics were grounded in 19th century explorations of electrical and chemical technologies, to which machine tools contributed. But they introduced something basically new to the machine tool using sector. Rosenberg finished his machine tool a paper by asking whether 20th century industries played "the same role of information production and transmittal" that machine tools had played, noting the value of "theory which assumes that most technological change enters the economy 'through a particular door.'"[49] If machine tools and the sector using them formed one door, electrical and chemical technologies formed two others whose convergent knowledge transformed the machine tool sector a century after the door of mechanical technology had been opened.

[49] Rosenberg, "Technological Change in the Machine Tool Industry," p. 31. Rosenberg demonstrates the workings of one 20th century door in "Chemical Engineering as a General Purpose Technology."