Technological Change in the Machine Tool Industry, 1840-1910

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I

TECHNOLOGICAL change has come to absorb an increasing share of the attention of the economist in recent years. Several attempts have been made to assess the quantitative importance of technological change, as opposed to increases in factor supplies, in accounting for the secular rise in per capita incomes in the United States. It appears, in all these studies, that technological changes (shifts in the production function) have been far more important than has the mere growth in the supplies of capital and labor inputs, as conventionally measured (movement along an existing production function).[1] In a sense, this should be cause for deep concern, since the comparative neglect of the process of technological change (with the major exceptions until very recent years, of the works of Marx, Schumpeter, and Usher) suggests a serious malallocation of our intellectual resources. If the studies of such people as Abramovitz and Solow are even approximately correct with respect to orders of magnitude, then the contribution of technological change to rising per capita incomes absolutely dwarfs the contribution from a rising but qualitatively unchanging stock of capital. It would appear that we have indeed been playing Hamlet without the Prince.

Even the recent quantitative studies referred to in the previous paragraph provide the beginnings of only a very partial corrective to this neglect. For what they attempt to establish are, essentially, the quantitative *consequences* of technological innovation. From the point of view of our understanding of the process of economic change, the critical, unanswered question is: what are the major causes of technological change? Why do some firms, industries,

[1] Robert Solow, "Technical Change and the Aggregate Production Function," *Review of Economics and Statistics,* XXXIX, No. 3 (Aug. 1957), 312-20; Moses Abramovitz, "Resource and Output Trends in the U.S. Since 1870," *American Economic Review Papers and Proceedings,* XL, No. 2 (May 1956), 1-23; Benton Massell, "Capital Formation and Technological Change in U. S. Manufacturing," *Review of Economics and Statistics,* XLII, No. 2 (May 1960), 182-88.

regions, countries, show an apparently greater readiness and ability to undertake technological innovations than do other firms, industries, regions, countries? The question may be given a further historical dimension if we seek to explain the apparent variations in innovative activity for the same firm (industry, region, country) at different points of time.[2]

The present paper constitutes a modest attempt to examine and to explain the rapidity of technological change in a sector of the American economy which played a strategic role in the industrialization process.

In the past decade or so, the attempt to formulate a theory of the "take off" into economic growth has centered upon the process whereby an economy, in a relatively short time period, sharply accelerates the annual rate of net additions to its capital stock.[3] This has been an important and fruitful line of inquiry, if only because it has generated historical research which now reveals the considerable diversity of different economies during the growth process. Historical data accumulated by Kuznets for twelve countries show no individual case of abrupt increases in net investment of the magnitude implied by the take-off hypothesis, and cast overwhelming statistical doubt upon any attempt to link precisely the acceleration in the rate of growth of per capita income with rising capital formation proportions.[4]

It seems apparent, then, that changes in rates of investment are only a part of the process by which economic growth is initiated and maintained, and that attention may be usefully directed to other aspects of the transition to growth. Recent work by Gallman and Kuznets makes it clear that growth has been associated with major changes in sector shares of commodity output and with an associated sharp *compositional* shift in the pattern of investment

[2] The two most important works which should be consulted by anyone interested in this area of research are H. J. Habakkuk, *American and British Technology in the 19th Century* (Cambridge [England]: The University Press, 1962), and W. Paul Strassmann, *Risk and Technological Innovation: American Manufacturing Methods During the Nineteenth Century* (Ithaca: Cornell University Press, 1959).

[3] W. W. Rostow, "The Take-Off into Self-Sustained Growth," *Economic Journal*, LXVI, No. 261 (Mar. 1956), 25-48, and W. A. Lewis, "Economic Development with Unlimited Supplies of Labour," *The Manchester School*, XXII, No. 2 (May 1954), 139-91.

[4] Simon Kuznets, "Quantitative Aspects of the Economic Growth of Nations: VI. Long-Term Trends in Capital Formation Proportions," *Economic Development and Cultural Change*, Vol. IX, No. 4, Part 2 (July 1961).

activity.[5] It is with the latter point that we are primarily concerned.

The development process in the United States has been characterized by a significant increase in the importance of manufactured producers' durables and a decline in the relative importance of construction goods. This suggests that an important aspect of industrialization may be illuminated by examining the changing historical role of the capital goods industries, and more particularly that growing portion of them which is devoted to the production of producers' durable goods. The role of these industries in introducing and in diffusing technological change is obviously multidimensional, but two aspects at least may be singled out: (1) All innovations—whether they include the introduction of a new product or provide a cheaper way of producing an existing product—require that the capital goods sector shall in turn produce a new product (capital good) according to certain specifications. We may usefully look upon the capital goods sector as one which is, in effect, engaged in custom work. That is, firms in this industry have typically become highly specialized, in the sense that most firms produce a relatively narrow range of output (at least in industrialized economies) in response to technical specifications laid down by a wide range of customers in the consumer goods or other capital goods industries. (2) In addition to this "external" adaptation there is an important "internal" one. Quite simply, members of the producers' durables industry have an internal motivation to improve their own techniques in the production of the durable goods themselves. Their success in accomplishing this improvement in turn affects the price of their machinery output and therefore is an important determinant, first, of investment activity throughout the economy and second, of the rate at which technological innovations, once made, will be diffused—that is, of the speed with which the economy will install and apply new techniques of production once they have been discovered. Moreover, third, cost reduction by the capital goods industries is thus capital saving for the economy, and cost reduction here also raises the marginal efficiency of capital of other industries. For these reasons it is suggested that a significant—and so far largely unexplored—

5 Robert Gallman, "Commodity Output, 1839-1899," *Trends in the American Economy in the Nineteenth Century* (Studies in Income and Wealth, 23 [Princeton, N. J.: Princeton University Press for NBER, 1960]) 13-67; Simon Kuznets, *Capital in the American Economy* (Princeton for NBER, 1961), ch. iv.

dimension of the transition to economic growth lies in the ability of the capital goods sector to assimilate and develop proficiency in the new machine technology and thus both to generate, and to adapt itself to, the continually altering technological requirements of an industrializing economy. It will be argued that the machinery-producing industries possess certain unique characteristics which played a major role in accounting for the rapid production and diffusion of technological innovations, which were such a well-known and outstanding feature of the period under consideration.

Machine tools are the most important members of the larger classification of power-driven metalworking machinery. The basic distinction is that machine tools shape metal through the use of a cutting tool and the progressive cutting away of chips, whereas other metalworking machinery shapes metal without the use of a cutting tool—by pressing (forming, stamping, punching), forging, bending, shearing, etc. There is considerable complementarity and substitution between the two classes of tools, and occasional reference will necessarily be made in what follows to developments outside the category of machine tools as defined here.

II

In 1820 or so, there was no separately identifiable machine-tool or machinery-producing sector in the American economy. Although machines of varying degrees of complexity were, of course, being used, the production of the machines had not yet become a specialized function of individual firms.[6] Machines were, by and large, produced by their ultimate users on an *ad hoc* basis. For many years, the most intractable problems associated with the introduction of techniques of "machinofacture" lay in the inability to produce machines which would perform according to the special and exacting requirements and specifications of the machine user.[7]

6 "There were mules and steam-engines before there were any labourers whose exclusive occupation it was to make mules and steam-engines; just as men wore clothes before there were such people as tailors." Karl Marx, *Capital,* I (Modern Library Edition [New York: Random House, 1936]), 417.

7 The experiences of Eli Whitney with his government musket contract are by now legendary. See Jeanette Mirsky and Allan Nevins, *The World of Eli Whitney* (New York: Macmillan Company, 1952). Compare H. J. Habakkuk, "The Historical Experience on the Basic Conditions of Economic Progress," *International Social Science Bulletin,* VI, No. 2 (1954), 189-96.

A skeptical note on Whitney's role in developing the "American system" has recently been struck in Robert S. Woodbury, "The Legend of Eli Whitney and Interchangeable Parts," *Technology and Culture,* II, No. 2 (Summer 1960), 235-53.

A major episode, then, in the process of industrialization lay in the emergence of a specialized collection of firms devoted to solving the unique technical problems and mastering the specialized skills and knowledge requisite to machine production.

It is useful to examine the growth of the machinery-producing sector from the point of view of the learning process involved. For, as we shall see, most machinery production poses a broadly similar set of problems and involves a broadly similar set of skills and technical knowledge in their solution. Moreover, the pace of industrialization was, in large measure, determined by the speed with which technical knowledge was diffused from its point of origin to other sectors of the economy where such knowledge had useful applications.

The growth of independent machinery-producing firms occurred in a continuing sequence of stages roughly between the years 1840-1880.[8] These stages reflect both the growth in the size of the market for such machines and the accretion of technical skills and knowledge (and growth in the number of individuals possessing them) which eventually created a pattern of product specialization by machine-producing firms which was closely geared to accommodating the requirements of machine users.

In the earliest stages, machinery-producing establishments made their first appearance as adjuncts to factories specializing in the production of a final product. Thus the first machine-producing shops appeared in the textile firms of New England attached directly to such firms as the Amoskeag Manufacturing Company in Manchester, New Hampshire, and the Lowell Mills in Lowell, Massachusetts. As such shops achieved success as producers of textile machinery, they gradually undertook, not only to sell textile machinery to other firms, but to produce a diverse range of other types of machinery—steam engines, turbines, mill machinery

[8] It is not an historical coincidence that specialized machinery producers began to emerge on the national scene during precisely the same period as the development of our national railway network. Until roughly 1840, machinery production was not only relatively unspecialized—each producer typically undertaking a wide range of output—but it was also, because of the high cost of transporting machinery, a highly localized operation—each producer typically producing for a very limited geographic radius. The growing specialization in machine production after 1840, characterized by the emergence of large numbers of producers each of whom typically concentrated on a very narrow range of machines, was closely linked with the transportation improvements and consequent reduction in freight costs during the period.

and (most important) machine tools—as well. In the early stages then, skill acquired in the production of one type of machine was transmitted to the production of other types of machines by this very simple expedient whereby a successful producer of one type of machinery expanded and diversified his operations. Thus, with the introduction of the railroads in the 1830's, the Lowell Machine Shop (which became an independent establishment in 1845) became one of the foremost producers of locomotives.[9] Similarly, locomotives were produced by the Amoskeag Manufacturing Company; and the locomotive works in Paterson, New Jersey, grew out of the early cotton textiles industry in that city. The most successful of all American locomotive builders, the Baldwin Locomotive Works in Philadelphia, grew out of a firm previously devoted, *inter alia,* to textile-printing machinery.[10]

Whereas the production of heavier, general-purpose machine tools—lathes, planers, boring machines—was initially undertaken by the early textile machine shops in response to the internal requirements of their own industry and of the railroad industry, the lighter, more specialized high-speed machine tools—turret lathes, milling machines, precision grinders—grew initially out of the production requirements of arms makers. Somewhat later, the same role was played by the manufacturers of sewing machines and, toward the

9 *A Chronicle of Textile Machinery 1824-1924* (Boston: Saco-Lowell Shops 1924) pp. 16-20.

The number of locomotives built by the Locks and Canals Company and by the Lowell Machine Shop between 1835 and 1861 is given, together with the purchasing railroad companies, in George S. Gibb, *The Saco-Lowell Shops* (Cambridge: Harvard University Press, 1950), appendix 6, p. 641.

10 John L. Hayes, *American Textile Machinery* (Cambridge, 1879), pp. 57-58; Jonathan T. Lincoln, "Machine Tool Beginnings," *American Machinist,* LXXVI (Aug. 3, 1932), 902-3. Although Mattias Baldwin in 1852 described himself as a "Manufacturer of Locomotive, Marine, and Stationary STEAM ENGINES," his advertisements also added: "All kinds of Machinery furnished to order." *Journal of the Franklin Institute,* L (June 1852), opposite p. 444. A report of British observers for the same period states, "The practice which prevails of combining various branches of manufacture in the same establishment, would . . . render separate descriptions of each somewhat complicated. In some cases the manufacture of locomotives is combined with that of mill-gearing, engine-tools, spinning, and other machinery. In others, marine engines, hydraulic presses, forge-hammers, and large cannon are all made in the same establishments. The policy of thus mixing together the various branches arises, in addition to other causes, from the fact that the demand is not always sufficient to occupy large works in a single manufacture." *The Industry of the United States in Machinery, Manufactures and Useful and Ornamental Arts,* (compiled from the official reports of Messrs. Joseph Whitworth and George Wallis [London, 1854]), p. 3.

end of the period under consideration, by the demands of bicycle and automobile manufacturers.[11]

Thus the machine tool industry itself was generated as the result of the specific production requirements of a sequence of industries which adopted techniques of machine production throughout the period. In each case, the introduction of a new process or a new product required an adaptation and adjustment in the capital goods industries to new technical requirements and specifications which did not initially exist. There took place, as it were, a period of technical gestation at the intermediate stages of production, during which time the appropriate accommodations were made to the specific technical needs of the new process or product. As the demand for particular kinds of machines became sufficiently great, reflecting the fact that the same machines came to be employed in a progressively increasing number of industries, the production of that machine itself came to constitute a specialized operation on the part of individual establishments.[12]

The machine tool industry, then, originated out of a response

[11] Joseph W. Roe, "Machine Tools in America," *Journal of the Franklin Institute* (May 1938), pp. 499-511.

[12] As early as 1855, a team of British engineers which had traveled to the United States for the purpose of inspecting American methods of arms manufacture felt compelled to make the following observations on the extent to which specialized machinery had been developed in American industry: "As regards the class of machinery usually employed by engineers and machine makers, they are upon the *whole behind those of England, but in the adaptation of special* apparatus to a single operation in almost all branches of industry, the Americans display an amount of ingenuity, combined with undaunted energy, which as a nation we would do well to imitate, if we mean to hold our present position in the great market of the world." *Report of the Committee on Machinery of U. S.* (H. C., 1855), p. 32. Similar observations and admonitions appear through a succession of reports by British observers to international exhibitions through the subsequent decades of the nineteenth century. See, for instance, the report on machine tools in *Reports on the Paris Universal Exhibition, 1867, Presented to both Houses of Parliament* (1868), IV, especially 370-73, and "Machines and Tools for working Metals, Wood and Stone," in *Reports on the Philadelphia International Exhibition of 1876, Presented to both Houses of Parliament* (1877), I, especially 228-35. In the latter report, Mr. John Anderson, the author, states: "To realize the nature of the competition that awaits us, their [American] factories and workshops have to be inspected, in order to see the variety of special tools that are being introduced, both to insure precision and to economize labour; this system of special tools is extending into almost every branch of industry where articles have to be repeated. This applies to furniture, hardware, clocks, watches, small arms ammunition, and to an endless variety of other things. The articles so made are not only good in quality, but the cost of production is extremely low, notwithstanding that those employed earn high pay." (p. 235). Mr. Anderson closes with a rhapsody on the tool-using and tool-making abilities of the Americans, and on the urgency of Britain's girding her loins for the coming industrial and engineering competition.

to the machinery requirements of a succession of particular industries; while still attached to their industries of origin, these establishments undertook to produce machines for diverse other industries, because the technical skills acquired in the industry of origin had direct application to production problems in other industries; and finally, with the continued growth in demand for an increasing array of specialized machines, machine tool production emerged as a separate industry consisting of a large number of firms most of which confined their operations to a narrow range of products—frequently to a single type of machine tool, with minor modifications with respect to size, auxiliary attachments, or components.

> In late years . . . manufacturers starting in this branch of industry [metal-working machinery] have very generally limited their operations to the production of a single type of machine, or at the most to one class embracing tools of similar types. For example, there are large establishments in which nothing is manufactured but engine lathes, other works are devoted exclusively to planers, while in others milling machines are the specialty.
>
> This tendency has prevailed in Cincinnati perhaps more than in any other city, and has been one of the characteristic features of the rapid expansion of the machine-tool industry in that city during the past ten years. During the census year there were in Cincinnati 30 establishments devoted to the manufacture of metal-working machinery, almost exclusively of the classes generally designated as machine tools, and their aggregate product amounted to $3,375,436. In 7 shops engine lathes only were made, 2 were devoted exclusively to planers, 2 made milling machines only, drilling machines formed the sole product of 5 establishments, and only shapers were made in 3 shops.[13]

In 1914, there were 409 machine tool establishments in the United States producing an output of $31,446,660.[14] In the same year the *American Machinist*, in a survey which was admittedly incomplete, published a map showing the locations of 570 firms engaged in the production of "machine tools, small tools, machinist's tools and machine tool appurtenances. . . ." These firms were all in the northeast quadrant of the country, with Ohio leading with

[13] *Twelfth Census of the United States* (1900), X, Part 4, "Manufactures," 385. This report also refers to the existence of a total of ninety metal-working machinery firms in the five leading centers of Cincinnati, Philadelphia, Providence, Hartford, and Worcester. For a breakdown by value of output of major categories of metal-working machinery in 1900 and 1905, see *Special Reports of the Census Office* (1905), "Metal-working Machinery," p. 227.

[14] *Census of Manufactures* (1914), II, "Reports for Selected Industries," 269. For the same year there were 277 metal-working machinery plants, other than those producing machine tools, with an output valued at $17,419,526.

117 and then Massachusetts with 98, Connecticut with 66, Pennsylvania with 60, New York with 57, and Illinois with 42.[15]

III

A proper understanding of the "portentously rapid" rate of technological innovation which accompanied American industrialization during the period under consideration requires that we focus attention upon a particular aspect of the changing nature of manufacturing activity. For this purpose it is necessary to discard the familiar Marshallian approach, involving as it does the definition of an industry as a collection of firms producing a homogeneous product—or at least products involving some sufficiently high cross-elasticity of demand. For many analytical purposes it is necessary to group firms together on the basis of some features of the commodity as a final product; but we cannot properly appraise important aspects of technological developments in the nineteenth century until we give up the Marshallian concept of an industry as the focal point of our attention and analysis. These developments may be understood more effectively in terms of certain functional processes which cut entirely across industrial lines in the Marshallian sense.[16]

It is a common practice to look upon industrialization as involving, not only growing specialization, but also growing complexity and differentiation.[17] While this is certainly true in the sense that there takes place a proliferation of new skills, facilities, commodities, and services, it also overlooks some very important facts. The most important for present purposes is that industrialization was characterized by the introduction of a relatively small number of broadly similar productive processes to a large number of industries. This follows from the familiar fact that industrialization in the nineteenth century involved the growing adoption of a metal-using technology employing decentralized sources of power.[18]

[15] *American Machinist*, XL (Jan. 29, 1914), 210.

[16] We suggest, only in passing, that such a focus may also provide a more fruitful approach to a theory of the multiproduct firm.

[17] ". . . industrial differentiation . . . has been and remains the type of change characteristically associated with the growth of production. Notable as has been the increase in the complexity of the apparatus of living, as shown by the increase in the variety of goods offered in consumers' markets, the increase in the diversification of intermediate products and of industries manufacturing special products or groups of products has gone even further." Allyn Young, "Increasing Returns and Economic Progress," *Economic Journal* XXXVIII, No. 152 (Dec. 1928), 537.

[18] A. P. Usher, *History of Mechanical Inventions* (Cambridge: Harvard University Press, 1954), especially chs. xiii-xv.

If we look at the vertical dimension of productive activity in the sense of the sequence of stages involved in the production of a final product, it appears that in preindustrial economies, skills and techniques tended to be much more specific and tied down to individual vertical sequences than was the case in industrial economies. The central role, in industrial economies, of the application of decentralized power sources in the working of metals has meant the employment of similar skills, techniques, and facilities at some of the "higher" stages of production for a wide range of final products. Thus, in contrast to sequences of parallel and unrelated activities, we find a phenomenon which we will call "technological convergence." This convergence exists throughout the machinery and metal-using sectors of an industrial economy. Throughout these sectors there are common processes, initially in the refining and smelting of metal ores, subsequently in foundry work whereby the refined metals are cast into preliminary shapes, and then in the various machining processes through which the component metal parts are converted into final form preparatory to their assembly as a finished product. It is with the machinery stages, of course, that we are primarily concerned here.

The use of machinery in the cutting of metal into precise shapes involves, to begin with, a relatively small number of operations (and therefore machine types): turning, boring, drilling, milling, planing, grinding, polishing, etc. Moreover, all machines performing such operations confront a similar collection of technical problems, dealing with such matters as power transmission (gearing, belting, shafting), control devices, feed mechanisms, friction reduction, and a broad array of problems connected with the properties of metals (such as ability to withstand stresses and heat resistance). It is because these processes and problems became common to the production of a wide range of disparate commodities that industries which were apparently unrelated from the point of view of the nature and uses of the final product became very closely related (technologically convergent) on a technological basis—for example, firearms, sewing machines, and bicycles.

This technological convergence had very important consequences for both (1) the development of new techniques and (2) their diffusion, once developed.[19] The intensive degree of specialization

[19] On this point it is difficult to avoid the conclusion that we are still suffering, in

which developed in the second half of the nineteenth century owed its existence to a combination of technological convergence plus what Stigler has called vertical disintegration—that is, a tendency for individual sequences in the production of a final product to be undertaken as separate operations by separate firms. Stigler suggests that vertical disintegration, and therefore increasing process specialization by firm, is likely to be characteristic of growing industries.

> If one considers the full life of industries, the dominance of vertical disintegration is surely to be expected. Young industries are often strangers to the established economic system. They require new kinds of qualities of materials and hence make their own; they must overcome technical problems in the use of their products and cannot wait for potential users to overcome them; they must persuade customers to abandon other commodities and find no specialized merchants to undertake this task. These young industries must design their specialized equipment and often manufacture it, and they must undertake to recruit (historically, often to import) skilled labor. When the industry has attained a certain size and prospects, many of these tasks are sufficiently important to be turned over to specialists.[20]

It seems clear that the extraordinary degree of specialization achieved in the machine-producing sector of the American economy is attributable, not only to the growth of individual industries experiencing vertical disintegration in Stigler's sense, but also to the simultaneous growth of several industries which were technologically convergent in our sense. The extent of machinery specialization which was achieved would not have been possible if there were only vertical disintegration *without convergence.* For the degree of specialization achieved owed its existence in large part to the fact that certain technical processes were common to many industries.

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our understanding of technological innovation, from a Schumpeterian blight. For all his profound understanding of the capitalist process, Schumpeter never quite overcame his preoccupation with the charismatic aspects of leadership and its role in instituting changes in the operation of the economic system. As a result, his own towering intellectual leadership in this area has led to an excessive concern with the more dramatic and discontinuous aspects of innovation, with the circumstances surrounding the initial "breakthrough," and to a neglect of the less spectacular dimensions of innovation. We refer, in particular, to two other aspects: (1) the cumulative impact of relatively small innovations (which were of great importance in the design, development, and adaptation of machines), and (2) the determinants of the rate and the area over which an innovation, once made, is eventually diffused. These points will be treated subsequently in this paper.

[20] George Stigler, "The Division of Labor is Limited by the Extent of the Market," *The Journal of Political Economy,* LIX, No. 3 (June 1951), 190.

Individual firms producing nothing but milling machines would not have emerged in an economy where only firearms manufacturers employed milling machines, nor would specialized grinding machine producers have emerged in an economy where only bicycle manufacturers employed grinding machines. With technological convergence, however, milling and grinding became important operations in a large number of metal-using industries, thus permitting a degree of specialization at "higher" stages of production which would not otherwise have been possible. Since, as Adam Smith, Allyn Young, and George Stigler have taught us, "the division of labor is limited by the extent of the market," the unique degree of specialization developed in the American machinery-producing sector owed as much to technological convergence as it did to the expansion in the demand for individual final products.

The importance of this specialization must be conceived, not only in a static sense, but in a dynamic sense as well. For there is an important learning process involved in machinery production, and a high degree of specialization is conducive not only to an effective learning process but to an effective *application* of that which is learned. This highly developed facility in the designing and production of specialized machinery is, perhaps, the most important single characteristic of a well-developed capital goods industry and constitutes an external economy of enormous importance to other sectors of the economy.

Metal-using industries, therefore, were continually being confronted with similar kinds of problems which required solution and which, once solved, took their place in short order in the production of other metal-using products employing similar processes. Using Usher's useful terminology, metal-using industries were continually engaged in a "setting of the stage" for particular problems which, once they were solved, produced free technological inputs to other metal-using industries.

In all of this the machine tool industry, as a result of technological convergence, played a unique role both in the initial solution of technological problems and in the rapid transmission and application of newly-learned techniques to other uses. We suggest that the machine tool industry may be regarded as a center for the acquisition and diffusion of new skills and techniques in a machinofacture type of economy. Its chief importance, therefore, lay in its strategic role in the learning process associated with industrialization. This role, as I have asserted and will now elaborate further, is a dual one: (1) new skills and techniques were developed or perfected here in response to the demands of specific customers; and (2) once they were acquired, the machine tool industry was the main transmission center for the transfer of new skills and techniques to the entire machine-using sector of the economy.

IV

In this section we will examine the nature and the consequences of technological convergence. An exhaustive cataloguing of specific instruments is neither possible nor, fortunately, is it necessary for our purposes. The basic pattern which I wish to emphasize with respect to both the origin and diffusion of machine tool innovations will be explored by reference to its historical role in four industries: firearms, sewing machines, bicycles, and automobiles. If time and space permitted, a more comprehensive account would include also a wide spectrum of machine-tool-using industries ranging from watches and clocks, scientific instruments, hardware, and typewriters to agricultural implements, locomotives, and naval ordnance.

What is important here is an historical sequence in which the need to solve specific technical problems in the introduction of a new product or process in a single industry led to exploratory activity at a vertically "higher" stage of production; the solution to the problem, once achieved, was conceived to have immediate applications in producing other products to which it was closely related on a technical basis; and this solution was transmitted to such other industries via the machine tool industry. The machine tool industry may be looked upon as constituting a pool or reservoir of skills and technical knowledge which are employed throughout the entire machine-using sectors of the economy. Because it dealt with processes and problems common to an increasing number of industries, it played, during this period, the role of a transmission center in the diffusion of the new technology. The pool of skill and technical knowledge was added to as a result of problems which arose in particular industries. Once the particular problem was solved and added to the pool, the solution became available, with perhaps minor modifications and redesigning, for employment in technologically related industries. Thus, as a result of technological convergence, external economies of enormous importance were rapidly generated.

Throughout the whole of the first half of the nineteenth century and culminating perhaps with the completion of Samuel Colt's armory in Hartford in 1855, the making of firearms occupied a position of decisive importance in the development of specialized, precision machinery. The notion that the system of interchangeable parts sprang full-blown from Whitney's genius in musket manufacture has now been accorded a decent burial.[21] What is clear is that the new machinery and technology were the joint product of efforts to overcome the same group of problems, not only by Whitney, but by men employed at such places as Robbins and Lawrence, Ames Manufacturing Company, Colt's armory, and the government armories at Springfield and Harper's Ferry as well.

The introduction of Thomas Blanchard's stocking lathe for the shaping of gunstocks, in 1818, represents an interesting transitional innovation, inasmuch as it was originally developed for the shaping of wooden materials but involved a principle which eventually found wide applications in other materials for reproducing irregular patterns. Blanchard's lathe, which replaced the tedious and time-consuming hand techniques of shaping the gunstock by whittling, boring, and chiseling, was introduced at the national armories at Springfield and Harper's Ferry during the 1820's.[22] The principle embodied in the machine was quickly applied to such sundry items as hat blocks, handles, spokes of wheels, sculptured busts, oars, and shoe lasts. [23]

The firearms industry was instrumental in the development of

21 Woodbury, "Legend of Eli Whitney." (See n. 7.)

22 Charles Fitch, "Report on the Manufactures of Interchangeable Mechanism," *Tenth Census of the United States* (1880), II, 13-19. (Hereafter cited as Fitch, *Report.*)

23 The application to the last item was apparently too quick, for Blanchard was upheld, as late as 1849, in an infringement suit involving the application of his lathe to turning shoemaker's lasts. See *Journal of the Franklin Institute* XLVII (1849), 259-62.

The British commission on arms manufacture which visited the United States in 1853 was particularly impressed with the gunstock lathe, at the time apparently still unknown in England. "It is most remarkable that this valuable labour-saving machine should have been so much neglected in England, seeing that it is capable of being applied to so many branches of manufacture, its introduction into the armory will prove a national benefit." *Report of the Committee on Machinery of U. S.* (H. C., 1855), p. 39. The British Government subsequently purchased these machines from the Ames Manufacturing Company of Chicopee, Massachusetts.

the whole array of tools and accessories upon which the large-scale production of precision metal parts is dependent: jigs (originally employed for drilling and hand-filing), fixtures, taps and gauges, and the systematic development of die-forging techniques.[24]

The milling machine, perhaps with the turret lathe one of the two most versatile of all modern machine tools, owed its origin in the United States to the attempt of arms makers to provide an effective machine substitute for highly expensive hand filing and chiseling operations. Although here, as in so many other cases, its exact origins are shrouded in obscurity, it is clear that both Eli Whitney and Simeon North employed crude milling machines in their musket-producing enterprises in the second decade of the nineteenth century, as did John H. Hall at the Harper's Ferry Armory.[25] Its subsequent development was largely the work of the national armories, especially the highly important work of Thomas Warner at the Springfield Armory,[26] and such gun-producing firms as Robbins and Lawrence, of Windsor, Vermont. The design of the plain milling machine was stabilized in the form which came to be known as the Lincoln miller, in the 1850's, and rapidly assumed a prominent place in all the metal trades. Fitch states that, between 1855 and 1880, ". . . nearly 100,000 of these machines or practical copies of them, have been built for gun, sewing-machine and similar work."[27]

The final major contribution of the arms makers was the role played in the development of the turret lathe which, together

24 Fitch reports that die-forging machines were employed at Harper's Ferry as early as 1827. (Fitch, *Report*, p. 20.) The most significant subsequent improvements were achieved at the Colt armory under the guidance of its ingenious superintendent, Elisha K. Root. Although the sewing-machine industry relied more heavily upon casting than on forging, drop forging with dies was introduced into sewing-machine manufacture as early as 1856. (Fitch, *Report*, p. 37.) Compare also W. F. Durfee, "The History and Modern Development of the Art of Interchangeable Construction in Mechanism," *Transactions, American Society of Mechanical Engineering*, XIV (1893), especially 1,250-51.

25 Fitch, *Report*, pp. 22-26; Joseph W. Roe, "History of the First Milling Machine," *American Machinist*, XXXVI (June 27, 1912), 1,037-38; Robert S. Woodbury, *History of the Milling Machine* (Cambridge: M. I. T. Press, 1960), chs. i and ii. Woodbury's book, which is part of a series devoted to the history of machine tools, is an invaluable guide to the detailed technical development of the milling machine.

26 Fitch, *Report*, pp. 3 and 25; Felicia J. Deyrup, *Arms Makers of the Connecticut Valley* (Northampton: Smith College Press, 1948), pp. 153-54.

27 Fitch, *Report*, p. 26. Fitch cites examples for 1880 of armsmaking plants where milling machines constituted between 25 and 30 per cent of the total number of machines in use (p. 22).

with the milling machine, was indispensable to the production of all commodities based upon interchangeable parts. The turret lathe, holding a cluster of tools placed on a vertical axis, made it possible to perform a sequence of operations on the work piece without the need for resetting or removing the piece from the lathe. It therefore revolutionized all manufacturing processes requiring large volumes of small precision components, such as screws—which were, in short order after the development of the turret lathe, produced on turret lathe machines.[28]

The origin of the turret lathe (initially employing a horizontal axis for the turret) has been attributed to Stephen Fitch, of Middlefield, Connecticut, in 1845, while he was engaged on a government contract for the production of percussion locks for an army horse pistol.[29] The turret lathe principle was employed and improved at the Colt armory (where Root introduced a double-turret machine in 1852) and by Frederick W. Howe while superintendent of the Robbins and Lawrence Company at Windsor, Vermont; and turret lathes were built and sold commercially by that company in 1854. A turret screw machine, designed in 1858 by H. D. Stone, was sold commercially by the Jones and Lamson Company.[30] From this point on, the machine was adapted and modified for innumerable uses in the production of components for such products as sewing machines, watches, typewriters, locomotives, bicycles and, eventually, automobiles. Its most important subsequent improvement was introduced by Christopher Spencer, a former Colt employee and the inventor of the Spencer repeating rifle. As a result of a machine which he invented for turning sewing-machine spools, Spencer went on to explore methods for making metal screws automatically and, in so doing, invented the automatic turret lathe.[31] The importance of this innovation is difficult to exaggerate,

28 *Ibid.*, p. 28.

29 E. G. Parkhurst, "Origin of the Turret, or Revolving Head," *American Machinist*, XXIII (May 24, 1900), 489-91. Compare also Guy Hubbard, "Development of Machine Tools in New England," *American Machinist*, LX (Feb. 21, 1924), 272-74.

30 Fitch, *Report*, pp. 27-28; Joseph W. Roe, *English and American Tool Builders*, (New Haven: Yale University Press, 1916), p. 143. The successors of the Robbins and Lawrence Company, the Jones and Lamson Machine Company, remained one of the leaders in turret lathe production for many years. See James Hartness, *Machine Building for Profit* (Springfield, Vt.: Jones & Lamson Machinery Co., 1909). Hartness introduced the flat-turret lathe and was a pioneer in the application of hydraulic feeds to machine tools.

31 Guy Hubbard, "Development of Machine Tools in New England," *American Machinist*, LXI (Aug. 21, 1924), 314; Roe, *Tool Builders*, p. 176.

since the self-adjusting feature of the cam cylinder with adjustable strips, through which automaticity was achieved, was eventually to make possible all modern automatic lathe operations. Together with the subsequent perfection of multiple spindle techniques, it was instrumental in a major acceleration in the pace of machine tool operations.

From the 1850's through the 1870's, the technical requirements of the sewing-machine industry played a major role as a source of machine tool innovations. Although sewing-machine production was virtually nonexistent in 1850, it constituted a flourishing industry in 1860,[32] and grew with remarkably swift strides, nationally and internationally, in the following decade.[33] Out of the innumerable modifications of the sewing machine grew the vast boot-and-shoe and men's and women's ready-to-wear clothing industries; and the machine, by 1890, was used extensively in the production of such items as awnings, tents and sails, pocketbooks, rubber and elastic goods, saddlery and harnesses, etc., and in bookbinding. The rapid diffusion of the sewing machine after 1860 was due to the fact that it provided a highly effective mechanical device for performing an operation common to many industries. It therefore constitutes a major historical example of what we have called technological convergence.[34]

[32] *Manufactures of the United States in 1860* (compiled from the original returns of the Eighth Census), p. clxxxix. The Twelfth Census conveniently collates the basic earlier census data on the sewing machines; *Twelfth Census* (1900), X, 404. An illustration and description of the Singer Sewing Machine, as it appeared when patented in 1851, appears on the front page of *Scientific American*, Vol. VII, Number 7 (November 1, 1851).

[33] "In the Exhibition at London in 1851, only two very imperfect sewing machines were exhibited. In 1855, at Paris, there were 14 varieties of sewing machines, some of which were so perfect that little or no material advance has since been made; and in 1862, in the London Exhibition, about 50 different arrangements of machines were shown. . . . In the 'Exposition Universelle,' now open in Paris, there are no less than 87 exhibitors of sewing machines. Their manufacture is now very general in European countries. France has 27 exhibitors, America 21, and England 12. Even so small a principality as Hesse has two exhibitors of sewing machines; the colony of Canada, five." Captain Hichens on "Apparatus for Sewing and Making up Clothing," in *Reports on the Paris Universal Exhibition, 1867. Presented to both Houses of Parliament* (1868); V, 131-32.

[34] See the summary of census statistics for 1880 and 1890 for industries in which the sewing machine was employed extensively, in Chauncey M. Depew (ed.), *One Hundred Years of American Commerce* (New York, 1895), II, 538. See also the description of sewing machines for specialized purposes in Frederick A. Paget, "Report on the Machines and Apparatus used in Sewing and Clothing," *Reports on the Philadelphia International Exhibition of 1876. Presented to both Houses of Parliament* (1877); I, 242-43.

The machining requirements and processes of sewing-machine manufacturing were broadly similar to those of firearms production, and sewing-machine manufacturers were quick to adopt these processes.[35] However, just as in the case of firearms, the solution of technical problems in sewing-machine production resulted in major additions to the stock of machine-cutting instruments which, in turn, were applied to the production of other metal-using products. The most important innovations in the sewing-machine industry were products of the remarkable Brown and Sharpe Manufacturing Company of Providence, Rhode Island.

The Brown and Sharpe Company was founded in 1833 by David Brown and his son, Joseph R. Brown. Until 1850, the firm was engaged in the production and repairing of clocks, watches, and mathematical instruments. In 1850, the firm introduced a fully automatic linear dividing engine and shortly thereafter a vernier caliper and then, in 1855, a precision gear-cutting machine.[36] In 1858, the firm commenced production of the Willcox and Gibbs sewing machine, which was an immediate success and resulted in a very considerable plant expansion. The unique machine tool contributions of this firm were generated primarily by the necessity to provide the appropriate machinery for their sewing-machine operation. But the results of these efforts were machine tools of a general usefulness far surpassing the industry of origin.[37]

The first of these machines, a turret screw machine devised for sewing-machine parts, was impressed into other uses upon the outbreak of the Civil War and thereafter became a major tool in machine shop practice generally.[38] The primary purchasers of

[35] The sewing-machine industry relied much more heavily than did the firearms industry upon cast iron and was instrumental in bringing about important improvements in foundry operations. The molding press, for example, was introduced by Albert Eames, who was at the time (around 1873), foreman of the foundry at the Wheeler and Wilson Sewing Machine Company and who was earlier employed in firearms manufacture. The molding press played an important role in the production of sewing-machine parts, in hardware generally, and in other industries dependent on casting. Fitch, *Report*, pp. 36-37; also Fitch, "Report on the Manufacture of Hardware, Cutlery, and Edge-tools," *Tenth Census of the United States* (1880); II, 10.

[36] Roe, *Tool Builders*, pp. 202-6; Robert S. Woodbury, *History of the Gear-Cutting Machine* (Cambridge: M. I. T. Press, 1958), pp. 80-81. Brown and Sharpe undertook the production of automatic gear cutters in 1877.

[37] Woodbury, *History of the Grinding Machine* (Cambridge: M. I. T. Press, 1959), pp. 60-61.

[38] *Ibid*. Compare Luther D. Burlingame, "The Universal Milling Machine," *American Machinist*, XXXIV (Jan. 5, 1911), 9.

Brown and Sharpe's screw machine were producers of hardware and tools, sewing machines, shoe machinery, locomotives, rifles and ammunition—and machine tools.[39]

Another machine tool extensively developed by Brown and Sharpe arose out of a major production problem in the building of sewing machines and one which was to assume even greater proportions in the future production of automobiles—that is, the precision grinding, to a fine finish, of hardened steel parts. This problem was encountered by Brown and Sharpe in providing components of the Willcox and Gibbs sewing machine—needle bars, foot bars, and shafts.[40] Brown finally produced a cylindrical grinding machine which was employed within his own firm and was sold to other firms (including foreign firms) beginning in 1865.[41] After several years of extensive modification and redesigning, the firm introduced a universal grinding machine of far greater versatility which was exhibited at the Centennial Exhibition in Philadelphia in 1876. This machine is the direct ancestor of the modern heavy production grinding machines.[42]

The development of the universal milling machine by Brown and Sharpe is, perhaps, the most outstanding example of a machine which was initially developed as a solution to a narrow and specific range of problems and which eventually had enormous unintended ramifications as the technique was applied to similar productive processes over a wide range of metal-using industries.

The universal milling machine had its immediate stimulus in the production of Springfield muskets by the Providence Tool Company at the outbreak of the Civil War. One of the gun parts (the nipple) required a hole to be drilled in it, and for this purpose the Providence Tool Company employed twist drills, the twist drills in turn being made by a crude process of hand filing the spiral grooves in tool-steel rods or wire. Frederick W. Howe, at the time superintendent of the company, brought the matter to the attention of Joseph Brown, whose appreciation for the problem was heightened

39 I am grateful to Professor Duncan McDougall for kindly placing at my disposal his data on the sale of machinery output of the Brown and Sharpe Company.

40 Woodbury, *Grinding Machine,* pp. 60-61.

41 *Ibid.,* pp. 61-62; Guy Hubbard, "100 Years of Progress in American Metalworking Equipment," *Automotive Industries,* CXIII, No. 5 (Sept. 1, 1955), p. 315.

42 Woodbury, *Grinding Machine,* pp. 64-71. Brown and Sharpe applied the hydraulic feed technique to the grinding machine in 1902, a technique which makes it easier to operate any machine tool automatically. *Ibid.,* p. 139.

by the fact that Brown and Sharpe employed similar drills in the production of the Willcox and Gibbs sewing machine. Brown's solution was the universal milling machine, the first of which was sold to the Providence Tool Company in March 1862. It was an amazingly useful machine, which would not only cut the grooves of spiral drills but could be employed in all kinds of spiral milling operations and in gear cutting, as well as in the cutting of all sorts of irregular shapes in metal.[43] Within the first ten years, Brown and Sharpe sold universal milling machines to manufacturers of hardware, tools, cutlery, locks, arms, sewing machines, textile machinery, printing machines, professional and scientific instruments, and locomotives, to machine shops and foundries, and of course to machine tool manufacturers. Later on in the century, with each successive product innovation, universal milling machines were sold to a succession of firms producing cash registers, calculating machines, typewriters, agricultural implements, bicycles, and automobiles. Even this impressive list of users is far from exhaustive. Toward the end of the nineteenth century, heavy-duty milling machines increasingly undertook machining operations previously performed by planing and shaping machines.

The Brown and Sharpe sales records show, furthermore, that the largest single group of buyers of their universal milling machine was other machine tool producers. Thus, the creation of a new machine tool to solve technical problems in the production of a final product resulted in a significant source of increased productive efficiency in the machine tool industry itself.

By 1880, the proliferation of new machine tools in American industry had begun to reach torrential proportions.[44] Although there were relatively few dramatically new machines comparable to the milling machine or turret lathe, the period from 1880 to 1910 was characterized by an immense increase in the development of machine tools for highly specialized purposes, by a continuous adaptation of established techniques such as automatic operation to new uses, and by a systematic improvement in the properties of materials employed in machine tool processes. The introduction of high-speed

[43] Burlingame, "Milling Machine" (cited in n.38).

[44] An admirable descriptive survey, profusely illustrated, of the "state of the arts" in machine tools in 1880 may be found in *Tenth Census* (1880), Vol. XXII, "Report on Power and Machinery Employed in Manufactures."

steel in machine-cutting tools and the use of superior artificial abrasives such as silicon carbide in grinding processes are the outstanding examples of the last development. In all of this the emergence of the new forms of transportation, most notably the bicycle and automobile, played a vital role.

Although high-wheeled English bicycles were exhibited at the Philadelphia Exposition in 1876 and at that time engaged the interest of Colonel Albert A. Pope, who was to play a pioneering role in their eventual introduction in the United States, they did not achieve large-scale popularity until they assumed their modern "safety" form in the early 1890's.[45] The industry's spectacular growth during the 1890's and its subsequent abrupt decline are indicated by the fact that there were 27 establishments producing bicycles and tricycles in 1890, 312 in 1900, and 101 in 1905. The value of the industry's output was $2,568,326 in 1890, $31,915,908 in 1900, and $5,153,240 in 1905.[46]

Many of the unique problems associated with the production of a satisfactory bicycle—given its source of locomotion—revolved around the need for lightness,[47] hardened precision parts, and efficient power transmission and friction reduction. In solving these problems, bicycle manufacturers and machine tool makers not only introduced novel techniques but redesigned, perfected, and popularized techniques which antedated the bicycle and thus made them available for numerous new uses. The most important direct beneficiaries of the innovations in bicycle production were the automobile makers. But, in some measure, these innovations were transferred and made an important impact in all forms of manufacturing where friction reduction and power transmission constituted serious

[45] It is of more than passing interest as evidence of technological convergence between sewing machines and bicycles to note that, in England as well as in the United States, the earliest bicycles were produced in sewing-machine plants. Colonel Pope in 1878 produced his first "Columbia" in a corner of the Weed Sewing Machine Company plant at Hartford. In England in the late 1860's, the Coventry Sewing Machine Company played a similar role.

See *Twelfth Census* (1900), X, 331; Albert A. Pope, "The Bicycle Industry," in Depew, *One Hundred Years*, II, 550; G. C. Allen, *The Industrial Development of Birmingham and the Black Country*, 1860-1927 (London: G. Allen, 1929), p. 243; J. Clapham, *An Economic History of Great Britain* (Cambridge: The University Press, 1952), II, 96-97.

[46] *Special Reports of the Census Office* (1905), Part 4, "Selected Industries," p. 289. Compare *Thirteenth Census of the United States* (1910), X, "Manufactures," 825-28.

[47] Some of the earliest bicycles are reported to have weighed over one hundred pounds.

problems and wherever the newly designed machine tools had useful applications.

The problems posed by large-scale bicycle production were instrumental in improving and popularizing two highly important machining techniques and applying them to new uses: the forming tool and the oil-tube drill. Although the forming tool was employed previous to 1890, its use was confined to metals of soft composition, such as were used in making caps for salt and pepper boxes. Its much more important application to hardened metals, which made of it a standard machine shop practice, resulted from the transfer of the technique to the production of bicycle-wheel hubs. Similarly, the oil-tube drill, which had an oil channel leading to or near the point, and which made possible the lubrication and cooling of cutting edges as well as the removal of chips, had been employed before 1890 in drilling gun barrels. Its rapid diffusion after 1890 resulted from its extended application, together with the forming tool, in the drilling of holes in bicycle-wheel hubs.[48]

The requirements of bicycle production played a crucial role in the development of effective techniques for making ball bearings which, in turn, had an incalculable impact through reducing the effects of wear and friction on all machine processes. The highly exacting requirements of the ball bearing, as well as of the hardened cup and cone on which the bicycle balls roll, necessitated grinding operations of great precision.[49] In some cases the grinding machines which had been designed by Brown and Sharpe for grinding sewing-machine needle bars were adapted for this new use.[50] The eventual solution to the grinding problems involved, however, as they pertained both to the bicycle and automobile, relied heavily upon the improvements in grinding from the work of men like Charles H. Norton[51] and Edward G. Acheson, who revolu-

[48] *Twelfth Census* (1900), "Manufactures," pp. 385-88. See also Fred Colvin, *Sixty Years with Men and Machines* (New York: Whittlesey House, 1947), 88-89.

[49] "The successful ball bearing depends upon having the balls themselves perfectly spherical and all of identical diameter. The ball must run in races perfectly circular, perfectly concentric, and of exact dimensions. Not only must the balls and their races be machined to a fine surface finish, but all these dimensions must be held to close tolerances, and all these parts must be hardened. Only grinding could deal with this problem." Woodbury, *Grinding Machine*, p. 110.

[50] *Ibid.*, p. 111.

[51] A former Brown and Sharpe employee, who had been initiated earlier into the problems of grinding at the Seth Thomas Clock Company.

tionized grinding operations through the introduction of artificial abrasives on the grinding wheel itself.

The bicycle industry was responsible also for numerous other innovations and modifications whose ultimate use extended far beyond the bicycle industry. The flat-link chain, an integral part of the safety bicycle, was applied to numerous other uses as a convenient device for the transmission of power. The chainless bicycle had focused attention on the need for hardened bevel gears, and the resulting improvements in gear-cutting machinery, such as those of Leland and Faulconer Company, were of considerable importance in the automobile.[52] The production possibilities of the turret lathe and of the automatic screw machine in mass production operations were extended by the "demonstration effect" of their application to new uses in the bicycle industry.[53] The need for metals with specific properties, such as the light tubular steel employed in the frame, and the high-tensile-strength steel wires employed in the wheel spokes, led to metallurgical explorations which were of great benefit in other metal-using industries.[54]

The automobile was in the earliest stages of its phenomenal growth in the first decade of the present century. The value of automobile output in 1900 was less than $5,000,000, and—although there were 57 establishments engaged in automobile manufacturing—their work was still essentially experimental.[55] In 1909, there were 265 establishments manufacturing complete automobiles and 478 manufacturing automobile bodies and parts; the corresponding figures for 1914 were 300 and 971, respectively. The value of automobile output rose from $26,645,064 in 1904 to $193,823,108 in 1909 and to $503,230,137 in 1914. For the same years, the number of automobiles made was 21,692, 126,570 and 568,781.[56]

[52] Woodbury, *Gear-Cutting Machine*, pp. 78-126.

[53] "The bicycle impinged upon the locomotive through the medium of machine tools when the new turret lathes, which had been developed to form wheel hubs, were applied to the manufacture of locomotive crankpins . . ." Colvin, *Sixty Years*, p. 89.

[54] In 1894, Pope's bicycle plant in Hartford built ". . . what was then the most up-to-date mill in the country for making cold drawn steel tubing. There was also a research department for testing metals and improving bicycle design." John B. Rae, *American Automobile Manufacturers* (Philadelphia: Temple Press, 1959), p. 9.

[55] *Special Reports of the Census Office* (1905), Part 4, "Manufactures," p. 269. In the 1900 Census Reports, the brief treatment of motor vehicles appears in the chapter on locomotives. Most of the 4,192 motor vehicles mentioned in that report were in fact powered by steam or electricity. *Twelfth Census* (1900), "Manufactures," pp. 255-59.

[56] *Census of Manufactures* (1914), II, "Reports for Selected Industries," 731-32.

The massive requirements for heavy, high-speed and increasingly automatic tools generated by this growth in automobile output quickly made of the automobile industry the largest single buyer of machine tools, and in so doing they exerted a profound effect on the industry and on the designing of machine tools.[57] But while it is easy to look upon the automobile industry as something *sui generis,* such an attitude would reflect an immature appreciation of the technological basis underlying automobile production. For by 1900, as we have seen, there existed an extensive accumulation of technological and engineering experience in the production of machine tools and a highly developed sophistication in designing and adapting basic types of machine tools for special production purposes.

The problems of large-scale automobile production involved the extension to a new product of skills and machines not fundamentally different from those which had already been developed for such products as bicycles and sewing machines. Underlying the discontinuity of product innovation, then, were significant continuities with respect to productive processes. The transition to automobile production for the American economy after 1900 was therefore *relatively* easy, because the basic skills and knowledge required to produce the automobile did not themselves have to be "produced" but merely transferred from existing uses to new ones. This transfer was readily performed by the machine tool industry.

The transfer process is seen most clearly in the further evolution and adaptation of the grinding machine, which, as we have seen, had been developed to an advanced state before the advent of the automobile. The automobile, however, far surpassed the relatively modest needs of the sewing machine and bicycle in its need for precision-finished, hardened steel parts. Until confronted with the compelling needs of the automobile, the grinder had been used either for relatively light operations or for finishing components which had acquired their basic shapes upon a lathe. In response to the needs of automobile production, the grinding machine was converted into a tool capable of heavy production operations in the course of which it frequently replaced entirely the lathe and other machine tools. Its role here was indispensable in that it

[57] Woodbury states that after 1900 the automobile industry became ". . . the largest single customer of the machine tool industry, taking 25 to 30 per cent of the output. . . ." Woodbury, *Grinding Machine,* p. 120.

provided, for its time, the only way of undertaking the precision machining of the stronger and lighter alloy steels which played such a prominent part in automobile components.

Thus, within a few years after 1900, specialized grinding machines were devised for vital parts of the automobile engine and transmission, including special ones for crankshafts, for camshafts, for piston rings, and for cylinders. Perhaps most far reaching of all, because of their importance elsewhere, were the contributions to gear cutting. The automobile generated a demand for strong, durable gears which was quite unprecedented. Here the technological interrelations between the bicycle and the automobile are particularly clear, since the most important innovator in the grinding of gear teeth was the Leland and Faulconer Company. "Faulconer was, in 1899, the first to design a machine for production grinding of hardened bevel gears for bicycles."[58] This was the same firm which was later to become the Cadillac Automobile Company. The earliest automobile firms drew very heavily upon the business and technical leadership, plant facilities, and skilled labor of the bicycle industry, the decline in which coincided exactly (in the first decade of the century) with the rapid growth of automobiles.[59]

The requirements of automobile production induced innovations or substantial improvements across the whole range of machine tools, in drilling and tapping, in milling, in lathe work generally, etc. Moreover, it brought about a significant substitution of one machine process for another, most particularly as a result of the development of power presses and dies. Intricate automobile components which would once have been produced by the lathe, drill press, milling machine, or casting or forging, were increasingly stamped directly out of sheet metal—a technique which had been given considerable impetus in the production of bicycles.[60]

[58] *Ibid.*, p. 99.

[59] "When the demand for bicycles decreased some manufacturers turned to the automobile, and many establishments that made only bicycles in 1900 are now [1905] devoted primarily to the manufacture of automobiles, while others make them to a greater or less degree in connection with the manufacture of bicycles. . . ." *Special Reports of the Census Office* (1905), Part 4, "Manufactures," p. 289. See also Rae, *American Automobile Manufacturers*, pp. 8-10. The emergence of early automobile firms out of bicycle firms is a sequence which was reproduced in Great Britain. See S. B. Saul, "The Motor Industry in Britain to 1914," *Business History* V, No. 1 (Dec. 1962), 22-44.

[60] H. J. Hinde, "Relation of Power Presses and Dies to the Automobile Industry," *Mechanical Engineering*, XLIII (Aug. 1921), 531.

The relations between the machine tool builders and the automobile industry also provided compelling evidence of the manner in which technological convergence produces learning experiences which generate diffuse and unanticipated benefits—for the automobile, itself a machine of considerable complexity, encounters many problems in its operation similar to those of the machines which produce it. As a result, not only were existing machine tool techniques adapted to the production of this new product, but important features of the automobile itself were actually transferred and embodied into machine tools.[61] Thus, the transmission for the drive and feed mechanisms of machine tools was considerably improved when machine tool builders adopted the alloy steel sliding gears and integral keyshafts developed by automobile designers. Moreover, the introduction of antifriction bearings into key points of the machine tool resulted from the demonstration of their usefulness in automobiles. Finally, the whole approach to the lubrication of machine tools was radically revised as a result of the automobile. An important problem in the maintenance of machine tools had been the frequent breakdowns when inexperienced or negligent operators failed to attend properly to the numerous separate lubrication points of their machines. The solution, of course, was the eventual adoption of the centralized, self-acting lubrication system of the automobile, which went into operation automatically as soon as the machine was activated.[62]

[61] Just as, at an earlier date, the working action of the Colt revolver was incorporated into machines used for *producing* the revolver. ". . . the same arrangement of parts characteristic of the Colt revolver seems to have been carried through the principal machines for its manufacture, the horizontal chucking lathes, cone-seating and screw machines, barrel-boring, profiling, and mortising machines, and even the compound crank-drops, exhibiting the same general arrangement of working parts about a center." Fitch, *Report*, pp. 27-28.

[62] S. Einstein, "Machine-Tool Milestones, Past and Future," *Mechanical Engineering*, LII (Nov. 1930), 961; F. K. Hendrickson, "The Influence of the Automobile on the Machine-Tool Industry in General," *Mechanical Engineering*, XLIII (Aug. 1921), 530. In discussing the relationship between the milling machine and the automobile, Einstein concluded: "The automotive industry asked of the machine-tool designer automatic machines, either through modification of standard designs or machines of entirely special design—quick-acting fixtures, either hand-operated or automatically operated—more powerful and stronger machines occupying a minimum amount of floor space. On the other hand, the automotive industry supplied the machine-tool designer with a vast variety of highly successful machanisms and constructive details, from which he could draw freely such elements and such ideas as could be adapted to the design of machine tools." "Discussion at the Machine Shop Practice Session," *Mechanical Engineering*, XLIII (Aug. 1921), 534.

V

We have attempted to show how, with the growing volume of manufacturing output, increasing vertical disintegration from the point of view of a single industry was accompanied by technological convergence of larger groups of industries. The result of this convergence was a growth in a relatively small number of process specializations the consequences of which, for the production and diffusion of new technical knowledge, we have examined by focusing attention on a sequence of industries which played a most important role in this development. A few further comments appear to be called for.

An explanation of many of the technological changes in the manufacturing sector of the economy may be fruitfully approached at the purely technological level. This is not to deny, of course, that the ultimate incentives are economic in nature; rather, the point is that complex technologies create internal compulsions and pressures which, in turn, initiate exploratory activity in particular directions. The notion of imbalances in the relation *between machines* is virtually *de rigueur* in any treatment of the English cotton textile industry in the eighteenth century (Kay's flying shuttle leading to the need for speeding up spinning operations, etc.). We suggest that, *within a single complex machine or operation,* even more important imbalances frequently exist among its component parts. A concept of technological disequilibrium may be helpful here. At any time, the component parts of a machine vary in their ability to exceed their present level of performance, which is determined by the capacity of some limiting component. Any important improvement in the operation of a component, whether it be the currently limiting one or not, is likely to create new obstacles, in the form of limitations imposed by another component, to the achievement of a higher level of performance. Thus single improvements tend to *create* their own future problems, which compel further modification and revision.

The interdependence between the forming tool and the oil-tube drill in the machining of bicycle hubs, referred to earlier, is an important case in point. The introduction of the forming tool for the outside of bicycle hubs created a disequilibrium between the operations carried on for the outside and the inside of the hub. Since the forming tool worked more rapidly on the outside of the hub than the old-fashioned drills worked on the inside, the fullest gains from the use of the forming tool required a speeding up of drilling operations. This imbalance was corrected by the oil-tube drill which, in speeding up drilling operations, brought about a closer synchronization between the two operations. Numerous other instances of the role of disequilibrating forces could easily be cited,[63] but the induced improvements in machine tool design following the introduction of high-speed steel around the turn of the century are easily the most important within our period.

When Frederick W. Taylor and his associates introduced high-speed steel (a steel alloy which drastically improved the ability of a cutting tool to maintain its hardness at high temperatures) it became possible at once to remove metal by cutting operations at dramatically higher speeds. But it was impossible to do so on machines designed for the older carbon steel cutting tools, because they could not withstand the stress or provide sufficiently higher speeds in the other components of the machine tool. As a result, the availability of high-speed steel for the cutting tool quickly generated a complete redesign in machine tool components—the structural, transmission, and control elements:

> During the first decade of the 20th century we see high-speed steel revolutionizing the lathe—as it does all production machine tools. Beds and slides rapidly become heavier, feed works stronger, and the driving cones are designed for much wider belts than of old. The legs of big lathes grow shorter and shorter, and finally disappear as the beds grow down to the floor. On these big machines massive tool blocks take the place of tool posts and multiple tooling comes into vogue.[64]

The final effect, then, of this redesigning which was initiated by the use of high-speed steel in cutting tools was to transform

63 For example, the redesigning of milling cutters at the Cincinnati Milling Machine Company, when it was discovered that ". . . the cutters of the time were not as strong as the machines that were driving them and therefore gave out long before the maximum power of the machine was reached." Woodbury, *Milling Machine*, p. 80.

64 Guy Hubbard, "Metal-Working Plants," *Mechanical Engineering*, LII (Apr. 1930), 411. See also Frederick W. Taylor, *The Art of Cutting Metals* (New York: American Association of Mechanical Engineers, 1907); *Special Reports of the Census Office* (1905), Part 4, "Metal-working Machinery," pp. 232-33; Ralph Flanders, "The Influence of the Automobile on Lathe Practice," *Mechanical Engineering*, XLIII (Aug. 1921), 532; Carl J. Oxford, "One Hundred Years of Metal Cutting Tools," *Centennial of Engineering 1852-1952* (Chicago: American Association of Engineers, 1953), pp. 346-50; S. Einstein, "Machine-Tool Milestones, Past and Future," *Mechanical Engineering*, LII (Nov. 1930), pp. 959-62.

machine tools into much heavier, faster, and more rigid instruments which, in turn, enlarged considerably the scope of their practical operations and facilitated their introduction into new uses.

Many aspects of technological change, in order to be adequately understood, must be examined in terms of particular historical sequences, for in technological change as in other aspects of human ingenuity, one thing often leads to another—not in a strictly deterministic sense, but in the more modest sense that doing some things successfully creates a capacity for doing other things. We have indeed already explored this theme at some length: given what we have called technological convergence, experience in the production of firearms made it a relatively simple matter to produce sewing machines,[65] just as the skills acquired in producing sewing machines and bicycles greatly facilitated the production of the automobile. This is even more apparent, in microcosm, in the chronological history of certain individual firms, some of which, over a period of several decades, ran the entire gamut of the sequence of products—or of the machinery for producing the products—which we have considered here. This was true of the Pratt and Whitney Company. Beginning with the Civil War and over the next fifty years, Pratt and Whitney introduced in succession machinery for the production of firearms, sewing machines, bicycles, and automobiles, as well as numerous other kinds of high-precision specialized machinery.[66] A machinery plant in Hartford which was originally owned by the Robbins and Lawrence Company, and later acquired by the Sharps Rifle Manufacturing Company, ran through a succession of owners (including the showman Phineas T. Barnum) and produced successively machine tools, guns, sewing machines, bicycles, motorcycles, and automobiles.[67] The Leland, Faulconer and Norton Company (later the Cadillac Automobile Company) of Detroit, which was founded in 1890 as a producer of machine tools and special machinery, introduced machinery for producing bicycle gears during the brief heyday of the bicycle, switched to building

[65] Just as it simplified, for example, the development of the typewriter, whose problems remained unsolved until it was placed in the hands of the skilled machinists and technical experts of E. Remington and Sons, gun manufacturers at Ilion, New York. *Twelfth Census* (1900), "Manufactures," p. 442.

[66] *Accuracy for Seventy Years, 1860-1930* (Hartford, Conn.: Pratt & Whitney Co., 1930).

[67] Guy Hubbard, "Development of Machine Tools in New England," *American Machinist,* LX (Jan. 31, 1924), 171-73.

gasoline engines for motor boats when the bicycle industry began to decline, and by 1902 had undertaken the production of automobile engines.[68]

An examination of these continuities in technology provides a basis for understanding historical events which otherwise appear to be random or capricious. The interesting thing about the group of industries discussed here is that they were all dependent, in their development, upon technological changes dealing with a limited number of processes and that the solution to problems posed by these processes eventually became the specialized function of a well-organized industry. A question of more contemporary interest is whether similar technological convergences are occurring in twentieth-century conditions; whether, for example, the chemicals and electronics industries are playing the same roles of information production and transmittal that machine tools played at an earlier stage in our history.[69] The answer to the question may be very important, even from the point of view of pure theory. For a theory which assumes that most technological change enters the economy "through a particular door," so to speak, might turn out to be much simpler, and therefore more elegant, than one which assumes that technological changes may be initiated, with equal probability, anywhere in the economy.

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68 C. B. Owen, "Organization and Equipment of an Automobile Factory," *Machinery*, XV (Mar. 1909), 493.

69 The government's current role in subsidizing research and development activity has an earlier and interesting parallel in the innovations emerging out of firearms production—an industry where, as we have seen, the government played a role as a major producer as well as "consumer."