The Firm and Technological Change: From Managerial Capitalism to Nineteeth-Century Innovation and Back Again

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What roles do firms play in technological change? A new technique involves interests such as profit and growth. It also involves new knowledge. Just as economic development for Joseph Schumpeter is a new combination of existing elements [1961, pp. 65-66], so technological change combines and develops existing knowledge. To learn what roles firms play in generating (or blocking) technical change, we must study how knowledge is socially distributed and how firms acquire existing knowledge needed to innovate or spread knowledge to other innovators.[1]

This essay will try to identify innovative roles that United States firms played in the past two centuries, which requires an appropriate conception of the firm and its role in innovation. This conception must meet several criteria. Because technological change is closely tied to growth of firms, an adequate notion of the firm must be dynamic, concerned with accumulation over time. Recognizing that firms organize knowledge and vary in how they do so, an adequate theory would have to be knowledge-oriented and evolutionary. Because firms cannot know beforehand the feasibility, cost, or results of any technical change, the theory must give a place for the choice of strategies by firms. Finally, an adequate conception of the firm must be historical in that it can illuminate how the firm's role changes as it develops and faces new environments.

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Edith Penrose maps out important contours of such a conception of the innovative firm, and this article will begin by considering her theory. For Penrose, the firm is an organization that profits and grows by developing knowledge. Her analysis of the firm as a system of organized knowledge is well suited to understanding technical change. She is not the first to connect growth, knowledge, and technical change; Adam Smith and Karl Marx developed this line of thought long before. But neither arrived at a fully articulated theory of the firm. Nor has neoclassical economics gotten far with the problem. In its analysis of the choice of technique and appropriability, it does discuss the incentives firms have to develop or introduce new techniques. But its static market orientation leaves little space for firm growth or--ironically given its choice-theoretic character--even real discretion by firms. Moreover, its common assumption that knowledge is freely and immediately available to all, which underlies its notions of production functions and best-practice techniques, makes it hard to think about technical change or the firm's role in it.[2]

This article will then use ideas about the firm and innovation to interpret technological change in the United States. I will proceed historically, by examining nineteeth-century innovation and contrasting it to twentieth-century experience. This procedure will help identify the more limited role of premanagerial firms in developing new techniques, the centrality of interfirm relations in premanagerial innovation, and the changes that accompanied the rise of the managerial firm. Placing the twentieth-century firm in historical context will help us understand how intrafirm and interfirm elements together engender technological change in a managerial setting. The managerial firm internalizes some--but not all--of the functions previously performed by separate firms. Its innovation just as much hinges on its position in an increasingly complex network communicating technological knowledge.

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2 Since 1959, when Penrose's major work was finished, neoclassical theories of the firm have developed considerably, most notably in the work of Oliver Williamson [1975, 1985]. For an argument that such work remains limited by its neoclassical underpinnings, see William Lazonick [1991, ch. 6, 7].

I. The Managerial Firm and Innovation

In her major theoretical work *The Theory of the Growth of the Firm* (1959), Penrose conceives of the modern industrial firm as an administrative organization that uses the services of physical and especially human resources to make profits and grow. She restricts her focus to the management-run corporation that arose in the late nineteeth-century. Following current terminology, I call this the managerial firm. Five attributes of her theory illuminate the managerial firm's role in technological change.

1. *Growth.* Penrose's most basic proposition is that the firm aims at growth. This dynamic focus differs sharply from neoclassical economic theory, with its eye fixed on the static allocation of resources. Penrose translates the static question--the limits to firm size--into the dynamic one of the limits to firm expansion. Firms can expand indefinitely, so there is no optimal size. The firm is an entity in process; its size at any time is the outcome of its past growth, and its structure is the basis for future growth.

2. *Firm-specific resources.* In understanding growth, Penrose focuses on the internal capabilities of the firm. For her, growth should be thought of as "an **internal** process of **development** leading to cumulative movements" in particular directions [1959, p. 1]. She, of course, recognizes that the growth of the firm can be limited by external factors such as product or factor markets and the behavior of other firms. But she holds that resources internal to the firm and the "self-conception" emerging out of the practice of the firm are fundamental determinants of firm growth.

Firms have different capabilities for growth mainly because their key resource--personnel, especially managerial personnel--differs from firm to firm. Management forms a team of individuals whose mutual experience gives them greater effectiveness than they would have outside the team. Managerial teams differ in effectiveness because their decisions rely not only on knowledge that can be easily transmitted, but also on experiential or tacit knowledge, which develops through the interaction of team members. The firm thus develops its resources by using them, and its ongoing learning determines its prospects for future growth.

The firm-specific character of knowledge poses a fundamental limit to the growth of the firm. The firm can expand only as fast as new personnel can be integrated into the firm's organization. New workers learn the routines of the firm through often-protracted training processes. Such training requires the attention of existing managers. The firm is limited in its growth by the time that managers can take away from ongoing operations to train new workers.

3. *Resource underutilization.* The existence of firm-specific resources helps to explain why firms innovate, what they innovate, and how they innovate. These resources give the firm advantages in innovating, and growth over the long run requires that these innovative advantages be utilized. Past innovation develops the firm's capacity for entrepreneurship, including specialized knowledge and routines. Once an innovation has been completed, the entrepreneurial resources are not utilized unless the firm continues to innovate. To prevent the underutilization of these valuable resources, the firm must again innovate. This implies an internal pressure to expand, even in the absence of changes in the external world. Diversification into new product lines may result, fostered by innovative managerial and technical skills.

Limits to demand growth may also cause diversification. When the growth rate of output for existing products declines, the firm is more likely to find its production and distribution resources underutilized, its retained earnings unabsorbed, and its future growth in question. The firm might then diversify into related products. Diversification helps explain how firms can overcome limits to their size imposed by the size and growth of their markets.

4. *Resource-directed innovation.* According to Penrose, innovation will follow lines created by the firm's strengths, principally its production technologies and marketing systems. Firms will thus innovate where they have advantageous technological and marketing knowledge, which reduces their risks and costs of innovating relative to other firms. Competition makes innovation imperative; without developing its own novelties, the firm cannot overcome threats from other firms' new techniques or products. Technological change is required for the survival and growth of the firm.

The industrial research lab is a central means to this end. In its research lab, the firm brings together knowledge of innovative objectives and knowledge that can complete these innovations. An experienced lab not only reduces the cost of a given innovation, it also originates many ideas for new lines of research.

5. *Growth through resource acquisition.* Firms grow by acquiring and developing resources. The pace of growth depends on the ability to absorb and effectively use outside resources. Growth is greater when investments require fewer additional managers in proportion to current management. For this reason, growth is greater when a) internal resources have been released, for example, when workers have completed innovations; b) investment occurs along the same lines, requiring less learning; c) investment occurs in labor-saving machinery, requiring the hiring and training of fewer workers; d) technological or marketing convergence exists with other activities of the firm; and e) other firms are acquired instead of developing new functions inside the firm. The last of these occurs when small firms arise in the interstices of the economy (that is, growth areas not seized by existing firms). Acquisition provides technological and managerial services that the firm does not possess but needs to move into new areas.

When taken together, these propositions interpret technological change to be an ongoing process tied to the firm's growth and evolving organization of knowledge. The firm must innovate to grow; this Marx also emphasized. Penrose adds a key element--an administrative organization that can use, diffuse, and generate knowledge. At the same time the firm uses its resources, it also develops them. Through experience, its personnel learn to identify feasible innovative directions in which the firm has advantages over other firms. The firm must innovate to utilize these entrepreneurial resources. Its internal knowledge base, combined with the acquisition of outside knowledge through hiring workers and buying firms, makes innovation viable and gives it direction. In the process of innovation, the firm further develops its resources, starting the dynamic anew.

Penrose's importance lies in her integration of growth, the organization of knowledge, and innovation. Her emphasis on growth puts the firm in a dynamic context that sheds light on the conditions and incentives for technological change. By focusing on the firm's specific organization of knowledge, she is able to show how the firm matters in technological change. This focus also helps to explain how the firm appropriates the benefits of its innovation and so avoids free-rider problems. By then examining how new techniques create conditions for growth and further innovation, she brings us back to the evolution of the firm. The firm in this conception cannot overcome the uncertaintly that faces any effort to form something new; far from predetermined, its decisions depend on the strategy it adopts. Yet in the firm's need to utilize its resources and its advantages over other firms, Penrose has located important determinants of innovational success.[3]

She illustrates the usefulness of her conception historically. Dynamic conceptions of the firm are often coupled with insightful business and economic history; Schumpeter, Alfred Eichner [1969, 1976], and Alfred Chandler [1977, 1990] provide examples. In her study of the Hercules Powder Company--published in the *Business History Review* [1960] and originally written as part of *The Theory of the Growth of the Firm*--Penrose falls squarely in this tradition. Hercules pursued and achieved growth by means of diversification. Formed in 1913 out of the breakup of DuPont, its initial technological base was in explosives. The decline of demand after World War I and the underutilization of its innovative and marketing personnel led it to diversify in directions where its resources gave it advantages: nitrocellulose (a raw material of explosives production with many other uses) and cellulose chemistry, naval stores, and finally petrochemicals. Its R&D lab, established in 1919, generated a stream of new products. Trained technical personnel sold the product and learned of new po-

3 The significance of Penrose's arguments is also evidenced by her intellectual influence, which includes the economic theory of managerial capitalism [Marris, 1964; Uzawa, 1969], the analysis of business strategy [Moss, 1981], resource utilization and diversification [Chandler, 1977, 1990; Teece] and competitive dynamics [Best]. More generally, she has shaped post-Keynesian and other dynamic theories of the firm. It must be said that her work has had little effect on orthodox economics. One reason was anticipated by Wiliam Miller's review of her book in *Business History Review,* which noted that Penrose "writes in the tradition of Marshall himself, but more in the tradition of *Industry and Trade* than the *Principles of Economics*" [1960, p. 509]. *Industry and Trade*, with its historical focus and open-ended dynamic reflections, has had much the same reception.

tential markets. At several crucial junctures, Hercules acquired smaller firms to enter new lines of business. That Hercules Powder did not grow especially rapidly--less rapidly than the portion of the company that kept the DuPont name--makes it more a typical case [cf. Hounshell and Smith, 1988].

To identify the broader historical role of the firm in technological change, we will have to extend Penrose's theory in four directions. First, she knowingly underplays financial and market factors in order to focus on the firm's knowledge and human resources, but these factors affect both growth and innovation.[4] Second, she does not elaborate how the dissemination and development of knowledge is related to the structure of the firm, though the flows of knowledge among those involved in planning, production, marketing, and research are central to the firm's role in innovation. Third, the intrafirm learning on which Penrose focuses is complemented by learning from other institutions. Knowledge is not just firm-specific; its character as a quasi-public good implies that technological change involves interfirm learning [Nelson, 1993]. Finally, Penrose's analysis is limited to the managerial firm. Clearly technical change occurs outside this context, as Penrose's discussion of small firms suggests. Indeed, nonmanagerial firms were the typical nineteeth-century innovators and even now often generate the techniques that later lead to the growth of managerial firms.

II. Technological Change before the Managerial Firm

Like many others, Penrose defines the nonmanagerial industrial firm negatively. In contrast to the managerial firm--which is large, corporate, integrated into research and marketing, managerially complex, and which possesses economies of scale and scope--the nonmanagerial firm is small, owned individually or in partnerships,

4 Three quite different limits to growth must be integrated in complete theory of the firm. Besides the managerial limits that Penrose focuses on, firm growth can be limited by markets -- as emphasized by the product cycle literature [Shapiro; Thomson, 1986] -- and by financial factors affecting the rate of reinvestment and access to credit [Marris]. Each of these limits can affect the direction and pace of technological change.

unintegrated into marketing or research, managerially simple, and enjoys few economies of scale or scope. Following Phillip Scranton [1983], I call these firms proprietary in recognition of the inseparability of ownership and management.[5]

Proprietary firms' ability to pursue technological change differs markedly from that of managerial firms. Penrose argues that the key limit to the growth of proprietary firms comes from the connection between the types and extent of the firm's activites and the personal financial condition of its owners. Faced with risk of personal loss, the owner is less willing to invest heavily in fixed capital and to delegate authority to managers, thus limiting the firm's size and managerial complexity [Penrose, 1959, p. 6]. The firm's financial and managerial ability to develop expensive new techniques is therefore limited. Moreover, limits to growth and to innovation reinforce each other.

Penrose's analysis of knowledge suggests a related contrast between proprietary and managerial firms. Proprietary firms may not possess or have easy access to the kinds of knowledge needed to develop and introduce new techniques. The managerial firm can succeed at technical change because it develops or acquires knowledge of opportunities, technical problems, and--particularly in its research lab--ways to solve problems. The proprietary firm may find barriers to attaining the needed knowledge. Its work teams can recognize problems in its production process, but the team may not have the technological knowledge needed to solve these problems. Unintegrated into marketing and concentrating on a single industry, the firm may not perceive new opportunities outside its traditional purview. Finally, the firm may not be able to locate or incorporate those with knowledge that could solve its technical problems.

This argument by no means implies that proprietary firms will not innovate or grow; many did both. Rather it points to limits on growth and innovation more constraining than those experienced by managerial firms. The argument also illuminates the direction and pace of

5 How to understand proprietary firms on their own terms is an important and difficult project, but one I cannot undertake here. (See Scranton 1991 for some of the issues.) It is plain, however, that some proprietary firms are larger and more integrated than are many small corporations.

technological change within and among industries. For the ways that firms acquired and transmitted technological knowledge distinguished forms of technological change, and these forms were principal determinants of technical change and of the growth and transformation of the firm. Before managerial capitalism as well as within it, growth and innovation were connected by the organization of knowledge.

A. Self-Usage

Invention to be used in one's own shop was a common method of changing techniques, a method I call *self-usage*. To invent for self-usage, the firm had to identify limits in its production process and either generate or acquire knowledge to overcome these limits. Such improvements were common in craft shops, where workers trained in the craft modified their skills, means of production, or shop organization. Shoemaking improvements such as the pegging process originated in this way [Thomson, 1989]. These changes often enabled and required the growth of the firm, which in turn was a source of modest economies of scale among nonmechanized, antebellum firms [Sokoloff, 1984].

Self-usage was considerably harder in mechanized production because firms using machines did not typically have the mechanical knowledge needed to improve machines or materials. Still, firms in two of the most important early mechanized industries--textiles and firearms--did improve and in cases radically transformed their own production processes. In part they did so through self-usage.

Two features of the birth of factory textile production help us understand the relation of firm growth, knowledge, and technical change. First, technical change resulted from the organized acquisition, development, and transfer of knowledge within the firm. Begun with technology transferred by British mechanics, factory textile firms often integrated vertically to improve their own machinery and its utilization. This was particularly true of the Boston Manufacturing Company and later the Lowell firms, which, while formally independent, were owned by a small group of people who coordinated the firms' activities. The Locks and Canals Company came to be principally responsible for building and improving textile machinery for Lowell firms, though it was less innovative than the Boston Manufacturing Company and relied more on purchased patent rights [Gibb, 1950].[6] It hired and trained workers not only from the nascent machinist trade, but also from occupations with some mechanical skill, such as carpenters, smiths, millwrights, and wheelwrights. Because this machine shop operated in close coordination with textile factories, new machinery needs could be easily identified. Moreover, through well-documented learning-by-doing processes, textile companies improved labor productivity by perfecting operations with the same machinery [David, 1975; Lazonick and Brush, 1985]. Integration from textile machinery and even early machine tools through weaving fostered information flows that led to further technical change.

Management was at the center of these information flows, particularly factory superintendents and foremen. They drew together knowledge of the technical needs of the plant and frequently invented. Perhaps the most famous of the Lowell inventors was Paul Moody. Employed as the superintendent of the Boston Manufacturing Company, the Merrimack Manufacturing Company, and finally Locks and Canals, Moody took out patents to improve many textile operations. His innovations extended to mill design improvements, including the use of leather belting instead of metal gearing. The close relation of production and invention had the advantage of focusing attention on process improvements that could be achieved within the organization of textile firms. But the same interweaving of invention and production limited the attention that managers could direct to technical changes for use outside their industry.[7] Self-used invention did not easily lead to diversification into other products.

6 The Lowell companies were corporations, though closely held ones. Indeed, many nineteenth-century firms with large-scale production processes were corporations. Corporate status did indeed reduce risk, as did the long-term government contracts and financing that early private armories enjoyed. In the case of the Lowell firms, the owners were typically not also managers, so the firms have managerial features. Yet because their managerial structure lacks the complexity of the modern firm, they can be grouped with unincorporated owner-operated firms.

7 Firms outside Lowell were less integrated, but technical change similarly centered on managerial personnel, as Scranton's studies of Philadelphia area textile producers document [1983, 1989]. The distinctive organization of the Lowell firms is interesting because it illustrates how organizational and technological innovations are interrelated.

Second, technical change was closely linked to the growth of the firm. Locks and Canals needed a substantial investment to perfect its machinery and a substantial market to warrant this investment. Initial investments of hundreds of thousands of dollars made Lowell textile firms among the largest U.S. industrial enterprises. With these investments came high-profit rates and rapid growth [Zevin, 1971]. Yet their growth remained confined to textiles; there was little diversification outside. This is unsurprising in the rapid textile growth through the mid 1840s, when profits could be reinvested easily. But even after growth slowed, firms did not successfully expand to different products. Locks and Canals and other machine shops then tried to diversify into other machinery, including locomotives. But this diversification largely failed. The tight integration of textile production and invention did not give the textile machine firms advantages in other lines of business. Their advantage was in process changes in textile manufacture. They might increase the scale of the plant, seek geographically new markets or, like Philadelphia textile companies, concentrate on specialty products. But the jump in managerial size and complexity needed to effectively diversify was a great obstacle to firms still typically managed from a single room in a single factory.

Firearms innovation occurred through a similar route. The great revolution that led to interchangeable parts production was led by firearms firms, which developed whole lines of woodworking and metalworking machinery for their own usage. Managers played a similar role in developing production, though inside contractors, including Thomas Blanchard, were more important than they were in textiles. As in textiles, firearms innovation involved large markets, substantial investments, and a dynamic of production-based learning, though successful technologies did not always lead to firm growth. Finally, for the most part, firearm firms did not successfully diversify--or even try. This is not because their technology was too specific; the milling machine, turret lathe, and the concept of interchangeable parts mass production were among the most widely applicable technologies. Among the factors explaining their continued focus on firearms were the close ties between invention and production, firms' limited managerial knowledge of other goods, the unique early market in government contracts, and the narrow possibilities in mass production in antebellum America [Smith, 1977; Cooper, 1991].

Textile and firearms firms shared one additional characteristic. Until about 1850, they made most of their own machine tools. This trait was widespread; machine tools did not become a distinct industry until mid-century. Firms thus had to bring together knowledge of their own production processes, of the production of their machinery, and of the machine tools to make their machinery. From these examples, the limits of inventing for self-usage are evident. Self-usage requires that knowledge of technical problems and of their solutions be combined in one firm. This is relatively easy to attain for incremental improvements. It is much more challenging when the principles needed to solve a problem are not held by producers. As the case of mechanization shows, invention may be substantial scale requirements. Management must also organize production so that the needed skills are brought into and developed within the firm. When the firm is too small or the right kinds of knowledge are lacking, self-usage cannot readily generate new techniques. Yet other forms of technical change, relying more on the sharing of knowledge among firms, may succeed where self-usage fails.

B. Commodity Usage

New product development by capital goods firms was another means for firms to acquire knowledge needed to innovate. Capital goods firms did not have to consolidate all of the relevant knowledge within their firms; they could learn from firms that used their products. Such learning occurred when firms demonstrated, sold, and serviced products and trained users. This learning could lead to innovation to improve existing products or develop new ones. In contrast to self-usage, which occurs within the using firm, I call this form of innovation *commodity usage*.

In two industries critical to U.S. mechanization, textile machinery and machine tools, capital goods firms were born in the first half of the nineteeth-century. David Wilkinson, an early associate of Samuel Slater, began a job shop making textile machinery along with gearing and water works. His inventions included the first American lathe patent--a screw lathe with a slide rest--invented at about the time of Henry Maudslay's more famous British lathe. Boston Manufacturing, and later Locks and Canals, sold some textile machinery and licensed patent rights to independent firms, though until Locks and Canals became an independent company (renamed the Lowell Machine Shop), most of its output was used by other firms within the Lowell group. After about 1825, textile machinery firms in southern Massachusetts and Rhode Island were considerably more innovative than the Lowell firms, as evidenced most notably by their invention of the ring spinning process [Gibb, 1950]. By mid century, capital goods firms typically produced textile machines.

Specialized machine tool firms appeared in the 1840s. Their origin was quite different than that of textile machinery firms. Because machine tools are used to make all machines, machine tool firms were born out of many industries. Textiles, railroads, woodworking, and metalworking industries were all sources of these firms. The transition to independent machine tool firms was often protracted; Brown and Sharpe did not get most of its revenue from machine tools until the end of the century, a half-century after its formation. Many other firms combined the sale of machine tools with other machinery. Still, by mid-century, machinery use was wide enough that firms began to specialize in machine tools [Thomson, 1991b].

Penrose's analysis helps to explain the origin of capital goods in textile machinery and machine tools. For George Stigler, using the example of textiles, the birth of machinery firms was a vertical disintegration process in which firms specialized as the scale of production grew [1951]. Penrose's argument differs substantially. She argues that vertical disintegration arose from limits to growth experienced by existing firms, not from any technological or organizational trait that required new firm development instead of the formation of new divisions within existing firms. New firms form most readily when opportunities for profitable expansion exist that established firms cannot take up. Nineteenth-century firms, she argues, faced many growth opportunities that they could not utilize because of limits to obtaining finance or absorbing large numbers of new managers [1959,pp. 71-72n.].

Early nineteeth-century firms using textile machines or machine tools had substantial knowledge of these machines and of the products they made. They possessed resources and faced opportunities for innovation in each--in textiles and in textile machinery or in machine tools and the products they shaped. Limited financially or managerially, firms could not innovate in both. A few specialized in new capital goods, particularly those that made superior textile machines or machine tools. Most chose existing commodities, preferring to produce in known, usually thriving markets for textiles, firearms, or hardware and to purchase machinery from others. This strategy did not utilize firms' innovative resources, and workers holding these valuable but unused resources--often superintendents and foremen--often formed their own capital goods firms. The modest capital requirements of most machinery production eased this transition. In both textile machinery and machine tools, the superior products of capital goods firms were sold to firms that had made their own equipment, which then concentrated on their own products. For this reason, it was not rapid growth per se that occasioned vertical disintegration, but rather barriers preventing firms from growing rapidly enough to utilize the opportunities presented by market growth. Moreover, as capabilities grew, managerial authority was extended. Many early factory producers in textile machinery, firearms, and machine tools delegated managerial authority to inside contractors and later in the century replaced these contractors with foremen supported by personnel departments [Englander, 1987].

The new capital goods firms actively engaged in technological change. Innovation for commodity usage differed from self-usage in the incentives to learn. The firm was motivated by sales rather than cost-cutting. Correspondingly, this form had advantages when users were many and too small to conduct their own innovation. Moreover, commodity usage varied in the organization of learning. The firm could learn from sales efforts and from interactions with users of its product. This learning, dubbed learning by selling, was an important means to bridge the specialization of knowledge among firms.

As machines tools illustrate, the transition from self-usage to commodity usage had four effects on the communication of technological knowledge. First, knowledge of machine tool design and production became concentrated in machine tool firms. This knowledge was used by the firm itself and also by personnel who would later form their own firms. Second, machine tool firms spread knowledge of innovations through the sale of their product. Unlike self-users, which hid their innovations or made no efforts to spread them, machine tool firms engaged in sales efforts to spread their innovations widely. As sales grew, so did feedback about the limitations of machines. Compared to self-usage or even the licensing of patent rights, diffusion almost certainly quickened within industries using machine tools.[8] Third, machine tool producers sold their products to firms making machinery and equipment for many industries. They thus became centers of interindustry communication. Because similar problems developed in many industries (a phenomenon Nathan Rosenberg terms technological convergence [1976]), advances made for one industry could be applied to others through a learning-by-selling process. Fourth, machine tool firms learned from the product innovations of their competitors.

These changes in the social organization of knowledge were important factors in the acceleration of machine tool invention. Metalworking lathe patents in a sample of about 250 inventors grew from 1 per year in the 1830s and 40s to almost 7 in the 1850s, 19 in 1870, 50 in 1890, and 92 in 1910 [Thomson, 1991c]. The share of lathe patents by those who invented for machine tool firms grew from none before 1850, to half from 1870 through 1890, and to 72 percent in 1900 and 1910 [Thomson, 1991b]. The specialized knowledge of these firms gave them advantages in innovation and in knowledge of needed opportunities. And they learned from past invention. As a result, inventors for capital goods firms were more likely to continue inventing; the 78 sampled lathe inventors for these firms averaged 7.1 lathe patents, compared to 3.0 for the sampled self-users. Moreover, inventors for machine tool firms averaged 5 patents for other machine tools, while self-using inventors averaged less than 1 [Thomson, 1991c].

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8 Licensing combines features of self-usage and commodity usage. Like commodity usage, it spread techniques via sale and gave the owner of patent rights an incentive to make the invention widely known. Yet it did not typically involve training of users, nor did it guarantee the adequacy of production incorporating the invention. As Cooper shows for the case of Thomas Blanchard, licensing at times diffused a technique over many regions, but diffusion was often protracted and partial [1991]. Licensing often arose as an afterthought once self-usage had been achieved; as such it was not a motive for inventing. As Blanchard illustrates, licensing often complemented self-usage, spreading a technique beyond the market area served by production for self-usage. In some cases, such as the sewing machine, licensing was an early, limited form of diffusion that gave way to the organized sale of capital goods.

One of the outcomes of innovation was knowing how to innovate. This knowledge was concentrated among those in positions of authority, and invention was concentrated among the same individuals. One-half of the 155 lathe inventors for whom occupations could be determined were managers (including firm owners, superintendents, foremen, and contractors). Their average of 8.8 machine tool patents was twice that of nonmanagerial inventors.

Invention often aimed at problems that arose in the use of existing products. New firms commonly undertook invention for fundamentally different uses. For example, Charles Norton perfected light grinding machines for Brown and Sharpe before forming his own firm to develop heavy grinders to make automobiles and other heavy equipment. Inventors learned from each other. The most prolific firms had many inventors, led by Pratt and Whitney's 8 and Brown and Sharpe's 7. Unlike later R&D workers, these inventors were integrated with machine tool production and sale. But like R&D workers, their invention was planned, cooperative, and fostered the growth of their firms.

Output of capital goods firms grew not only because demand for the final product grew, but also because new capital goods displaced older models and were purchased by firms that formerly made their own equipment. Successful firms also developed markets in new areas. Textile machinery companies, for example, cultivated the market in the South after the Civil War and so spread textile production to new regions. Gross machinery sales and assets of the Lowell Machine Shop trended upward but decelerated as the century progressed [Gibb, 1950]. Brown and Sharpe averaged 29 machine tools shipped per year from 1865 through 1879, 112 in the 1880s, 329 in the 90s, and much larger numbers in the twentieth-century [McDougall, 1966]. Growth was also tied to attempts at diversification. Facing market limits, some firms diversified widely in the 1840s. The Lowell Machine Shop moved into such products as railroads, boilers, shafting, planing machines, papermaking machinery, and cotton gins. Interindustry diversification was a transitory and largely failing strategy; more specialized shops with better knowledge of relevant technology had strong advantages. Intraindustry diversification was more successful. In the same year that Penrose published *The Theory of the Growth of the Firm*, Alfred Chandler presented a paper at the Business History Conference in which he identified sequential kinds of diversification

[1990]. The first was diversification within an industry to develop a full line of machinery. The second was the development of multiple product lines in separate industries. The last was continuous product turnover. Nineteenth-century textile machinery firms often succeeded at the first. The Lowell Machine Shop came to equip whole textile factories. William Mass showed that George Draper & Sons diversified through a remarkable series of textile machine developments [1989a, 1989b]. It was a path that took Draper to and beyond the limits of the proprietary firm.

Similar intraindustry diversification occurred in machine tools. Pratt and Whitney printed large catalogs offering to equip whole plants with their specialized machine tools. They also diversified more widely into hammering and forging machines needed to make firearms and sewing machines. Others diversified into products of machine tools, such as screws, or into goods to complement specialized lathes, such as the railroad equipment sold by Niles-Bement-Pond. But the extent of diversification should not be exaggerated. Many machine tool firms such as the leading-edge firms around Cincinnati became more specialized over time, concentrating on specific types of machine tools.

The birth of a capital goods sector reduced the scope of production from that of self-users but added to the scale of machine output. The scale was not typically large, but it was large enough to effectively bring together knowledge needed to develop and diffuse new products and to diversify into a full line of machinery. While vertical disintegration reduced the scope of the firm, lateral integration into complementary machines increased scope. Though limited in size and complexity, proprietary firms sustained a process of ongoing technical change.

C. Districts, Lineages, and Communities

The role of the firm in technological change extends beyond its own innovative efforts. Firms also spread knowledge in ways that unintentionally fostered technical change by other firms. These externalities were a critical attribute of nineteeth-century technical change. They helped to shape industrial districts, lineages of firms, and inventive communities.

Industrial Districts

Proprietary firms often located in industrial districts within which they gained external economies derived from their better access to regional suppliers and labor markets. Penrose's ideas help to explain the formation of these districts. Proprietary firms developed technical, organizational, and marketing knowledge but faced managerial limits to growth that prevented them from seizing on opportunities to innovate. With their capabilities underutilized and perhaps underremunerated, firm personnel spread knowledge in two ways. First, some left the firm to set up their own firms. This increased the number of firms and spread the firm's knowledge. Knowledge of nearby suppliers, purchasers, and employers often kept these new firms within the region. Second, in a region with growing numbers of firms, some personnel formed capital goods firms. Their activities were complemented by specialization among suppliers. Both paths of knowledge diffusion limited firm-specific knowledge but reinforced district-specific knowledge. Such knowledge, in turn, became a further reason to locate within the region and for the region to grow relative to other regions.

The forces favoring regionalization operated in the textile industry. The mass-production firms around Lowell were more like a single firm than a district of complementary firms. But Philadelphia textile firms did form such a region. They benefitted from lower costs and higher skill levels. Perhaps more important, as Scranton has shown, they developed an ability to innovate by finding new specialty products and adapting their production to frequent product changes. This strategy ceded the standardized trade to mass production firms but retained a broad niche of batch production.[9]

9 This choice of strategy was ultimately limiting; when Southern textile producers (using textile machinery made in New England) entered their market in the twentieth century, Philadelphia firms lost market share, and many of their dominant practices were abandoned. This illustrates an important point: a strategy that succeeds in one period may lock an industrial district into an industrial structure that ultimately leads to decline. Lazonick interprets the decline of Britain in these terms [1993].

Michael Best interprets the antebellum firearms industry in similar terms [1990]. In this case, the federal government shaped an industrial district centered around the Springfield Armory. Like other districts, this one developed skilled labor and specialized suppliers that spread large-scale firearms production through the Connecticut River Valley. Federal policy explicitly called for interfirm cooperation. To enjoy the benefits of risk-reducing, long-term contracts and access to government finance, firearms firms were expected to share knowledge of techniques and organization of interchangeable parts mass production. This coordination established distinctive knowledge flows that greatly supported the development of mass production. It fostered the design, use, and diffusion of jigs, fixtures, and such mass-production machine tools as the milling machine and turret lathe. The government thus supported the development and diffusion of a new conception of production. By the time Samuel Colt built his Hartford armory in the 1850s, interchangeable parts metalworking was well advanced and available [Best, 1990; Smith, 1977].

Agglomeration economies in industrial districts fostered the knowledge flows so important for innovation. Firms in the same district in effect cooperated; each contributed skills and techniques that benefitted others. There may also be explicit cooperation without governmental inducement, such as the shared knowledge by British ironworking firms that Robert Allen documents. Best argues that explicit interfirm cooperation is critical to recent north Italian successes. Yet outside firearms and some cooperation around standard-setting, explicit cooperation does not appear to have been central to districts of proprietary capitalists. But even without such cooperation, the district was a meaningful unit. David Hounshell showed that interchangeable parts technology spread quickly to sewing machine production in Wheeler and Wilson's Bridgeport factory yet much more slowly to Singer's Elizabeth plant [1984]. The difference was not simply due to regional markets for machine tools; after 1864 Brown and Sharpe regularly sold more machine tools in the middle states than in New England, and sewing machine firms made most of their own machine tools. Wheeler and Wilson's location in a district of mass production metalworking brought it skills critical to its success.[10]

Lineages of Firms

Proprietary firms were training grounds for future firms. Skilled employees who identified innovative opportunities could set up their own firms or secure managerial positions in other firms. The offspring of established firms, new firms were common in industrial districts, but they also moved far outside the areas in which they were born. In effect, a family of such firms constituted an alternative to the managerial firm. The managerial limits to the growth of proprietary firms were in part compensated by the proliferation of related firms, including innovating firms spun off from parent firms.

Machine tools present a good example. Major companies such as Robbins and Lawrence, Colt, Brown and Sharpe, and Pratt and Whitney did more than develop new techniques. They also trained workers who would become prolific inventors elsewhere. For example, Robbins and Lawrence, located in Windsor, Vermont, fostered innovation in Providence metalworking (through Frederick Howe at Providence Tool and Brown and Sharpe), in Hartford firearms, sewing machine, and machine screw works (through Charles Billings and George Fairfield), in Bridgeport sewing machine production (through J. D. Alvord), in Philadelphia machine tools (through George Hubbard), and in Illinois railroads (through Frank Chase) [Roe, 1976; Hubbard, 1924].

The movement of trained personnel diffused techniques within and among industries. It connected not only inventions but industries. From firearms, Robbins and Lawrence employees left to produce firearms, sewing machines, shoe machinery, screws, railroads, and, of course, machine tools. Related families then extended these connections to clocks, bicycles, automobiles, and electrical industries.

10 In industrial districts, knowledge spread between industries more by the movement of labor, especially superintendents and contractors, than by the diversification of firms. Techniques in firearms converged with those of many other industies, but Remington failed in efforts to apply its firearms knowledge to sewing machines and agricultural implements. Only after reorganizing did it succeed in typewriters. Until the managerial firm, the spread of knowledge among industries was a byproduct of innovation and growth within industries.

Worker movement also spread forms of business organization and invention. Robbins and Lawrence invented largely for self-usage, a practice that many of its workers spread. Brown and Sharpe invented machine tools for sale, and its extensive lineage included mostly machine tool producers. Parent firms had a widespread legacy through the practice of their offspring.

Inventive Communities

Producers' social relations enmeshed them in communications networks that went well beyond the firms or districts in which they were employed. Many individuals were parts of groups whose interactions developed technological knowledge, groups I call *inventive communities* [Thomson, 1991a]. These groups operated at many levels. They functioned within firms, like the "technological community" of turbojet practitioners that Edward Constant investigated [1980, 1987]. They could connect firms in "technological systems," such as the electric light and power system that Thomas Hughes examined [1983, 1989]. These communities fit well with Penrose's knowledge-based analysis of the firm.

Inventive communities also fostered technological change across sectors. In a century when firms diversified little among industries, such inventive communities were particularly important sources of technological change. Four features of inventive communities help us understand intersectoral technological change. First, capital goods firms were central to inventive communities. Capital goods firms broadened the learning of their workers. Because they attempted to sell their products widely, they provided their workers--particularly those in managerial positions--with knowledge of the technical needs of other firms, how to find usage with capital goods firms, and how to establish such firms.

This led to greater inventiveness by these workers not only within but across industry lines. Thus, in a sample of 264 shoemaking patentees, those who gained use as capital goods had more patents than those with shoemaking self-usage (5.1 to 1.8), which indicates the importance of commodity usage for ongoing technical change. An inventive community extended beyond shoemaking, particularly for those with commodity usage. Their 5.5 nonshoemaking patents far exceeded the

0.7 for self-users. Inventors for capital goods firms used their knowledge of the practice of these firms to achieve far higher rates of usage and continued patenting for nonshoemaking patents [Thomson, 1993].

Lathe inventors present a somewhat different case. Sampled lathe inventors gaining usage with lathe firms had fewer patents outside machine tools than did those with self-used lathe patents (7.3 to 9.5). Inventors with self-used lathe patents concentrated their other inventions on related operations of their lathe-using firms. By contrast, inventors whose lathes were sold by machine tool firms were much more likely to invent in different sectors and gain usage with other firms, often firms that they helped to form [Thomson, 1991c].

A second important characteristic of inventive communities is locational. Geographical proximity to a variety of industries led to knowledge of and invention for these industries. This was true within localities. For example, 61 shoemaking inventors in towns dominated by shoemaking averaged 1.4 patents in other industries, whereas 35 shoemaking inventors in major cities had 7.3 other patents, over five times as many. Much the same was true of broader regions. Industrial districts were often centers of interindustry inventive movement. Within the Connecticut River valley, worker mobility from firearms to machine tools, sewing machines, and hardware exemplified this regional diffusion. An industrial region or district therefore might be better defined by a kind of technology (such as mass-production metalworking) than by a kind of product (such as firearms or shoes).

Third, certain industries and services were centers of technological communication. Inventive communities associated with these centers gave these industries and services an importance for technological change far out of proportion to their share of employment or output. The machinery sector was one such center. It was held together by similarities in machine design, common use of machine tools, and the employment of machinists. Design similarities meant that improvements of certain machines could be applied to others. Product markets put machine tool producers and inventors in touch with the technical problems of many industries. This is one reason why sampled metalworking lathe inventors patented so extensively outside machine tools. Their average of 6.3 patents outside machine tools exceeded the 5.2 patents that 112 woodworking lathe inventors averaged outside woodworking lathes or (in a somewhat narrower time period) the 5.0

nonshoemaking patents of shoemaking inventors.

Occupational groups associated with technological centers possessed and utilized knowledge needed to invent. Among woodworking lathe inventors, machinists took out four times as many patents other than woodworking lathes as did those from woodworking occupations. Likewise, machinists who received shoemaking patents took out almost four times as many nonshoemaking patents as inventor-shoemakers did.

Machinists could invent more widely because they were part of a communications network connecting those making and using inventions over much of the economy. Machinists were often trained in innovative firms, where they were able to invent and bring their inventions into use. They labored alongside others trained in a variety of machine shops with different practices. Their practice gave them knowledge of technical needs in other sectors and of how to gain usage for capital goods. Inventions were used by new firms, often formed by the inventor, or established firms improving their product or reducing costs. Altered production in turn improved machinists' training. Inventive communities and innovative firms went hand in hand.

Finally, the inventive community was connected by firms and other institutions specializing in technological change. Patent agents, draftsmen, modelbuilders, and patternmakers formed a national community united around the U. S. Patent Office, with an international extension to other patent offices. These occupations and businesses provided technical advice and spread knowledge around procedures for patent application, reissuance, and litigation [Cooper, 1993]. Journals such as *Scientific American* and *American Machinist* were important mechanisms for widely communicating technological and patenting knowledge. Scientific societies such as the Franklin Institute not only organized the flow of knowledge through seminars, demonstrations, and publications but were also instrumental in achieving such collective ends as the standardization of screw threads [Sinclair, 1974].

Inventive communities, lineages of firms, and industrial districts all diffused technical knowledge and invention, supporting later innovation in ways that could not be anticipated. The complex interactions of individuals with technological knowledge gave technical change a cumulative, economy-wide character. Firms undertook technological change that commonly fostered their growth and capability to innovate; Penrose focuses on this aspect. But the new knowledge also educated individuals who then applied it to other problems, in other industries, and through other firms. Such learning outside the firm goes beyond Penrose's framework. It involved interactions in occupations and inventive communities that had different purposes and organization than interactions within firms. It also involved convergence of knowledge between firms and sectors rather than the specificity of knowledge that Penrose emphasizes. Because technical change among proprietary firms was less associated with a single firm than is technical change among managerial firms, interfirm learning is central to innovation in proprietary capitalism.

The analysis of extrafirm learning must be seen to complement, not to replace, Penrose's understanding of the firm. Each considers the organization and development of institutionally embedded knowledge. Knowledge is always tied to institutions; it cannot be simply generic, disembedded, and costlessly available. The organization of occupations, districts, and inventive communities affects who will learn and what they will learn. Moreover, these institutions work in tandem with firms. The knowledge they transmit typically arises from firms. To make use of such knowledge, individuals must develop advances giving them advantages over others, which involves tacit knowledge and teamwork, though on a smaller scale than in the managerial firm. Finally, the dynamics of tacit knowledge and workteams gives birth to the managerial firm, with all its consequences for technological change.

III. The Managerial Firm and Nineteenth-Century Technical Change

The logic of technical change among proprietary firms does not fully encompass nineteeth-century technical change for the simple reason that managerial firms originating after 1850 also played an important innovative role. Managerial firms grew rapidly and were particularly important in industries with high output and productivity growth. They altered the process of knowledge acquisition and development common to procedures of proprietary firms. Sewing and shoe machinery demonstrate this evolution.

Sewing and shoe machinery originated in much the same way as other midnineteeth-century inventions. Small firms, formed by machinists, garmentmakers, and shoemakers, developed new techniques. Many firms, learning from each other and from prospective and actual users, perfected the techniques. All the elements of practical sewing machines had been invented by about 1854 and for shoe machines about a decade later. These were *technological* triumphs of proprietary firms [Thomson, 1989].

But *economic* triumph came with the managerial firm. Faced with a potential market of hundreds of clothing and shoe firms and (as sewing machine firms learned with time) enormous numbers of households, Singer, McKay, and other firms established company agency systems to overcome the limits of marketing by independent agents and patent licensing. Vertical integration into selling required companies to expand and train personnel. As sales grew, firms developed mass-production metalworking techniques, particularly for generic sewing machines then selling in the hundreds of thousands annually. Growth brought coordination problems that management solved by forming managerial hierarchies to organize production and marketing and to plan for future growth. Finally, in the last third of the century, sewing machine and shoe machine industries diversified within their respective industries [Thomson, 1989]. The crucial elements of Chandler's managerial firm were in place: mass production, mass marketing, and managerial organization [1990].

Various forms of this path were followed by many firms in the last third of the century. Not all firms successfully innovated in the face of limits to marketing or scale. Those that succeeded changed their growth trajectory. Singer and McKay learned how to establish branch plants and integrate them with the central office. This knowledge gave them an advantage over other firms, which they used to expand. In developing the rudiments of mass production, firms also learned how to develop mass production, which led them further along the mass-production trajectory. As they used their new capability, firms discovered that innovation increased their ability to innovate. They then cultivated this capacity, internalizing innovation, though not yet separating it from production and marketing.

Technological change in the managerial firm took a different direction from that of the proprietary firm. New techniques were still closely related to the products and production of the industry. But the managerial firm concentrated more on mass production techniques, some of which they developed for self-usage. For example, Westinghouse Air Brake, Singer, and McCormick Harvester each took out lathe patents. The firm no longer depended solely on the skilled work team; it began to rely on large numbers of specialized workers with sharper divisions between operatives and technical labor. Big firms also directed invention more toward intraindustry diversification, such as McKay's move from shoe-sewing to shoe-nailing, heeling, and lasting machines. For this, firms often had to develop complementary techniques for their own usage, including the nail-making machines that McKay invented to supply its shoe-nailers.

Managerial sewing and shoe machinery firms evolved along paths that Penrose would recognize. They quickly surpassed the size: of propriety machinery firms. Their expansion into national and international markets reflected important lines of the marketing advantages. The pace of their growth was constrained not only financially, but also by the ability to absorb new management. Thus they could not make use of all the opportunities they confronted. And the prospect of underutilized resources--profits, plant, marketing networks, and innovative skills--led these companies to diversify. Their resources directed them to other kinds of shoe and sewing machinery, a choice reinforced by competitive struggles to sell complete product lines. Firms also expanded through acquiring or merging with other firms; these combinations allowed them to enter new markets, pool patents and technological knowledge, and avoid technological competition. McKay was particularly active in these mergers. By 1900, firms had formed the self-conception of growth through ongoing innovation and resource acquisition.

The emerging structure of managerial firms helped to identify and achieve strategies of innovative growth, in which growth and innovation reinforced each other. Not only did marketing and production organizations sell and make products, they also communicated information that directed innovation. The plant supplied personnel who used their training in sales and servicing outlets. Sales offices relayed comments of product deficiencies and opportunities for new products to the plant, where invention continued to be undertaken, often by managers. The greater feedback led to more learning and invention. Thus, the 11.6 shoe manufacturing patents averaged by inventors from firms diversifying among shoe machinery was well above the 5.1 of single-product capital goods firms and still farther above the 1.8 patents of self-using inventors [Thomson, 1993].

Managerial firms, however, continued to depend on proprietary firms. Competition between them persisted, though this was often mitigated by market segmentation, such as that between makers of general-purpose and specialized industrial sewing machines. More importantly, the managerial firm relied on other companies to develop products that it acquired by merger. It also depended on other firms to train workers that it hired. Though they marketed outside principal industrial districts, managerial firms often still located in these districts; thus McKay was centered in Boston and Goodyear Shoe Sewing soon moved there from New York City.

The managerial firm also relied on complementary proprietary firms. Sewing and shoe machinery firms continued to learn from users of their products. They purchased inputs, including machinery. Successful machine tool firms reduced the need for managerial firms to develop their own machine tools and so allowed them to concentrate on problems in which they had advantages. Thus, during the heyday of expansion of shoe and sewing machine industries in the decade after the Civil War, Brown and Sharpe sold about 40 percent of its machine tool output to these industries [McDougall, 1966]. Machine tool firms sold to managerial firms in many industries. For example, in 1893 Jones and Lamson sold its first hundred Hartness turret lathes to firms making machinery for cotton, cable, woodworking, mining, agriculture, hydraulics, printing industries, and to other firms making steel, elevators, electrical equipment, locomotives, and machine tools [Broehl, 1959, p. 19]. Managerial firms were prominent among these buyers. The presence of vertically specialized firms in some sectors added to the growth of managerial firms in others.

The managerial firm not only depended on proprietary firms; it also influenced them. The competitive advantages that brought it growth also limited the growth of proprietary competitors. Its prowess in marketing and production and the associated capital costs were important barriers to proprietary firms. No longer was growth typically accomplished by multiplication of firms; both Singer and McKay dominated their markets and expanded into new ones. Moreover, managerial firms developed related new products; new firms no longer typically brought new products to maturity. New companies might succeed in new sectors, as did buttonhole sewing machine firms, but they often had to emulate the practices of larger firms to do so. And managerial firms integrated into other stages of production, such as Singer's integration into cabinetmaking [Hounshell,1984]. Because they marketed around the United States and beyond, they undercut one advantage of firms within industrial districts. For example, Singer had widespread agencies by 1860, and McKay opened branches outside the eastern Massachusetts shoe district as quickly as it did inside.

Technical change in 1900 thus involved both managerial and proprietary firms. Managerial firms dominated in some industries. In part, they benefitted from economies of size: scale advantages associated with mass production and distribution. As Penrose emphasizes, they also benefitted from economies of growth: their administrative organization overcame barriers to expansion and thus provided first-mover advantages that were seldom overcome. But they still relied on proprietary firms to supply inputs, generate techniques, and often purchase output. Managerial firms in turn accelerated technical change among proprietary firms making garments, shoes, and many other commodities. With the shift in the structure of the firm came an irreversible transformation in the way the economy organized and developed knowledge.

IV. Twentieth-Century Innovation in Historical Context

Nineteenth-century experience helps illuminate twentieth-century innovation. In important ways, technological change in the new century resulted increasingly from the firm's organized utilization of its own resources. Firms developed systematic processes of technical improvement. Research and development labs had little existence before 1900 but were common by 1950, particularly in technologically dynamic sectors. Industrial research was separated from production in a way that nineteeth-century innovation rarely was, which allowed labs to acquire information and explore problems that would not have arisen from the shop floor. Labs became centers for the development of new, often science-based techniques and for the identification of research targets [Mowery and Rosenberg, 1989].

Firms also successfully diversified outside their primary industries. Diversification into industries with similar production and marketing techniques sustained the expansion of many firms when growth in their initial industries slowed. Industrial research helped firms diversify, for research labs could provide techniques that gave firms advantages in new sectors. Diversification accomplished much of what the movement of new firms among industries had done in earlier periods. And because managerial firms became more important in industrial production, technological change was increasingly the outcome of innovation within the firm. The scope for innovative proprietary firms fell accordingly.

Still, when viewed from the nineteeth-century vantage point, it is clear that the managerial firm did not internalize all of the factors that had accounted for earlier technical change. First, even the internal workings of the firm depended on their interaction with outside factors. As Chandler's strategy and structure approach grasps, technical change undertaken by the managerial firm was embedded in social relations within and outside the firm [1962]. Strategy rested not only on the firm's internal resources but also on its conception of its niche, which resulted in part from its history of successes and failures and its relations to customers.

The firm's structure affected the types and potential success of its innovation. Though industrial research grew, technical change was also directed by the social organization of laboring, which allowed firms to learn from their shop floor workers. This factor goes some way to explain recent differences between U.S. and Japanese productivity growth [Lazonick, 1993; Best, 1990]. Industrial research also depended on factors outside the firm. The most productive research was undertaken in ongoing communication with the firm's customers. The linear conception of technical change--moving from invention to development to commercialization--should give way to a feedback view in which the firm changed the goals of its research when confronted with responses to its marketing efforts or innovation by others. The radio, for example, was only a wireless telephone until commercial broadcasting was invented [J. Smith, 1993]. Ongoing learning by using between producers and users of durable goods was a further source of productivity growth [Rosenberg, 1982]. Finally, the firm's technical change was affected by competition from other firms or--later in the United States than in many other countries--cooperation with other firms [Mowery and Rosenberg, 1989].

Second, like earlier technical change, the firm's innovation built on that of other firms. As Chandler has noted, managerial firms were better at developing and commercializing inventions than at conducting basic invention [1993]. There are, of course, examples of firms such as DuPont that succeeded at basic invention. But DuPont often profited from outside invention [Hounshell and Smith, 1988]. Given many opportunities for expansion, firms chose those closest to their competence, which minimized the risks of innovation. Managerial firms often specialized in building large systems of production and distribution, so they hesitated to invest in radical new technologies [Hughes, 1989]. To enter new fields, they often bought new firms [Shapiro, 1986] or acquired services from outside firms, such as chemical design firms, which helped bring flow production to the chemical industry [Landau and Rosenberg, 1992].

As Penrose suggests, here lay an opportunity for new firms. When research costs were not high, inventive labor could form firms to develop new technologies. Though industrial research workers were mostly employed by managerial firms, many small firms were research-intensive. For radical technologies not fitting into the niche of managerial firms, the new firm occasionally brought the product to commercialization. More commonly, innovators sold to companies that developed and commercialized the product. An informal division of labor between invention in small firms and development and sales in managerial firms sustained technical change.

Third, the labor market continued to bring the firm knowledge from other firms. While much of the worker's knowledge was tacit and had little use outside specific work teams, knowledge of techniques and how to develop them could be transmitted. Put in Richard Nelson's terms, firm-specific knowledge could not easily be transferred and integrated, but generic knowledge could be widely used [1993]. Managers as well as technical laborers held generic knowledge, and firms hired managers who knew how to sell large batches of complex goods or organize flow production. The movement of managers transmitted not only techniques but whole conceptions of production and of the firm.

Fourth, a firm was embedded in a sector of complementary firms. Its technical changes depended on problems and solutions that other firms developed. Systems of related firms--both managerial and proprietary--grew larger and more complex in the new century. For example, autos depended on oil firms to develop cracking processes. Auto firms also relied on machine tool firms such as Norton to develop mass-production heavy grinding, not to mention the innumerable machine shops that surrounded major auto centers [Hughes, 1989].

Not only did the new century maintain some established interfirm relations; it also formed new institutions that affected the firm's invention. Science-based R&D was associated with institutions that developed science; one cannot imagine modern technical change outside the university/government research establishment. Industrial research also depended on university education to supply generic knowledge that could never be gotten by experience on the job. Richard Nelson and Gavin Wright argue for the importance of this factor: "Though university-trained engineers, scientists, and managers were no more than a small percentage of those employed in American industry, here if anywhere is a specific institutional basis for American technological leadership" [1992, p. 1948].

The government played roles in directing technical change. Just as for firearms before the Civil War, the government's demand and relations with firms had powerful effects on technical change. Government policies about interfirm cooperation were important reasons for the different paths taken by the United States, Germany, and Japan [Chandler, 1990; Lazonick, 1991]. Government-sponsored research radically transformed the kinds, magnitude, and organization of research, with important long-run consequences.

The inventive community has also been reshaped. Industrial districts declined as production spread out across the country and world. The nexus around patent agencies probably declined in importance as firms formed their own legal staffs and research teams. But professional associations proliferated, and these played a powerful role in shaping the content and organization of technology inside and among countries.

Clearly, the managerial firm's technological change depended on its position in a broader institutional setting. However, this recognition does not undercut the autonomy of the firm. As Penrose argued, the firm mattered because its internal organization and goals did indeed influence technical change. Its firm-specific knowledge provided lead times that, when coupled with complementary investments and perhaps patent protection, allowed firms to appropriate sufficient shares of the benefits to warrant innovation. At the same time, the specificity of the firm was a source of variation that kept diverse techniques alive. This diversity supported later learning based on techniques that might otherwise have been threatened [Nelson, 1993].

To counterpose the firm's internal determinants of technical change to those of its environment should not obscure the more basic point. In an innovative economy, innovative firms are conditioned by their relation to other innovative firms. There is a paradox here. When compared to the nineteeth-century economy, it is probably true that technological change is both more internalized in the managerial firm *and* that knowledge is more universally shared throughout the economy. The firm's innovation supports both its growth and innovation by others. The persistence of this paradox is at the core of the ongoing technological change of managerial capitalism.

References

Allen, Robert C., "Collective Invention," *Journal of Economic Behavior and Organization*, 4 (March 1983), 1-24.

Best, Michael, *The New Competition: Institutions of Industrial Restructuring* (Cambridge, MA, 1990).

Broehl, Wayne, *Precision Valley: The Machine Tool Companies of Springfield, Vermont* (Englewood Cliffs, NJ, 1959).

Chandler, Alfred D., Jr., "Integration and Diversification as Business Strategies--An Historical Analysis," *Business and Economic History*, 19 (1990), 65-73 (paper presented at the 1959 Business History Conference).

Chandler, Alfred D., Jr., "Learning and Technological Change: The Perspective from Business History," in Ross Thomson, ed., *Learning and Technological Change* (London, 1993), 24-39.

Chandler, Alfred D., Jr., *Scale and Scope: The Dynamics of Industrial Capitalism* (Cambridge, MA, 1990).

Chandler, Alfred D., Jr., *Strategy and Structure: Chapters in the History of Industrial Enterprise* (Cambridge, MA, 1962).

Chandler, Alfred D., Jr., *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, MA, 1977).

Constant, Edward, *The Origins of the Turbojet Revolution* (Baltimore, 1980).

Constant, Edward, "The Social Locus of Technological Practice," in Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch, eds., *The Social Construction of Technological Systems* (Cambridge, MA, 1987).

Cooper, Carolyn C, "Nineteenth-Century American Patent Management as an Invisible College of Technology," in Ross Thomson, ed., *Learning and Technological Change* (London, 1993), 40-61.

Cooper, Carolyn C., *Shaping Invention: Thomas Blanchard's Machinery and Patent Management in Nineteenth-Century America* (New York, 1991).

David, Paul, *Technical Choice, Innovation, and Economic Growth* (Cambridge, ENG, 1975).

Eichner, Alfred S., *The Emergence of Oligopoly: Sugar Refining as a Case Study* (Baltimore, 1969).

Eichner, Alfred S., *The Megacorp and Oligopoly* (Cambridge, ENG, 1976).

Englander, Ernest J., "The Inside Contract System of Production and Organization: A Neglected Aspect of the History of the Firm," *Labor History*, 28 (Fall 1987), 429-46.

Gibb, George, *The Saco-Lowell Shops* (Cambridge, MA, 1950).

Hounshell, David A., *From the American System to Mass Production: 1800-1932* (Baltimore, 1984).

Hounshell, David A. and John Kenly Smith, Jr., *Science and Corporate Strategy: Du Pont R&D, 1902-1980* (New York, 1988).

Hubbard, Guy, "The Development of Machine Tools in New England," *American Machinist* vol. 60-61, parts 14-19 (1924).

Hughes, Thomas, *American Genesis: A Century of Invention and Technological Enthusiasm, 1870-1970* (New York, 1989).

Hughes, Thomas, *Networks of Power: Electrification in Western Society, 1880-1930* (Baltimore, 1983).

Landau, Ralph and Rosenberg, Nathan,"Successful Commercialization in the Chemical Process Industries," in *Technology and the Wealth of Nations* (Palo Alto, 1992).

Lazonick, William, *Business Organization and the Myth of the Market Economy* (Cambridge, ENG, 1991).

Lazonick, William, "Learning and the Dyanamics of International Competitive Advantage," in Ross Thomson, ed., *Learning and Technological Change* (London, 1993), 172-97.

Lazonick, William and Thomas Brush, The 'Horndal Effect' in Early U.S. Manufacturing," *Explorations in Economic History*, 22 (1985), 53-96.

McDougall, Duncan, "Machine Tool Output, 1861-1910," in *Output, Employment and Productivity in the United States after 1800* (New York, 1966).

Marris, Robin, *The Economic Theory of "Managerial" Capitalism* (New York, 1964).

Mass, William, "Developing and Utilizing Technological Leadership: Industrial Research, Vertical Integration, and Business Strategy at the Draper Company, 1860-1930," *Business and Economic History* (1989a), 129-139.

Mass, William, "Sustaining Technological Leadership: Innovation, Standardization, and Flexibility in Weaving Technologies, 1890-1980" (1989b).

Miller, William, review of *The Theory of the Growth of the Firm*, *Business History Review*, 34 (Winter 1960), 508-9.

Moss, Scott J., *An Economic Theory of Business Strategy* (New York, 1981).

Mowery, David C. and Nathan Rosenberg, *Technology and the Pursuit of Economic Growth* (Cambridge, ENG, 1989).

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

Nelson, Richard R. and Gavid Wright, "The Rise and Fall of American Technological Leadership: The Postwar Era in Historical Perspective," *Journal of Economic Literature*, 30 (December 1992), 1931-1964.

Penrose, Edith, "The Growth of the Firm—A Case Study: The Hercules Powder Company," *Business History Review*, 34 (Spring 1960), 1-23.

Penrose, Edith, *The Theory of the Growth of the Firm* (White Plains, New York, 1959)

Roe, Joseph W., *English and American Tool Builders* (New Haven, 1916).

Rosenberg, Nathan, *Inside the Black Box* (Cambridge, ENG, 1982).

Rosenberg, Nathan, *Perspectives on Technology* (Cambridge, ENG, 1976).

Schumpeter, Joseph, *The Theory of Economic Development* (New York 1961).

Scranton, Philip, *Figured Tapestry: Production, Markets, and Power in Philadelphia Textiles, 1885-1941* (Cambridge, MA, 1989).

Scranton, Philip, *Proprietary Capitalism* (Cambridge, MA., 1983).

Scranton, Philip, "Small Business, Family Firms, and Batch Production: Three Axes for Development in American Business History," *Business and Economic History*, (1991), 99-106.

Shapiro, Nina, "Innovation, New Industries, and New Firms," *Eastern Economic Journal* (January-March, 1986), 27-43.

Sinclair, Bruce, *Philadelphia's Philosopher Mechanics: A History of the Franklin Institute, 1824-1865* (Baltimore, 1974).

Smith, John K., "Thinking about Technological Change: Linear and Evolutionary Models," in Ross Thomson, ed., *Learning and Technological Change* (London, 1993), 65-79.

Smith, Merritt R., *Harpers Ferry Armory and the New Technology* (Ithaca, 1977).

Sokoloff, Kenneth, "Was the Transition from the Artisanal Shop to the Nonmechanized Factory Associated with Gains in Efficiency?" *Explorations in Economic History*, 21 (Octber 1984), 351-82.

Stigler, George, "The Division of Labor is Limited by the Extent of the Market," *Journal of Political Economy*, (June 1951), 185-193.

Teece, David, "Towards an Economic Theory of the Multiproduct Firm," *Journal of Economic Behavior and Organization*, 3 (March 1982), 39-63.

Thomson, Ross, "Crossover Inventors and Technological Linkages: American Shoemaking and the Broader Economy, 1848-1901" *Technology and Culture*, (October, 1991a).

Thomson, Ross, "Economic Forms of Technological Change," in Ross Thomson, *Learning and Technological Change* (London, 1993), 80-99.

Thomson, Ross, "Firms and U.S. Lathe Development, 1790-1919." (1991b).

Thomson, Ross, "Invention, Markets, and the Scope of the Firm: The Nineteenth Century U. S. Shoe Machinery Industry," *Business and Economic History,* 18 (1989a), 140-49.

Thomson, Ross, "Machine Tools as a Technological Center" (1991c).

Thomson, Ross, *The Path to Mechanized Shoe Production in the United States* (Chapel Hill, 1989b).

Thomson, Ross, "Technological Change as New Product Development," *Social Concept*, (June 1986), 3-26.

Uzawa, Hirofumi "Time Preference and the Penrose Effect in a Two-class Model of Economic Growth," *Journal of Political Economy,* 77 (July-August 1969), 628-52.

Wagoner, Harless, *The U.S. Machine Tool Industry from 1900 to 1950* (Cambridge, MA, 1966).

Williamson, Oliver E., *The Economic Institutions of Capitalism* (New York, 1985).

Williamson, Oliver E., *Markets and Hierarchies: Analysis and Antitrust Implications* (New York, 1975).

Zevin, Robert. "The Growth of Cotton Textile Production after 1815," in Robert Fogel and Stanley Engerman, eds., *The Reinterpretation of American Economic History* (New York, 1971).