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8 Can a Nation Learn? American Technology as a Network Phenomenon

Gavin Wright

What is the relationship between the performance of business firms and the growth of the national economy? Economists who study economic growth commonly treat nations themselves as the performing units that save, invest, and experience technological change. But business historians following the lead of Alfred Chandler often imply that the record of the national economy is not much more than the aggregation of the successes and failures of its major corporations. To quote Chandler (1994, 57): "First, and most important, the United States is not going the way of the United Kingdom in terms of long-term competitive strength. . . . Today American companies remain powerful competitors in the most dynamic and transforming industries of the late twentieth century."

To resolve this dichotomy, we have to ask who does the learning that constitutes technological progress for the economy, and how that knowledge is accumulated and implemented over time. With specific reference to the American surge into world economic leadership in the decades bracketing the turn of the twentieth century, this paper advances two propositions: First, that technological progress was a network phenomenon, growing out of the actions of large numbers of interacting people—not necessarily in formally structured institutions of coordination. Second, that these networks were strongly national in character. An implication is that American industrial firms were able to institutionalize research and development systems after 1900, in large part because

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they could draw upon, extend, and channel the energies of previously existing technological networks. In a real sense the learning was national.

The term "network" has many valid meanings in economics. It may refer to a physically connected infrastructural system, such as railroads or pipelines, or by extension to an established pattern of interfirm supply relationships. As used by sociologists, "networks" are extrafirm linkages among business leaders, based on common social backgrounds and political interests over extended periods (Granovetter 1995). The usage here is broader and perhaps less precise, a technological learning network composed of people who are not necessarily acquainted with each other personally, but who share a common technical language and problem-solving environment—an "invisible college" in the language of the history of science (Price 1963, 85). The premise is that technology is not simply a body of abstract information, but is inherently social, embedded in terminology, in procedures, in physical equipment, and in products.

The point of this conceptualization is to try to draw insights from the analogy to interdependent physical systems, in which technological choices are affected by "network externalities." Most technological progress entails network externalities in that it builds upon an installed base of existing technology and improves some aspect of that base incrementally. Processes of this sort are subject to increasing returns to scale, multiple equilibria, and path dependence, in that historical events may have lasting effects on future developments.[1] Technological spillovers at the local or regional level have been conceptually familiar since Marshall (1920), and confirmed empirically with modern data (Jaffe, Trajtenberg, and Henderson 1993). This paper goes further, and argues that major historical spillovers were national. Although it would hardly be appropriate to say that the American economy became "locked in" at an early point to particular techniques of production, the paper contends that certain features of the process of technological change were distinctively national, and persisted across the vast organizational and scientific space dividing the nineteenth and twentieth centuries.

The paper begins by establishing that American economic growth in the nineteenth century did entail learning, and that this learning was substantially a national network phenomenon. The first of these assertions may seem trivially obvious, but it requires special attention here because of the practice now entrenched among economists of equating "learning" with changes in "total factor productivity," also known as the "residual." As will be argued, collective national learning may reside just as much in the discovery, expansion, and accumulation of the factors of production as in their productivity. Following the lead of Abramovitz and David (1973, 432), "Our point is that there may be *more* to technological change than the residual can capture, rather than less" (italics added).

1. The recent economic history literature on these topics begins with David (1985) and Arthur (1989). A theoretical review may be found in Katz and Shapiro (1994).

Pursuing this theme, subsequent sections focus, not on the rationality of technological choices (a preoccupation of much of the New Economic History), but on its network character. The venerable example of ring versus mule spinning in cotton textile technology is used as an example. The argument is then applied to minerals, building on evidence that the United States was far ahead of the rest of the world in resource development, and that these sectors drew increasingly upon advanced forms of knowledge and expertise. The following section identifies elements of continuity between these nineteenth-century patterns and the organized science-based industrial research technologies that arose after 1900. A salient feature of both regimes was the persistence of collective learning beyond the boundaries of sponsoring firms. A concluding section speculates on the implications of modern research institutions for national learning networks.

8.1 Dimensions of American Economic Performance

On one reading of American economic history, there is nothing to be explained. According to Angus Maddison's figures, the United States overtook the United Kingdom in gross domestic product per capita or per work hour around 1890, and moved into a position of world leadership for the subsequent century. But perhaps these events were only a reflection of favorable natural conditions and the rapid growth of factors of production, as opposed to technological progress. The historian Paul Kennedy (1987, 242–43) has written:

> With the Civil War over, the United States was able to exploit [its] many advantages—rich agricultural land, vast raw materials, and the marvelously convenient evolution of modern technology (railways, the steam engine, mining equipment) to develop such resources; the lack of social and geographic constraints; the absence of significant foreign dangers; the flow of foreign and, increasingly, domestic capital—to transform itself at a stunning pace. . . . Indeed, given the advantages listed above, there was a virtual inevitability to the whole process. That is to say, only persistent human ineptitude, or near-constant civil war, or a climatic disaster could have checked this expansion—or deterred the millions of immigrants who flowed across the Atlantic to get their share of the pot of gold and to swell the productive labor force.

Economists might find confirmation of this account in standard macroeconomic data, at least if they have become habituated to dividing growth into parts attributable to "expansion of inputs" on the one hand, and "technological progress" on the other. Not only did the United States enjoy a rapid increase in the size of its territory and population, but between 1890 and 1910 its rate of gross nonresidential capital formation was the highest in the world, culminating a century-long increase (Maddison 1991, 41). In this view, only in the twentieth century did the country experience knowledge-based economic growth—perhaps generated by the newly organized research efforts of modern

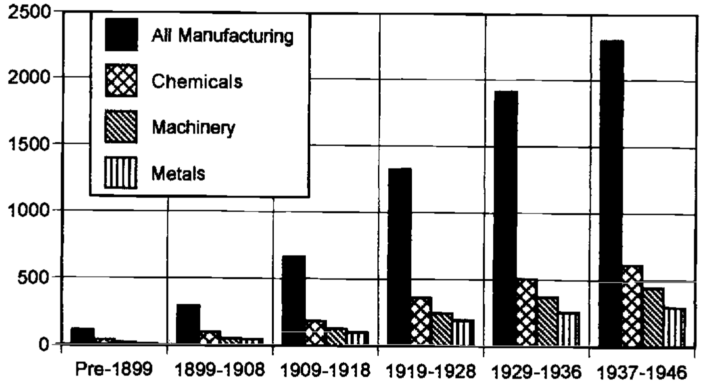

Fig. 8.1 Cumulative laboratory foundations in U.S. manufacturing
Source: Mowery and Rosenberg (1989, table 4.1).

business enterprises (fig. 8.1). By international standards, however, American leadership in science was long delayed. As late as 1940, the United States ranked a poor fourth to the United Kingdom, Germany, and France as a cumulative winner of Nobel Prizes in physics and chemistry (fig. 8.2).

To press this view further, Steven Broadberry's new estimates of productivity in manufacturing show that the United States maintained roughly a 2:1 lead over Britain and Germany in this sector as early as 1869, perhaps as far back as 1840 or even earlier (Broadberry 1993, 1994a, 1994b). The rise of the United States in world rankings could not therefore have come from an acceleration of relative productivity growth in manufacturing, despite the emphasis on that sector in much of the literature. Broadberry concludes that U.S. leadership must have originated elsewhere in the economy, and that high relative labor productivity in manufacturing was simply a feature of the environment. The difference between the United States and other leading countries, he suggests, "must surely be due to natural resources" (1994a, 536). Indeed, the United States was the world's largest producer of nearly every one of the major industrial minerals of that era, and Wright (1990) shows that the coefficient of relative resource intensity in American manufacturing exports was actually *increasing* across the period of ascendancy to economic leadership, from 1879 to 1928.

To accept these facts as indications that nineteenth-century American growth involved "no technological progress" or "no learning" would be unwarranted, a triumph of conventional methodology over history and common sense. The rapid expansion of the factors of production was not exogenous to the flow of American history, no more so than the "marvelously convenient evolution of technology." After showing that crude total factor productivity accounts for only about 10 percent of U.S. economic growth in the nineteenth

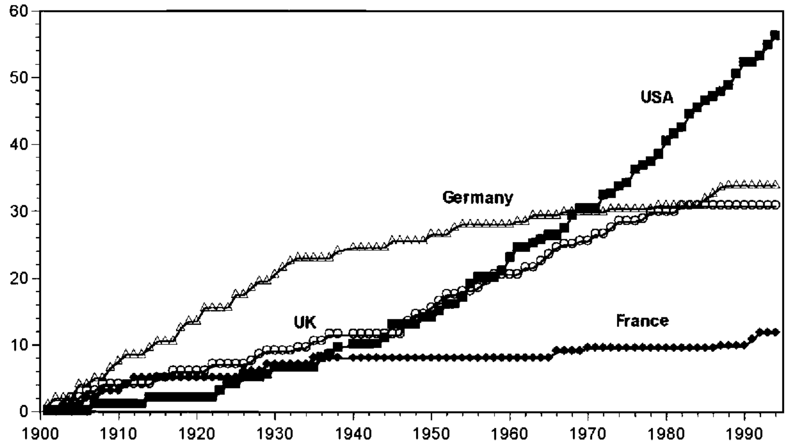

Fig. 8.2 Cumulative Nobel Prizes in physics and chemistry, 1901–94
Source: Nobel Foundation Directory (1995–96).

century, Abramovitz and David (1973) go on to argue that the stimulus to new investments was continually renewed by biased, capital-using, and scale-dependent technological change. Similarly, Olmstead and Rhode (1993) emphasize that the territorial expansion of American agriculture was not simply a replication of existing techniques on additional acreage, but was a vast learning experience in biological adaptation. And as will be argued below, world leadership in mineral production was not primarily the result of a fortunate geological endowment, but represented a return to advances in exploration, training, and the technologies of extraction, refining, and utilization. Only in retrospect was the national ascendancy a "virtual inevitability": clearly many people were gaining new and useful knowledge in nineteenth-century America.

In a sense this view is implicit in the literature on the "American system of manufactures," arising from the interpretive treatments of Habakkuk (1962) and Temin (1966). British engineers visiting the United States in the 1850s were struck by certain novel American technologies in small-arms manufacture and other industries, and economic historians have subsequently struggled to translate these observations into recognizable economic categories. Without attempting to summarize this entire discussion, we may say that one of its results has been a list of identifiable traits that differentiated American from British manufacturing practice. Some examples include

1. Greater use of natural resources relative to both capital and labor (David 1974). Particularly in the early years, American machines and products tended to be made of wood, which was relatively cheap, and the United States became a leader in woodworking (Rosenberg [1981] 1995).

2. The use of special-purpose machinery, allowing long production runs of

standardized commodities (Ames and Rosenberg 1968; Hounshell 1984, chap. 1). These products were adapted to American tastes and to the relatively equal distribution of income.

3. American manufacturing firms operated *faster* than their European counterparts, from machine speeds to the intensity of the work pace (Field 1983; Clark 1987). The intense use of the capital stock was a forerunner of the "high-throughput" systems perfected by large corporate enterprises around the turn of the twentieth century (Chandler 1977).

4. American technology did not necessarily substitute capital for "labor" generally, but deployed machinery to substitute unskilled labor for skilled craft labor (Harley 1974). Early American factories relied heavily on women and child labor, and subsequently on immigrants (Goldin and Sokoloff 1982; Sokoloff 1984). High labor mobility and frequent turnover were the norm, to which mechanization was an adaptation.

Putting these attributes together, and eschewing the fruitless effort to select one of them as the "single bullet" driving all of the others, what mattered most was the emergence in the nineteenth century of an indigenous American technical community, pursuing a learning trajectory to adapt European technologies to the American setting (cf. David 1974, chap. 1; Broadberry 1994b).

Hounshell (1984) throws much cold water on the notion of a continuous American technological thread joining Eli Whitney to Henry Ford, but his book presents numerous examples of individual mechanics who moved repeatedly from one industry to another during their careers, applying a common set of skills and principles to a diverse set of challenges. A notable case is Henry Leland, founder of the Cadillac Motor Car Company, who began in 1863 as an apprentice to a loom builder in Worcester, Massachusetts, moving on to Samuel Colt's armory in Hartford, and then to the sewing-machine section at Browne and Sharpe (p. 81). Through these years of employment, Leland gained a generalized mastery of the cutting-edge machine technologies of that day, to which he in turn contributed. As Rosenberg (1963) has argued, the high mobility of individuals among firms as well as regions, and the flexibility of machinery firms in adapting their skills to new industrial users, constituted a powerful mechanism for diffusing new paradigms throughout the economy. Even for a newer and more science-based technology like the telegraph, Israel (1992) shows that improvements grew largely out of a "shop culture" of practical experience, and many practitioners moved from the operating room into the manufacture of equipment. Other telegraph operators moved on to inventive careers in still newer industries like the telephone and electrical machinery, of whom Thomas Edison was only the most famous.

In a similar spirit, Thomson (1989) recounts the path from the sewing machine to mechanized shoe production at the end of the nineteenth century, tracing the lines of personal and technological linkage in minute detail. Thomson places particular emphasis on the spread of knowledge through networks of trade, or "learning by selling." During the early period of craft production, many improvements originated for the simple motive of self-usage. But the inventions that spread and were refined into an advanced state were those that entered into commodity exchange, greatly widening the circle of diffusion and feedback. Thomson shows that the impetus for technological change in shoe manufactures often came from outside the industry, through the efforts of "cross-over" inventors who saw an opportunity to apply their expertise in a new setting (pp. 185, 203). He concludes: "Established and potential inventors were integrated in a communications network that tied the diffusion and improvement of some machines to the birth and introduction of others. . . . New machines came to sustain their own learning processes, pulled inventors in to improve them, but at the same time generated inventors oriented to other new operations. . . . By the time Goodyear developed its system of machines, it could call on well-established solutions and professional inventors" (pp. 211–12).

8.2 Technological Independence in Cotton Textiles

These generalizations may be illustrated by the case of cotton textiles, the largest early manufacturing industry in both the United States and Britain. Aided by a protective tariff, the New England industry grew rapidly during the 1820s and 1830s on the basis of some famous innovations: the power loom (originally a British invention, but perfected in the United States); integration of spinning and weaving; and the dormitory or Lowell-Waltham system, under which young unmarried women were recruited to work for a few years prior to marriage—an institutional adaptation to labor scarcity. Although the dormitory system disappeared with the advent of mass immigration in the 1840s, in major respects the industry was set on its course of development for the next century.

American and British textiles technologies evolved very differently.[2] In cotton spinning, the two major technological alternatives were the ring and the mule. The mule was a British specialty dating from the eighteenth century, embodying the principle of intermittent spinning: the spindle travels on its carriage while drawing out and spinning the yarn, and then returns to its original position while the yarn is wound. The ring, descended from Arkwright's water frame, was a continuous spinning machine, effecting both spinning and weaving simultaneously. Continuous spinning simplified the machine-tending job, but put extra strain on the cotton fibers and produced a coarser yarn. Over more than one hundred years, the pace of development of these two competing strategies was uneven. The mule was in the ascendancy from the 1830s, following the introduction of the more highly mechanized self-actor. But the self-acting mule never became dominant in the United States, because of ongoing improvements in ring spinning, which increased the operating speed to 5,500

2. This section draws upon Saxonhouse and Wright (1984). The best technical account of the evolution of spinning technology is Catling (1970).

Table 8.1 Ring and Mule Spindles in Place, 1907–8

	Total Spindles in Place	% Mule	% Ring
United Kingdom	43,154,713	83.6	16.4
United States	23,200,000	17.7	82.3
Germany	9,191,540	55.8	44.2
Russia	7,562,478	50.2	49.8
France	6,609,105	60.0	40.0

Sources: Copeland 1909–10; International Federation of Master Cotton Spinners' and Manufacturers' Associations 1908.

rpm in the 1850s, to 7,500 rpm by the 1870s (the Sawyer spindle), and to 10,000 rpm by 1880 (the Rabbeth spindle). By the 1870s, American mule spinning was on a path to extinction, and by 1907–8 the United States and United Kingdom were at opposite ends of the international spectrum in their commitments to their favored spinning technology (table 8.1).

How can we explain this divergence? Although critics of the British have portrayed their love for the mule as an example of technological backwardness, scholars such as Sandberg (1974) and Lazonick (1981) suggest that the choices of technology were well-suited to initial conditions in the respective countries. Mule spinning was a skilled male occupation, while ring spinning was a machine-tending job that could be performed by girls and young women. Continuous spinning was less flexible, placing more stress on the cotton fibers; hence it was better suited for longer-staple cottons used in long production runs of standardized yarns and cloth. The mule was better adapted to variations in cottons and yarn counts, and thus allowed Lancashire to take advantage of its proximity to the world's largest cotton market in Liverpool, and to produce for diverse markets all over the world. Thus, the original divergence had a reasonably clear economic logic.[3]

For present purposes, the important point is that this logic of divergence became more compelling over time, because of positive feedback from the initial choice of technique to patterns of factor expansion and learning. The British began with a skilled labor force, and extended this "factor endowment" by training new mule spinners, through an informally organized program comprising "migration" (moving from machine to machine, or factory to factory), "following-up" (attaching a young worker to an experienced worker), and "picking up" (an even less formalized mode of learning by observing).[4] The

3. Sandberg's analysis is complementary to that of Harley (1974), stressing the relative scarcity of skilled labor in the United States. Lazonick's interpretation is more institutional, emphasizing both craft unions and vertical specialization between spinning and weaving as factors favoring the mule. Temin (1988) notes the role of the early U.S. tariff structure in channeling production toward the low-quality end of the product spectrum, and hence toward vertical integration and ring spinning.

4. See the account in More (1980, 107–30) and the estimated wage structure in Boot (1995).

American industry began with an unskilled labor force and replaced it many times over with new generations of immigrants. The dexterity and stamina of the factory workforce undoubtedly improved over time, but the primary locus of improvement was in the machinery, which soon came to be produced by specialized firms. These textile-machinery producers continued to improve the performance of ring-spinning machinery through cumulative incremental advance, moving on to the perfection of automatic weaving by the 1880s. Technology coevolved with the structure and labor force of the U.S. industry, including its southward migration as of the late nineteenth century.

Thus the two leading national textile industries came into the twentieth century with sharply contrasting systems. In each country, industry experts believed that theirs was the superior choice. Yet both industries were successful, the two largest in the world before World War I.[5] The "national" character of these choices pertained not just to the identity of the technicians, but to their coevolutionary interaction with domestic textile firms, the primary users.

American textile-machinery manufacturing had important technological linkages to many other branches of the machine-tools industry. As early as the 1830s, machine shops that were initially attached to textile factories began to diversify their product lines into steam engines, turbines, locomotives, and other machine tools. Through a process that Rosenberg (1963) calls "technological convergence," a common body of metalworking and mechanical knowledge came to be applied to a diverse range of industries. In contrast to the bifurcation across national boundaries, a tendency toward standardization within the country was observed very early, promoted both by long-distance sales of specialty firms and by the high geographic mobility of nineteenth-century mechanics. Leading machine-tool firms like the Matteawan Manufacturing Company of Beacon, New York, trained several generations of expert machinists only to find that these "alumni" left to take management positions or to found their own firms in new locations. A study of the careers of ten leading machinists found that they had worked for an average of 5.5 employers in 4.2 industrial centers (Lozier 1986, 33, 202).

8.3 Conceptual Issues

The existence of an American technological network in the nineteenth century seems well established. But what forces or institutions held it together? Why and in what sense was it national? For many years economics has grappled with the question, why does any private operator invest in the generation of new knowledge? To be sure, these investments are productive. But as

5. The ironic implication of recent research is that, despite its technological sophistication and leadership in productivity, the U.S. textile industry itself may never have achieved true international competitiveness. For evidence that most of the antebellum industry required tariff protection for survival, see Harley (1992). Yet this industry generated innovations that ultimately set the standard for the world!

formulated most clearly by Arrow (1962), investments in knowledge differ in two fundamental ways from conventional investments: they are subject to severe uncertainty, and even if successful, the discoverer may not be able to appropriate the resulting returns. The textbook conclusion is that market economies will tend to underinvest in knowledge generation.

In grappling with these issues, one must distinguish between "basic" technology on the one hand—pure ideas or information about scientific principles—and applied, or practical technologies on the other, which typically combine abstract ideas with a large component of "know-how," or experience-based knowledge. Uncertainty and appropriability are problems in both cases, but the institutions identified as mitigators of these problems tend to operate most effectively at the applied end of the spectrum: patents or other forms of intellectual property rights; cooperative or nonprofit research institutions; government procurement policy; private market power, existing or potential, which offers the promise of sufficient "first-mover advantages" to reward the investments; large, diversified research portfolios that protect against concentrated risk. Industries with long track records of successful research and development programs are those that have "solved" the uncertainty and appropriability problems through some combination of institutional arrangements like these. For example, Teece (1992) argues that firms investing in new technologies seek to embed their new knowledge deeply in product design, marketing, specific assets, personnel systems, and so forth, to make them as firm-specific as possible.

Yet this list of possibilities seems inadequate to account for nineteenth-century America's enthusiasm for new technologies. The search for patents was sometimes crucial, but many innovations were not patentable, and many patents were difficult to enforce or were subject to protracted and costly litigation. Government demand was important in a few areas like firearms. But neither the size of government nor the size and national market power of the largest private companies were anywhere near what they became in the twentieth century. Where else can we turn?

An article by Robert Allen (1983) considered this question and proposed a mechanism that he called "collective invention." Allen noted the steady incremental progress in the iron and steel industries of England and the United States, along such dimensions as the height of furnaces, the level of blast temperature, and the spread of fast driving. These improvements were not generally patentable, yet the firms involved disseminated all the relevant facts about their latest operating results, and this information in turn became the basis for further improvements elsewhere. The question is why. Allen suggests four possible mechanisms.

1. Owners and managers may have had professional ambitions that would be advanced by publishing information about their firm's operation and performance.

2. Where construction entailed participation by suppliers, contractors, and

consulting engineers, it may have been more difficult to maintain secrecy than to release the information.

3. Releasing information may actually have been profitable, if the firm had a stake in asset values that would be enhanced by dissemination (such as the value of regional mines).

4. Firms may have been party to norms of reciprocity, explicit or implicit, whereby divulging information gave them access to similar information from the other firms in the group.

These mechanisms have many plausible applications to nineteenth-century America. The role of professional ambitions became increasingly important as the century progressed, with the formation of engineering societies and growing interactions between business and universities. But long before "professionalization," skilled mechanics and machinists openly published detailed specifications of their machinery as a form of self-advertising.[6] Hoke (1990, 252) notes the pattern of hiring experienced watchmaking mechanics from established firms, as a mode of spreading a technology lodged in a "subculture of watch factory mechanics." These effects were intensified by the rise of specialized firms and individuals committed to "invention" as their primary occupation (Thomson 1993, 88–93). Whereas a chef with a recipe has reason to keep it secret, a machinery maker with command of a "general purpose technology" has every reason to spread the news and expand the range of its potential customers. Misa (1995) identifies producer-user interaction as the core element in the evolution of a distinctive American steel technology, taking up such examples as railroads, skyscrapers, factories, and automobiles.

A collective interest in property values could also serve as the basis for public or quasi-public support for investments in knowledge. Land-rich Stephen Van Rensselaer sponsored one of the first geological surveys in America in the New York county that bears his name, for obvious economic reasons (Hendrickson 1961, 358). By 1860, twenty-nine of thirty-three state governments had followed his example. The funding of state geological surveys was the leading form of direct aid that state governments provided for science in the antebellum era. In their dual role as landowners and suppliers of transportation services, American railroads also sponsored geological surveys and metallurgical research (Mowery and Rosenberg 1989, 38).

But behind these mechanisms and others that one might cite was an overarching factor serving to enhance their efficacy, namely the *scale* of the national economy. The importance of scale in the incentive structure for innovation is a major implication of models from the new or endogenous growth theory, pioneered by Paul Romer (1986, 1990). We may not be able to identify with precision the microlevel basis for positive returns to new knowledge, but

6. For specific examples, see Calvert (1967, 7). Calvert also notes the popularity of the sections in early mechanical-engineering periodicals called "shop kinks" or "shop hints," in which ideas and techniques developed in one shop were broadcast for all interested parties to share.

as Romer (1996, 204) argues, "a nonrival idea can be copied and communicated, so its value increases in proportion to the size of the market in which it can be used. . . . If people can sometimes establish property rights over a nonrival good like an operating system or a recipe . . . differences in scale will change the rewards for producing new ideas." Many of the mechanisms discussed above are scale economies at the industry or national level. Only an economy of sufficient size could support specialized machine-tools firms, inventors, and professional associations. The size of the national economy clearly differentiated the United States from other resource-abundant countries of recent settlement, such as Argentina, Australia, and Canada; and by the mid-nineteenth century, extensive growth was rapidly pushing the United States into a unique total-national-income size bracket.

But scale is a tricky economic concept. Mere bigness counts for little if the regions of the country are not integrated economically; other things equal, longer distances actually reduce the size of the relevant market. Sokoloff (1988) finds that inventive activity as measured by patents tended to concentrate in locations where cheap transportation offered access to larger markets. But even if the costs of distance are reduced by investment in transportation and communication, national "market size" would not be effective as an incentive to innovators unless the country were reasonably homogeneous in its patterns of consumer demand, and in the geographic characteristics to which technological change is adapting. Thus, the question of scale is intimately linked to what might seem to be cultural questions: why and in what sense were the learning networks national in scope? Fundamentally, they were national because the "problem-solving environment" was increasingly national, and this unity of focus reflected the growing integration of national product markets and the high level of internal population mobility across state lines.

Of course this national differentiation had a cultural dimension. A Scottish visitor of 1849–50 complained that American mineralogists disdained to label geological formations with the names of European localities, but insisted on using an independent national terminology (Bruce 1987, 26). But whereas such chauvinism in a small country might have generated isolation and backwardness, for the United States national technological particularity was positively reinforced by the ongoing expansion of the economy and of the relevant technological community along national lines. Scale economies may ultimately reside as much in the way knowledge is organized—the terminology, the conceptual categories, the standardized routines for testing and measurement—as in the incentives facing profit-seeking producers and innovators. But the realm of "ideas" and the realm of "things" were continually interacting. Historians of technology stress that knowledge often diffuses through the spread of producers' goods that physically embody esoteric scientific information and procedures, as in the example of the Prony dynamometer, which was of great importance in the indigenous American development of hydraulic turbines. According to Constant (1983, 186), in contrast to the European practice of custom turbine design, American producers "concentrated on development of cheap but highly efficient, empirically designed 'stock' wheels which could be merchandised like agricultural implements or hardware." By the 1880s, although the technology of turbine design was patentable and proprietary, knowledge about turbine testing was communal and consensual, "the common property of a well-defined community of practitioners" (p. 194).[7] National engineering associations and technical curricula were institutionalizations of the national focus of nineteenth-century technological networks.

An illustration of the advanced state of the American technological community as of the 1880s may be found in the contrasting experience of the South. Although the term "national" has been used to this point as a convenient shorthand, in many ways the South was not a part of the larger national accumulation of knowledge. Regional production problems were different in essential ways, from wage rates, education, and race to the resource base and the climate. But the South did not develop an early indigenous regional technological community, and found that the startup costs of a late beginning were high. When a group of Georgians set out in the 1880s to establish a state school of technology as a spearhead for regional industrial development, they chose the "shop culture" approach of the Worcester Free Institute over the "school culture" approach associated with Boston Tech (later MIT). The result was highly practical "trade school" training, producing "graduates who could work as machinists or as shop foremen, but who were not well prepared for engineering analysis or original research" (McMath 1985, 9). This may have been the only feasible choice at that time.

Even a quarter-century later, when U.S. Steel acquired the largest southern steel producer and embarked on an ambitious project of upgrading and modernization, it encountered a series of unexpected problems in labor costs and discipline, idiosyncrasies in resource quality and conditions of extraction, and problems with product quality control and marketing. After their initial burst of enthusiasm, the company largely neglected its Birmingham interests. Southern nationalists have seen this as part of a conspiracy to keep them down, but a more plausible interpretation is that the company's technological expertise—representative of the emerging "national" technology—was not well suited to conditions in the South (Wright 1986, 156–77).

8.4 American Mineral Development as a Knowledge Industry

One of the earliest and largest American technological networks was focused on exploitation of the nation's mineral potential. Contrary to learned intuition, resource-based development was not "low-tech," and world leadership in mineral production was not primarily based on geological endowment. David and Wright (1997) show that U.S. mineral production as of 1913 was

7. See also Layton (1979).

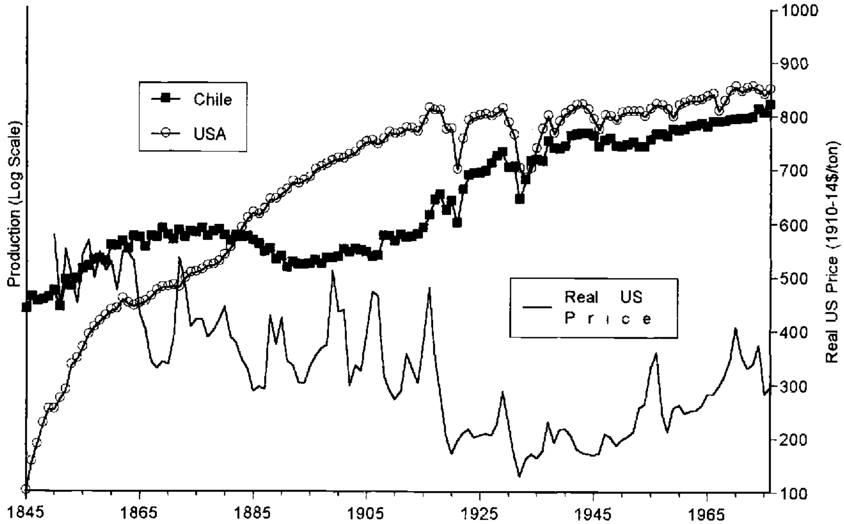

Fig. 8.3 Copper mine production, United States and Chile, and real U.S. price of copper, 1845–1976
Source: Schmitz (1979, 63–78, 270–72).

substantially disproportionate to what we now know to be the country's 1913 share of world mineral reserves. Within a thirty-year period, the United States achieved leadership or near leadership in coal, iron ore, copper, lead, zinc, silver, tungsten, molybdenum, petroleum, arsenic, phosphate, antimony, magnesite, mercury, salt, gold, and bauxite, a degree of simultaneity too extreme to have been coincidental. The example of copper is illustrative (fig. 8.3). Until the 1880s, Chile was the world's leading copper producer, and by the 1930s had nearly recovered its number-one ranking. During the fifty years in between, the action was in the United States.

Developing America's mineral potential was fundamentally a collective learning phenomenon, a return to decades of investment in exploration, transportation, and the knowledge infrastructure of mineral deposits; in training mining engineers and geologists; and in metallurgical revolutions that expanded the range of minerals that could be profitably extracted. Provision of geological information was the initial step. Geologists were among the most conspicuous of those antebellum scientists listed in the *Dictionary of American Biography* (about 14 percent of the total) who drew livelihoods chiefly from private industry rather than government or educational institutions (Bruce 1987, 139). As noted, state geological surveys were the leading form of direct aid for science in the antebellum era. The states supported not only the fieldwork of geologists, but also the publication of their sometimes voluminous reports (pp. 166–67).

Discoveries in the Michigan copper region in the 1840s provide a striking early instance of the role of these surveys and geologists' involvement in exploration and mineral-resource exploitation. A federal survey under the direction of Charles T. Jackson, a leading geologist and chemist in Boston, was completed in 1850, providing the first geological maps adequate to support rational exploration and development work. This venture launched not only the development of these copper fields, but a number of scientific careers. Josiah Whitney, a young protégé of Jackson's who had been sent off to Europe to pursue interests in chemistry, returned in the summer of 1845 to work as a geologist for a mining company. Forsaking chemistry, Whitney soon joined the staff of Jackson's survey in 1847, and within a few years had established himself as a leading industrial consultant. "Making five hundred dollars a month, he could not afford to be a Yale professor" (Bruce 1987, 139–40). His reputation was further enhanced by his publication the following year of *The Metallic Wealth of the United States*, the first comprehensive work on American ore deposits, a book that became widely known and helped him gain a position as director of a state survey for California in 1860.

Despite Whitney's remark about relative salaries, university professors of that era could sometimes be highly entrepreneurial while on the job. An early example was J. P. Lesley, who graduated from the University of Pennsylvania in 1838, and then worked on the first state geological survey.[8] After a decade in the ministry, he published *A Manual of Coal and Its Topography* in 1856, and in the same year became secretary of the American Iron Association. He also worked as a private consultant, and in 1857 his office stationery carried the following letterhead: "Geology and Topography. Geological and other Maps constructed; Surveys of Coal Lands made; Mineral Deposits examined; Geological Opinions given to guide purchasers, and Reports made to Owners and Agents. Orders for elaborate Topographical Surveys from Rail-road and other companies, will be executed in scientific principles, and in the highest style of the art." Two years later he joined the faculty of his alma mater, was made dean of the science department in 1872, and dean of the new Towne Scientific School in 1875. He was librarian, secretary, and vice president of the American Philosophical Society, and a charter member of the National Academy of Sciences. During all this time he continued his consulting activities, traveling in 1863 to Europe for the Pennsylvania Railroad to study the Bessemer steel process. He also served as state geologist, directed the second Pennsylvania geological survey, and for four years edited a weekly newspaper, *United States Railroad and Mining Register.* The overlapping sectoral engagements in Lesley's career vividly illustrate the learning spillovers among mineral exploration, transportation, and industrial development.[9]

With the opening of the trans-Mississippi west after the Civil War, there was

8. This account is adapted from Pursell (1972, 241–45).

9. The chemical labs set up by railroads and steel companies during the 1860s for testing materials were the first scientific laboratories in American industry. See Rosenberg (1985).

a commensurate expansion in the scale of resources committed to geological surveys. A number of ad hoc projects culminated in the establishment of the U.S. Geological Survey in 1879. Under directors Clarence King and J. W. Powell, the Survey emerged as the leading governmental research agency of the nineteenth century. The payoff to its early topographical and metallurgical work had a lasting impact on popular appreciation of the practical benefits of scientific research (Manning 1967, 4–14; Paul 1960; Owen 1975, 225). Although private professional work while on the Survey staff was not permitted, the organization acquired a reputation as an ideal stepping-stone toward career success in the mining sector (Spence 1970, 60). The Survey was particularly effective in changing attitudes toward petroleum geology in the industry, by publishing reliable field data and popularizing the anticlinal theory of the oil-bearing strata—a distinctively American doctrine (Owen 1975, 56, 95). While the major elements of the theory had been worked out before 1900, the discovery in 1911 of the rich Cushing pool in Oklahoma offered tangible evidence of its practical value. For the next fifteen years, most new crude discoveries were based on the surface mapping of anticlines (Williamson et al. 1963, 45–46).

Over roughly this same period, the United States also became the foremost location for education in mining engineering and metallurgy. Until the 1860s, advanced American mining students often attended the Bergakademie in Freiberg, Saxony; but with the founding of the Columbia School of Mines in 1864, enrollments abroad largely ceased. As early as 1871, mining expert John A. Church declared Columbia to be "one of the best schools in the world—more scientific than Freiberg, more practical than Paris" (quoted in Spence 1970, 38). The fact that an institution in New York City was training engineers for work in remote western localities is strong evidence that learning was nationally structured. But by 1893, more than twenty American schools offered degrees in mining (Christy 1893). Enrollment continued to grow over the next ten years or more, especially in the western states. With over 300 students enrolled in its mining college in 1903, the University of California claimed to be "without doubt the largest mining college in the world" (Read 1941, 84). The continuing flow of trained American mining specialists was reflected in a distinctly national professional identity. When the British Institution of Mining and Metallurgy held its first meeting in London in 1892, the organizers "found it more than a little irksome to have to acknowledge that in the United States some such organization had been operating successfully for nearly twenty years" (Wilson 1992, 8–9).

The national identity of mining engineers derived not just from their training within the United States, but from the interaction between mining schools and industry. Columbia organized the Summer School of Practical Mining, which helped students become familiar with working conditions they would meet after graduation. Professor Robert H. Richards perfected the Mining Laboratory, where practical problems in ore dressing and metallurgy could be worked out by students (Christy 1893, 461). Mining engineers increasingly assumed managerial and executive roles within large firms, and this expectation came to be reflected in the curricula of mining schools (Ochs 1992). Herbert Hoover, surely the most famous mining engineer of this era, favored this trend toward combining executive and technical functions, viewing it as an American strength (Hoover 1909, 185–91). The contrast was with the European tradition of training mining engineers to serve as inspectors, and in regulatory positions directing the activities of state mining monopolies. Large mining corporations became increasingly prominent after 1900.[10] Surveys of mining school graduates, however, indicate that most maintained professional independence throughout their careers, taking on a wide range of job assignments and consulting positions, often founding independent companies (Ochs 1992; Spence 1970, 79, 136–39, 275).

Perhaps the best evidence of the distinctive national character of American mining engineers is their role in overseas development. A 1917 manpower census for military purposes counted 7,500 mining engineers, 2,112 of them with working experience in foreign countries. Although Canada and Mexico were the two largest of these, the experience was in fact widely dispersed among the continents of the world (table 8.2). A survey of graduates of the Colorado School of Mines between 1900 and 1940 found that 64 percent had worked abroad at some time, 39 percent for several years (Ochs 1992). The American impact was notable in Australia, where into the 1880s most of the largest mines were managed by Cornishmen, who had much practical experience but were untrained in metallurgy and resistant to the use of new technology. A turning point came with the move in 1886 to recruit highly paid engineers and metallurgists from the Rocky Mountain states, a decision that "linked Australia to a new powerhouse of skills and attitudes" (Blainey 1969, 154, 252). In South Africa, because hard quartz-rock mining required techniques "unknown to most British mining engineers," Americans were offered princely salaries to come and direct mining operations in the 1880s and 1890s. An American served as the state mining engineer in the Transvaal in 1888, another was the first president of the South African Association of Engineers and Architects, and a third was one of the first presidents of the Chemical and Metallurgical Society formed in 1894 (De Waal 1985).

Many of these themes are well illustrated by the case of copper. The early developments in Michigan have been touched upon already; beginning in the 1870s, the national totals were augmented by production from newly discovered deposits in Arizona and Montana, though Michigan production continued to grow absolutely until the 1920s. What truly propelled the industry into the twentieth century, however, was a revolution in metallurgy, overwhelmingly an American technological achievement. In the 1880s and 1890s, the major

10. Of the fifty-eight U.S. companies represented in the world's largest hundred as of 1912, nearly one-third were in minerals, including petroleum (Schmitz 1995).

Table 8.2 Experience in Foreign Countries of U.S. Mining Engineers and Chemists, 1917

	Mining Engineers	Chemists
Africa	74	13
Australia	46	19
Canada	384	203
Central America	74	15
Cuba	68	60
Europe		
Austria-Hungary	7	24
Belgium	6	6
Denmark	1	19
France	23	38
Great Britain	116	117
Germany	61	231
Holland	2	10
Italy	5	11
Norway-Sweden	19	21
Russia	25	30
Spain	7	5
Switzerland	8	18
Others	22	10
Not specified	101	171
Far East	3	
Greenland	3	
India	11	
Mexico	679	117
Newfoundland	7	
South America	241	34
West Indies	17	32

Source: Fay 1917, 11.

breakthroughs were the adaptation of the Bessemer process to copper converting, and the introduction of electrolysis on a commercial scale for the final refining of copper. The dramatic new development of the first decade of the twentieth century was the successful application of the Jackling method of large-scale, nonselective mining, using highly mechanized techniques to remove all material from the mineralized area, waste as well as metal-bearing ore. Complementary to these techniques, indeed essential to their commercial success, was the use of the oil flotation process in concentrating the ore. Oil flotation called for and made possible extremely fine grinding, which reduced milling losses sufficiently to make exploitation of low-grade "porphyry" coppers economically feasible.[11]

Together these techniques made possible a steady reduction in the average

11. This account draws primarily upon Parsons (1933) and Schmitz (1986, 403–5).

Table 8.3 **Average Yields of Copper Ore (percentage)**

1800	English	9.27
1850	English	7.84
1870–85	English	6.56
1880	United States	3.00
1889	United States	3.32
1902	United States	2.73
1906	United States	2.50
1907	United States	2.11
1908	United States	2.07
1909	United States	1.98
1910	United States	1.88
1911–20	United States	1.66
1921–30	United States	1.53

Sources: Elliott et al. 1937, 374; Leong et al. 1940.

grade of American copper ore, as shown in table 8.3. By contrast, in copper-rich Chile—where output was stagnant—yields averaged 10–13 percent between 1880 and 1910 (Przeworski 1980, 26, 183, 197). From these facts alone, one might infer that the United States had simply pressed its internal margin of extraction further than Chile, into higher-cost ores. But figure 8.3 makes it evident that the real price of copper was *declining* during this very period, confirming that the fall in yields was an indication of technological progress. Indeed, there is an exponential link between the reduction in yield and the expansion of ore reserves, through a formula known to geologists as Lasky's law, an inverse relationship between the grade of ore and the size of the deposit (Lasky 1950). Capital requirements and long time horizons made copper an industry for corporate giants, enterprises that internalized many of the complementarities and spillovers in copper technology (Schmitz 1986). But these firms also drew extensively upon national infrastructural investments in geological knowledge and in the training of mining engineers.

8.5 The Organization of Knowledge: Chemical Engineering as an American Innovation

Textbooks say that, around the turn of the twentieth century, the technologies of the first industrial revolution (steam, coal, and iron) gave way to the more science-based technologies of the second industrial revolution (electricity, chemicals, and internal combustion). The change in underlying science shifted technology from its nineteenth-century demands for tangible capital and resources toward more intangible forms of capital such as knowledge and advanced education (Abramovitz and David 1996). From this vantage point, the rise of the industrial research laboratories depicted in figure 8.1 may be seen as a response to the opportunities created by these new technologies, and a vehicle for propelling them forward.

This description accounts for one aspect of the change between the centuries, but understates the extent to which the new American industries of the twentieth century drew upon the legacy of the nineteenth-century national technological community. To give a few examples:

1. As in the case of copper, the electrolytic metallurgical revolution of the 1890s was an extension of the long drive to develop and exploit the nation's mineral potential. Charles Martin Hall's electrolytic process of 1886 culminated a decades-long "search for cheap aluminum," and instantly raised the value of bauxite, or aluminum ore.[12] From the "worthless" brine under Midland, Michigan, the Dow chemical company was able to manufacture some 150 profitable electrolytic bromine products (Levenstein 1995).

2. Both electrical and chemical industries depended heavily on the nation's long-standing expertise in metal manufactures and metalworking. Having invented cheap aluminum, the forerunner of Alcoa had to draw upon the metallurgical, ingot-casting, and metalworking expertise of the Pittsburgh area, to perfect its manufacturing methods and develop new uses for the product. To facilitate this process, it followed a strategy of publishing its research results in full (Graham and Pruitt 1990, chap. 1). Alcoa and other electrochemicals firms worked closely with machinists and mechanical engineers, because equipment design was critical to their research. Although the Germans were the undisputed world leaders in chemical science before World War I, an informed observer wrote in 1900: "As far as I have been able to judge from my personal experience, the American Manufacturers [*sic*] are far ahead of all others, and their success has been entirely due to the apparatus employed" (quoted in Trescott 1982, 12).

3. The institutions of higher education and technical training that grew up originally around civil, mechanical, and mining engineering were well positioned to adapt to the new technological order. Trained chemists were employed in industrial laboratories as early as the 1860s, but before 1900 they chiefly worked on routine materials testing, well within the boundaries of frontier science of that time (Rosenberg 1985). Nonetheless, the pattern of academic adaptation to changing industrial demands was well established, in contrast to the traditions of training state engineers in France and Germany (Lundgreen 1990). Well before World War I, the United States became the world leader in years of higher education per capita, notwithstanding its lag in basic science (Maddison 1987, table A-12). Patterns of training and professional specialization also reflected a distinct American style, as illustrated by the rise of chemical engineering.

The origins of the term "chemical engineer" are shrouded in mystery. Some trace it back to antiquity, but an immediate forerunner to U.S. adoption was a

12. Trescott (1981) rejects the oft-heard statement that the methods of Hall and his French counterpart, L. T. Héroult, were virtually identical. Hall's method dissolved bauxite, while European methods focused on obtaining aluminum from its halide salts (p. 60).

series of lectures by George E. Davis of Manchester, England, in 1888. Elaboration of the hybrid as a professional specialty was, according to its historians, an American innovation (Guédon 1980; Trescott 1982). Although the nature of the specialty became clarified only some time after its founding, from the beginning the concept was not the same as applied chemistry. In fact, it grew most directly out of mechanical engineering, with a focus on the design, construction, and maintenance of plant and apparatus to perform chemical operations. MIT established its first course in 1888, and was quickly followed by Pennsylvania (1892), Tulane (1894), Wisconsin (1898), Michigan (1898), and many others. The American Institute of Chemical Engineers, a professional association, was founded in 1908.

What came to distinguish chemical engineering was the concept of "unit operations," a term coined by Arthur D. Little in 1915, to refer to the notion of breaking down chemical processes into elemental components such as evaporation, filtration, grinding, crushing, and so on, which had features common to many different chemical contexts. This increase in the level of abstraction and generality gave the core concept something of the effect of a "general-purpose technology."[13] The contrast was with the tradition of chemical analysis, in which the chemist developed an intimate but particularized knowledge of specific substances. Although Little's concept was not codified in the form of a textbook until the 1920s, the codification reflected the practices of industry-university relationships emerging over a more extended period of time (Soros 1980; Trescott 1982; Misa 1985). Certainly a strong orientation toward practical industrial utility was a feature of chemical engineering from the beginning. Indeed, Arthur D. Little was not a faculty member at the time of his 1915 report to the president of MIT, but his consulting firm was an active employer of MIT graduates. Not long after, nearly all the MIT chemical engineering faculty were engaged as consultants or employees in the oil industry (Weber 1980). At MIT and elsewhere, enrollments in the new field grew rapidly (table 8.4).

The most dramatic return to the new professional specialty came with the rise of petrochemicals during the 1920s. Here we truly have a marriage of old and new learning, as the entire technology of petroleum discovery, drilling, refining, and utilization had been an American specialty for nearly a century before. It can also legitimately be considered a return to scale at the national level, because the search for by-products was an outgrowth of the vast American enterprise of petroleum refining. Prior to the 1920s, however, there was little contact between petroleum companies and the chemical industry. With the shift of basic feedstock from coal tar to petroleum, the United States surged into the forefront, building on close university-industry partnerships like that between New Jersey Standard and MIT at the research facility in Baton Rouge, Louisiana (Landau and Rosenberg 1992). As the chemical engineer Peter Spitz

13. This analogy is suggested by Rosenberg (1998), with a theoretical citation to Bresnahan and Trajtenberg (1995).

Table 8.4 Baccalaureates Awarded in Chemistry and Chemical Engineering at MIT, 1885–1934

	Chemistry	Chemical Engineering
1885–89	38	—
1890–94	50	31
1895–99	98	49
1900–1904	78	51
1905–19	82	65
1910–14	50	132
1915–19	63	187
1920–24	52	419
1925–29	81	238
1930–34	71	240

Source: Servos 1980, 538.

(1988, xiii) has written: "Regardless of the fact that Europe's chemical industry was for a long time more advanced than that in the United States, the future of organic chemicals was going to be related to petroleum, not coal, as soon as companies such as Union Carbide, Standard Oil (New Jersey), Shell, and Dow turned their attention to the production of petrochemicals." After World War II, the German chemical industry required a substantial institutional and attitudinal readjustment to the petroleum base, which by then had become the world standard (Stokes 1994).

If chemical engineering transformed the configuration by which technological knowledge was accumulated, the discipline itself was transformed by its interactions with institutionalized research programs at major corporations. Du Pont in particular, which launched an ambitious research agenda in basic science beginning in the late 1920s, experienced the inadequacies of the then-current level of rigor in chemical engineering (with the possible exception of MIT). Under the leadership of Allan Colburn and Thomas Chilton, Du Pont contrived to put the discipline on a firmer scientific and mathematical footing. Another Du Pont chemical engineer, John Howard Perry, published the *Chemical Engineer's Handbook* in the 1930s, which sold over 150,000 copies over the next twenty years (Hounshell and Smith 1988, 275–85).

Despite the powerful influence of Du Pont and other large research-oriented companies, scientists maintained an independent professional identity. With academic employment as an option, companies often had to adapt their employment conditions to match the individual freedoms of a university setting (Wise 1980). At Alcoa, researchers were encouraged to "identify closely with their engineering and scientific professions, to attend professional conferences and society meetings, to write papers and generally to keep in touch with things going on in the outside scientific community" (Graham and Pruitt 1990, 203). In his 1926 memo proposing a program of fundamental research at Du

Pont, Charles Stine listed the advantages of recruiting Ph.D.'s as one of the prime reasons, holding out only the *possibility* that the project might lead to practical applications—though in the end it certainly did (Hounshell and Smith 1988, 223). Although company recruiters stressed the advantages of the absence of teaching (!), top research scientists were also eager to publish their findings in professional journals, often a subject of disputes with the company (e.g., p. 238). At Du Pont the most productive research teams did not stay together for more than a few years at a time, because of departures for universities or other employment (pp. 243, 283, 285). Through all its years of success, Du Pont never settled on a lasting institutional solution to these issues (Hounshell 1992).

This is not meant to imply that the entire corporate research enterprise was continually fraught with contradictions and instability. To the contrary, Du Pont's underlying commitment was firm. The point is that the evolution of American technological learning was shaped by the interactions between profit-seeking firms and semi-independent professional scientists, and this fact placed limits on the corporation's ability to appropriate knowledge and channel technologies in their most favored directions. The contrast is with Germany, which resisted chemical engineering as an autonomous discipline until the 1960s, opting instead for a team-based approach to the design of chemical plants and apparatus, combining chemists with mechanical engineers and other specialists (Guédon 1980; Schoenemann 1980). From a technical standpoint this solution may have been just as good. But whether it would have worked in America is doubtful.

What distinguished the U.S. chemical industry internationally was not so much the giant "all around" companies, but the numbers and vitality of smaller, more specialized firms (Arora and Gambardella 1998). The coexistence and complementarity of large and small technology-based firms has been a persistent feature of the United States in major twentieth-century industries.

8.6 Organized Corporate Research and National Learning Networks

If the argument of this paper is correct, it raises the question of what became of American learning networks across the rest of the twentieth century, and specifically what were the implications of organized industrial research for the strong *national* orientation of the networks they inherited. Because these networks were only partly visible and not subject to precise measurement, any proposed account of their changing shape and direction through time must be tentative. But available evidence seems consistent with the view that the first generations of formalized research structures actually intensified the national distinctiveness of American collective learning. Ultimately, however, progress toward increasingly abstract general scientific principles has been a force for the globalization of technological communities.

This conjecture begins with the evident correlation between research laboratories and the rise of large integrated corporations producing primarily for the national market. The essay by Steven Usselman (chap. 2 in this volume) calls attention to the powerful drive toward research coordination in the case of the railroad industry, whose capital stock really did consist of an interconnected national network. But the railroads were an extreme case. Most of the corporate entities that came out of the turn-of-the-century merger wave were oriented toward the national market, and Chandlerian coordination between production and distribution was central to the performance of those that succeeded. The sponsors of early research laboratories were major corporations with market power, such as General Electric, Westinghouse, Du Pont, Eastman Kodak, and AT&T. Indeed, protecting that market power through strategic patent development was in many cases a prime motive for initiating corporate research (Reich 1985).

But when corporate research labs evolved into a more progressive role, as they often did whatever the original intentions, more often than not their success took the form of new product development. The flow of new products often seemed to be driven by the internal logic of a technological trajectory, but their commercial success was unavoidably linked to the tastes and budgets of American households. The era from the 1920s to the 1960s gave rise to the theory of the "product cycle," according to which new products developed first in the United States because they drew upon new scientific knowledge, but also because they tended to be responsive to the wants of high-income American consumers, for telephones, automobiles, refrigerators, cameras, radios, nylons, cellophane, and many other novelties. The observation that some of these demand patterns were cultural idiosyncrasies rather than income effects only underscores the inference that producer-consumer interaction intensified the national distinctiveness of the learning process.

Product-demand channels were reinforced by improved coordination between university training and the specifications of corporate employment. These systems also tended to be national in scope. The establishment of uniform standards for graduate degrees under the American Association of Universities was a self-conscious effort at network creation, as a means of enhancing the reputation and effectiveness of the university system. The institutional arrangements were peculiarly American: mass provision of undergraduate education as a means of financing research and graduate training (Geiger 1986, 17–18, 68). Close linkages between university instruction and industrial demands for trained personnel was an accepted pattern from the late nineteenth century (Rosenberg and Nelson 1994). In the 1920s, the movement for technical standardization to achieve the "elimination of waste in materials" spilled over into formalized systems to define employee qualifications and job specifications, for "the elimination of waste in people" (Noble 1977, 82–83). Both sides of the exchange were nationally defined, often at considerable variance from practice in other countries. For example, curricula came to reflect the expectation that career paths in engineering would ultimately lead to positions in management, and this combination was a peculiar American specialty (Rae 1979).

Critics of American capitalism often interpret these developments as evidence of the excessive influence of large corporations on the direction of technological change and on the research and training decisions of universities. Corporate domination was never complete, however. The article by Lamoreaux and Sokoloff (chap. 1 in this volume) points to the continued vitality of independent inventors well into the twentieth century, as indicated by the registration of patents. Although the importance of in-house corporate research was on the ascendancy during the interwar period, according to David Mowery (1995) these facilities were complementary to externally contracted research services, and often functioned as a way to monitor and evaluate innovations originating elsewhere—mainly, in that era, elsewhere within the United States. At the universities, advice on employment opportunities may have been welcomed by both faculty and students, but the independence of academic research agendas and career paths is just as persistent a feature of the American tradition (Servos 1980). It would be more appropriate to say, therefore, that the interwar period was characterized by the crystallization of an advanced, internally compatible national network of innovation, within which organized corporate research was one major component. This view is quite compatible with that advanced by Leslie Hannah (chap. 7 in this volume), which suggests that the premier American corporations were not endowed with unusually long life, and seen in isolation they were more like than unlike their counterparts in other advanced nations. Much of their distinctive performance derived from their place in the dense networks of the U.S. economy.

But it is difficult to distinguish forces that may have been inherent in the drive for economic and institutional coordination, from the broader trends in the global economy during this era. The interwar years were a time of economic nationalism around the world, of disruption in the international trade and payments system, and of impending military crises that drove many countries toward self-sufficiency in technology as well as resources. Subsequently, the events of World War II pushed the United States into a position of science-based technological leadership far beyond anything that would have been generated by normal economic forces (Nelson and Wright 1992). At that time the American market was highly idiosyncratic, not just because of national tastes but because American incomes were so much higher than those of any other country in the world. With the postwar liberalization of world trade, dispersion of natural-resource supplies around the globe, and economic recovery in countries that had been devastated by the war, the extremes of national differentiation have greatly receded, increasing the degree of "technological congruence" between nations (Abramovitz and David 1996).

A more fundamental force behind the attenuation of national networks is that modern technologies increasingly draw upon science, and scientific networks are inherently international. Although the distinction between "scientific" and "nonscientific" technologies is difficult to define rigorously, the core idea is straightforward: scientific technologies draw upon general, abstract, and universal principles, as opposed to empirical observations and trial and error. Almost by definition, scientific innovations are more readily transferable from one application and one location to another (Arora and Gambardella 1994). It certainly appears that the "technology of technological change" has changed in this way, for reasons broadly associated with the evolution of organized research structures, academic and governmental as well as corporate.

Patent counts are by no means comprehensive measures of technological change, but the geographic origins of patents can give us some information about technological networks, and the evidence seems to support this view in broad terms. Between 1870 and 1930, more than 90 percent of U.S. patents were assigned to U.S. residents, with no apparent trend during this period. Between 1963 and 1968, the figure fell to 80 percent, and by the late 1970s to 60 percent. During the 1980s the share continued to fall, and in the 1990s it has stabilized at just over 50 percent. Of course these aggregate trends obscure significant variation between industries. But the trend toward internationalization seems to be strongest in those fields characterized by existence of a strong science base, and the presence of large managerial companies.[14]

This interpretation does not imply that the countries of the world are converging in every dimension into one homogeneous puree. Bruce Kogut has forcefully argued that many national institutional arrangements are far more persistent historically and less transferable than technological understanding itself. An example is what he refers to as "national organizing principles of work," a category encompassing such features as job tenure, hierarchy, job specifications, and skill acquisition (Kogut 1990, 1992). Features of the American "national innovation system" continue to be distinctive, linked to such enduring national traits and institutions as the antitrust tradition, high labor mobility and weak job attachments, a strong venture-capital sector, and independent universities and professions (Nelson 1993). If such differences are persistent, then we should expect to observe continuing national differences in the types of technologies that are developed and selected for implementation. But these observations do not gainsay the conclusion that technological networks no longer display the tight linkage between learning and national conditions that prevailed a century ago.

14. These figures are drawn from Cantwell (1989, 23); Pavitt (1988, 142–43); Thomson and Nelson (1996, table 1); National Science Board (1996, appendix table 6-7). The generalizations in the last sentence come from Thomson and Nelson.

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Comment Alexander J. Field

Research in economic history and administrative service in a university motivate both practical and scholarly interest in organizational persistence and dynamics. This conference has reinforced my belief in the value of an evolutionary perspective for understanding these phenomena. Such a perspective draws an analogy between the influence of environmental forces on the survival of organisms in biological populations, and corresponding processes affecting the persistence of organizations. There is one key difference, however, between natural selection as it occurs in the world of plants and animals and its functioning among organizations. This difference concerns the role of mutations, which in the biological context are largely random while in the organizational context are the results of specific human intervention.

In a rapidly changing environment, a new strategic departure may enable a firm to persist or grow. But if the nature of the environmental change is misperceived, or misforecast, or if the costs and benefits of the mutation are improperly estimated, such initiatives can create problems and in the worst case prove disastrous for the firm or organization because they will draw financial resources and administrative attention away from its core activities: those activities that exploit the differential capabilities that have given the firm its competitive advantage.

There has been so much written about the challenges of overcoming inertia that some leaders might be forgiven for thinking that their job was simply to maximize the rate of organizational mutation. This conclusion, of course, makes no more sense than a public-policy recommendation that we should increase the irradiation of the human population on the grounds that some of the resultant genetic changes might be evolutionarily adaptive. The challenge of organizational leadership is to establish a framework in which the ability of an organization to survive and prosper (its evolutionary fitness) and its ability to adapt to changing environmental influences (the two go hand in hand in a dynamic context) can be sustained. David Hounshell's discussion (chap. 5) of a key meeting at the Ford Motor Company in 1949 is a detailed dissection of such a critical meeting. Major strategic departures can save an organization,

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and we can only marvel at the adroitness with which Microsoft, in a very short time period, reoriented its strategy around the Internet. But bold departures can also come close to destroying an organization, if they do not prove evolutionarily adaptive. A case in point is Sears's entry into the real-estate and stock-brokerage businesses in the early 1980s, discussed in the paper by Daniel Raff and Peter Temin (chap. 6). In retrospect (it is of course easy to be a Monday-morning quarterback), Sears might have been better advised to stick to its retailing knitting, aggressively taking advantage of the new inventory-control, logistical, and point-of-sale opportunities created by advances in information technology, a policy it now appears to be following.

The Sears experience is a reminder that formal planning processes *alone* will not guarantee evolutionarily favorable outcomes. Indeed, in the 1980s, extensive multiparticipant strategic planning exercises appear, ex post, to have resulted in worse decisions than was true of the largely autocratic process of the 1920s, in which General (Robert) Wood, with the approval of only one other individual (the CEO) brilliantly set up retail establishments away from the center city in a manner that built on the organization's success as a mail-order firm and effectively (for a time) met the challenge of the automobile. What counts ultimately is the respective logic and analyses that underlie these decisions.

The evolutionary perspective is useful in helping us understand why organizations persist, and how we can influence the probability that they do. But in this context, it is also worth stepping back and reflecting on why we care. There are usually strong individual incentives for managers to maintain the viability of firms, and bankruptcy and firm shutdown incur clear personal costs. But why, from a social perspective, does it matter? After all, physical capital and personnel don't disappear just because an organization ceases functioning. Evolutionary theory helps us understand why we do and should care. First, when a successful organization emerges, it does so by stitching together resources and people in a manner that gives the entity collective capabilities that exceed the sum of the capabilities of the individuals, even if each of the firm's members were given a per capita share of the resources. These superior collective capabilities are what give the successful firm its evolutionary advantage. Some of this advantage results from indivisibilities in physical capital, giving rise to economies of scale, but much also comes from investment in both processes and knowledge. Some of these investments have limited value outside the organization.

Another way of thinking about investments in firm-specific capital is that they are the embodiment of the firm's particular history and culture. This knowledge, although valuable internally, is largely worthless outside of the firm. Enabling a firm to persist and prosper means that organization-specific resources—knowledge, processes, personnel—can continue to be effectively utilized. There is inevitably value lost—often substantial—when an entity is dismantled and its component parts (those with value outside the dismantling firm) redeployed. In extreme cases this is a necessary, even salutary, development. More often, it is a symptom of managerial failure.

The acquisition of organizational knowledge and capability is important even in a technologically stable environment. In Kazuhiro Mishina's paper (chap. 4 in this volume), for example, a clear argument is made that, in the case of the dramatic reductions in the costs of producing the Boeing B-17 bomber, the most critical learning took place among networks of managers as they discovered how to organize production, both physically and temporally, in the context of a dramatic and mandated increase in the speed of throughput. From the strict standpoint of aeronautical, mechanical, and electrical engineering, the technology underlying the production of the bomber had not altered, although the cost of manufacturing one fell dramatically.

Engineering breakthroughs that enable firms to move rapidly out along supply curves are sources of cost reduction more familiar to economic historians. Gavin Wright's innovation lies in insisting that we expand the scope for discussion of such learning from the individual firm to the nation. Focusing particularly on cotton textiles, mining, and chemical engineering, Wright identifies a number of national characteristics: antitrust, high labor mobility and weak job attachment, a strong venture-capital sector, and independent universities and professions that underlay and, perhaps to an attenuated degree, still underlie American *technological networks*. These networks, consistent with the complementary existence of large and small technology-based companies, provide the institutional underpinnings for talking about national technological styles, and perhaps national competitive advantages. Wright titles his paper "Can a Nation Learn?" but it is also about whether it is meaningful to talk about nations as economic actors, with distinctive technological personalities and capabilities that are more than the sum of the individual capabilities of firms and organizations.

On the general conceptual question, of course Wright is right: at the national level there is knowledge and learning that permits citizens collectively to accomplish more than if they were not stitched together by this specific human capital. An obvious example in many countries consists of language. An enormous amount of effort takes place in our educational systems to teach students spelling, the meaning of words, the rules of grammar, with the objective of turning out individuals who are effective oral and written communicators. That knowledge is of course valuable and enabling to the degree that others share it. It may not be valuable outside of the country or linguistic region, just as firm-specific knowledge may have little value outside of one organization.

In fact Wright elevates language to a more general metaphor describing learning at the national level in chemical engineering, geology, and the sciences of mining and mineral extraction. Through an infrastructure of governmental and educational institutions, the Geological Survey office and schools of mines at Berkeley, Colorado, and Columbia, for example, a language for thinking about mineral exploitation spread across the country in a way that enabled America, far more effectively than other regions similarly endowed with resources, to achieve world leadership. Americans insisted on their own names for geological strata, to the consternation of European scientists, but there is more to this than simple chauvinism. It had the effect of differentiating and protecting a particular style or network of national communication and learning, a network that gave the country differential capabilities. Here are examples in which it is meaningful to speak of collective capabilities that extended beyond the individual firm although not necessarily beyond the regional or national boundary.

Wright suggests toward the end of his paper that the importance of nations as loci for technological learning has diminished with the increasing dominance of science-based technologies, and that such learning at the end of the twentieth century is far more likely to take place on a transnational scale. Certainly the data cited on trends in the share of U.S. patents of domestic origin supports this view. But what of more localized, regionally based learning networks?

It may be useful to consider Alfred Marshall's description of external economies, surely motivated by the economic experience of places such as the Manchester-Liverpool conurbation or the networks of metalworking expertise in the Birmingham area. Small and medium-sized firms clustered together because they benefited from the easy interchange of ideas and personnel. Marshall (1920, 237) believed that the relative importance of external economies was increasing.

> For External economies are constantly growing in importance relatively to Internal in all matters of Trade-knowledge: newspapers, and trade and technical publications of all kinds are perpetually scouting for him and bringing him much of the knowledge he wants—knowledge which a little while ago would have been beyond the reach of anyone who could not afford to have well-paid agents in many distant places. Again, it is to his interest also that the secrecy of business is on the whole diminishing, and that the most important improvements in method seldom remain secret for long after they have passed from the experimental stage. It is to his [the small manufacturer's] advantage that changes in manufacture depend less on mere rules of thumb and more on broad developments of scientific principle: and that many of these are made by students in the pursuit of knowledge for its own sake, and are promptly published in the general interest.

Note that Marshall attributes the growing importance of external economies to the increased dominance of science-based over experiential learning. For Wright, the impact of that trend is less clear, in the late nineteenth century appearing to foster national technological networks, but in the twentieth to coincide with the migration of technological change into the orbits of either in-house R&D labs or more global learning networks. Although the Marshallian mechanisms described are similar to those in Wright's paper, Marshall's insights seem to have been motivated by more regionally localized learning than is the case for Wright. Partly this is because the former's ideas represented to a greater degree a distillation of the history of the more geographically compact British experience, whereas the latter's insights are more directly conditioned by studies of U.S. economic history.

Whether or not "national" learning has been largely supplanted by global networks, the kind of highly localized phenomena that gave rise to Marshall's insights about external economies are alive and well in the late twentieth century in the United States, as is clear to anyone living amid the booming Silicon Valley economy (this is written in spring of 1997). In spite of the great difficulty and high cost of finding commercial real estate, apartments, storage lockers, personnel, and so forth, many companies still desperately want to be close to the action. Marshall's description of external economies was put forth in some sense precisely to account for what Wright describes: an economy or sector marked by the complementary coexistence of large and small firms associated with an industry structure characterized by lack of dominance by large firms, high labor mobility, and weak job attachments. It would be hard to find a better description of the current organization of Silicon Valley software, semiconductor, mass storage, and networking hardware sectors.

Wright, however, describes networks of learning with greater geographic reach. His focus is explicitly on the emerging industries of the late nineteenth century, with their greater reliance on science and research conducted by professionally trained personnel. Thus Wright's emphasis on the role of independent universities and professions. In this context, the much greater geographic dispersion of American universities and in particular their lack of concentration in the national capital may help in understanding differences in national styles of learning, comparing the United States say with British or European counterparts. Most of the comparative references in the current version of the paper apply to Britain: more comparative study of the French and German cases might be useful.

How much of what Wright describes for the late nineteenth century is historically specific, reflecting, perhaps, the golden age of the consulting engineer? To what degree did the increased importance of organized, firm-funded R&D laboratories lead (contrary to Marshall) to a greater emphasis on secrecy, appropriability of investments in R&D, and a restriction on the freer flow of information through professional networks described here? Steven Usselman's paper (chap. 2 in this volume) describes, for example, the way the railroad industry attempted to canalize research effort in areas anticipated to be complementary to the national network being operated, and shut down or discouraged inquiry in areas viewed as likely to be unproductive or even to threaten the established technological paradigm.

Has the integration of research into more formalized R&D labs during the twentieth century meant that the more democratic style of research described by Wright is shut down? Is this trend counterbalanced by the emergence of "global academies" of scientific and professional communities interacting through international conferences, email, and scientific publication? R&D spending today is heavily concentrated in a small number of sectors: aeronautics, chemicals, instrumentation, electrical machinery, and so forth. Has this pattern remained relatively stable over time? Is it the case that, while the importance of professional networks has declined in some sectors, it has increased in others? Do more industries come to resemble what Usselman describes for railroads at the turn of the century? Or is there no real trend? Questions such as these are crucial for further research.

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