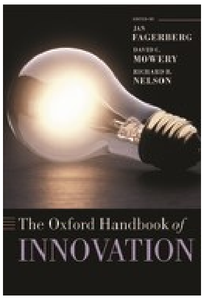

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CHAPTER

13 Innovation through Time

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Abstract

The discussion in this article highlights changes in the structure of the innovation process in successive periods, and is informed by the innovation system concept. In adopting this framework, this article focuses on the changing structure of economic activity, changes in relevant institutions, and changes in patterns of knowledge generation and flows within emergent industrial economies. This article begins by reviewing recent historical interpretations of the impulse toward industrialization in the world economy. It then discusses the changing structure of the innovation process in different phases of industrialization. This discussion includes the widespread appearance of shop-floor-driven technological innovation in eighteenth-century Great Britain and moves forward to consider the invention of the art of invention, to use the philosopher A. N. Whitehead's phrase, in the late nineteenth and early twentieth centuries, with the emergence of organized industrial R&D within the firm.

Keywords: innovation process, innovation system concept, economic activity, industrialization, shop-floor-driven technological innovation

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13.1 Introduction

MOST analysts of innovation emphasize the importance of a historical approach, with good reason. First, innovation is time consuming, based on conjectures about the future, and its outcomes typically are uncertain for long periods. Analysis of any innovation therefore requires an understanding of its history. Second, innovative capabilities are developed through complex, cumulative processes of learning. Finally, innovation processes are shaped by social contexts, as Lazonick has pointed out: “The social conditions affecting innovation change over time and vary across productive activities; hence theoretical analysis of the innovative enterprise must be integrated with historical study” (Lazonick 2002: 3).

Historical patterns of innovation are characterized by complexity, reflecting the heterogeneous nature of economic activity, and the diversity of processes of technology creation across sectors and countries. These characteristics make it problematic to construct overarching schemas of historical development. Nevertheless, some historians and analysts of innovation have developed taxonomies of epochs, often based
p. 350 on "critical technologies" that define whole periods of development. One ↳ form of this is the wave theory proposed by Schumpeter in *Business Cycles*, in which steam power drove the First Industrial Revolution, electricity the Second Industrial Revolution, and so on. Other work that does not rely on wave theories also stresses the role of a small number of technologies in driving broader processes of economic growth. Although valuable, many of these frameworks overemphasize the importance of the allegedly critical technologies while slighting other areas of innovation and economic activity that are no less important. In what follows we challenge some of the historical discussions that stress the transformative effects of "critical innovations." Instead, we emphasize the complex multisectoral character of innovation, and hence the need to take seriously the coexistence of a range of innovation modes, institutional processes, and organizational forms.

Our discussion of innovation through time highlights changes in the structure of the innovation process in successive periods, and is informed by the innovation system concept (discussed in Ch. 7 by Edquist, Ch. 11 by Asheim and Gertler, and Ch. 14 by Malerba). In adopting this framework, we focus on the changing structure of economic activity, changes in relevant institutions, and changes in patterns of knowledge generation and flows within emergent industrial economies.[1]

We begin the discussion below by reviewing recent historical interpretations of the impulse toward industrialization in the world economy. We then discuss the changing structure of the innovation process in different phases of industrialization, focusing on the First Industrial Revolution in Britain from roughly 1760 to 1850, the so-called Second Industrial Revolution during the late nineteenth and early twentieth centuries, and what might be called the Third Industrial Revolution after World War II. Our discussion thus includes the widespread appearance of shop-floor-driven technological innovation in eighteenth-century Great Britain and moves forward to consider the invention of the art of invention, to use the philosopher A. N. Whitehead's phrase (Whitehead 1925), in the late nineteenth and early twentieth centuries, with the emergence of organized industrial R&D within the firm. The Third Industrial Revolution, most clearly illustrated by the post-war United States, is one in which private and public institutions compete and collaborate in new fields of innovation, a mode of innovation that is not yet exhausted.

13.2 The First Industrial Revolution

13.2.1 Institutions, Innovation and the Impulses to Growth

Sustained innovation-based development is a recent and unevenly distributed historical phenomenon. A substantial literature on "world history" has sought to explain the rise of the West, and particularly the
p. 351 European breakthrough to ↳ sustained productivity growth, in the late eighteenth century. Why were some human societies able to break out of a Malthusian trap, shifting from "extensive" economic growth that relied on increased labor input and a wider division of labor to innovation-based intensive growth with sustained rises in real output per head? An important contribution to this historical debate is Pomeranz (2000), who argues that prior to the mid-eighteenth century, Europe, Japan, China, and India were at a broadly similar level of economic development—this was "a world of surprising resemblances." Why did only Northwestern Europe make the transition to innovation-based growth? Pomeranz suggests that two factors were crucial: the acquisition by the major European powers of colonies as markets for manufactures and sources of food and raw material, and the development within Europe of coal as a new energy source.[2]

An alternative explanation for the industrialization of Northwest Europe stresses institutional changes (see Braudel 1984; Wallerstein 1974; Landes 1998), focusing on the emergence of property rights as impulses to innovation. A variant of this institutional analysis is provided by Jones (2003) who argues that technology-based growth has occurred at several points in world history; the challenge is less to understand growth than to understand the forces that prevent growth. He stresses the inhibitory role of political institutions that are based on surplus extraction by political and military elites. Only when such rulers are weakened by crisis do opportunities arise for gain from innovation. Since the political power of established political elites in Northwest Europe eroded during the fourteenth to seventeenth centuries, the emergence of sustained, innovation-based economic growth first occurred in this region of the world economy.

There is disagreement within this literature over the timing of the divergence, as well as the relative importance of different factors in supporting the growth of such institutions as private property rights and the weakening of rent-seeking political and military elites. But all of the scholars adopting this approach emphasize institutional change as an indispensable precondition for sustained innovation-led growth.

13.2.2 Innovation in the First Industrial Revolution

Most economic historians regard the developments in Britain and Northwestern Europe from around 1760 as an economic and technological watershed. Innovation during this period is best conceptualized as an economy-wide process that involved technological, organizational, and institutional change, spanning many sectors and product groups. This view of British industrialization contrasts with the classic historical accounts that emphasize epochal technological breakthroughs in steam power and textile technologies (see e.g. Mantoux 1961). The debate is a significant one for the broader study of innovation, since important scholarly pieces in the field ↳ of innovation studies have followed the "key innovations" interpretation of the First Industrial Revolution (e.g. Freeman and Louçã 2002; for an economic history of industrialization in this framework, see Lloyd-Jones and Lewis 1998).

13.2.3 Sectoral Patterns of Technological Advance: The Patenting Evidence

One important source of evidence on the pace and sectoral distribution of innovative activities during the Industrial Revolution is patent statistics from the period. Although the high cost of patenting (approximately £120 for England, at a time when the annual income of a skilled worker was about £50) and limited access to patent attorneys by many inventors arguably make patent data a biased source of evidence, no other comparably comprehensive sources exist on innovative activity during the Industrial Revolution. MacLeod (1988) finds that patenting grew rapidly after 1750, especially in capital goods. The two technologies for which patenting grew most rapidly during this period are power sources and textile machinery. But patenting also expanded significantly in other capital-goods categories; including agricultural equipment, brewing, shipbuilding, canal building, and metallurgy. Although the share of all patenting accounted for by capital goods grew during the 1750–1800 period, this category nevertheless accounted for no more than 40 per cent of British patents in the half century between 1750 and 1800.

A great deal of inventive activity during this period focused on consumer goods. According to Berg (Berg 1998; see also Sullivan 1990), much of this consumer-goods patenting affected a vast number of small, novel products such as buckles and fasteners, cabinets and furniture, and spectacle frames. Indeed much of the patent activity within the textiles sector—roughly one-third—involved new products (Griffiths et al. 1992). Much of the inventive activity in this key sector within the Industrial Revolution involved new thread types and fabrics, and focused on a consumer market.

Patent evidence thus suggests that the period of the Industrial Revolution was a period of broad technological change. Nevertheless, in recognition of the limitations of patent data for tracking innovative activity, we turn now to more qualitative evidence on the sectoral structure of innovation.

13.2.4 Sectoral Patterns of Change: Technological Histories

13.2.4.1 Steam Power and Textiles

Four innovations—the spinning jenny, the water frame, the spinning mule, and the automatic mule—were associated with dramatic growth in the British textiles p. 353 ↳ industry of the First Industrial Revolution. Between the late eighteenth and the middle of the nineteenth century, the cotton textile industry grew spectacularly in the size of its output, in labor productivity, in the scale of enterprises, in capital employed, and in its share of national income. Value added in cotton rose from less than £500,000 in 1760 to about £25,000,000 by the mid-1820s. In spinning, the number of direct labor hours required to process 100 pounds of cotton declined from 300 in 1790 to 135 in 1820 (Mokyr 2002: 50–1), and the average annual input of raw cotton per factory rose by over 1,000 per cent during 1797–1850 (Chapman, 1972: 70). Dramatic as these changes were, they should be kept in proportion: textiles made up about 25 per cent of manufacturing output at their peak. Innovation and productivity were growing elsewhere as well.

Another critical innovation of this period was the steam engine of James Watt, first introduced in 1775. Watt's innovation is commonly described as the emblematic technology of the Industrial Revolution (see Toynbee 1908; Deane 1965). Yet von Tunzelmann's study of steam power (1978) showed that the machine diffused relatively slowly, that it had only modest economic advantages over existing power technologies (and hence could not significantly affect economic growth), and had limited backward and forward linkages with the rest of the British economy, further reducing its "catalytic" effects (see Box 13.1). As we noted earlier, the innovations that p. 354 ↳ contributed to British economic growth and industrialization spanned a broader group of technologies and sectors.

Box 13.1 Technological diffusion in the First Industrial Revolution

Since the economic effects of innovations depend on their widespread adoption (see Ch. 17 Hall by in this volume), it is important to recognize that many of the important innovations of the First Industrial Revolution in fact diffused relatively slowly. For example, the Watt steam engine, described above as an emblematic innovation of the First Industrial Revolution, diffused gradually through the British economy. By 1800, twenty-five years after the introduction of the Watt steam engine, Manchester (a central locus of industrialization in textiles) had about 32 engines, and Leeds (another emergent textiles center) about 20. By 1817 Glasgow had 45 engines, by 1820 Birmingham had about 60 engines, and by 1825 Bolton had 83. Growth rates of steam-generated horsepower averaged between 6 and 10 per cent per year in the late 1830s, more than 50 years after the Watt engine's introduction. Von Tunzelmann (1978) argued that this gradual pace of diffusion reflected the high costs of steam engines and their fuels through the 1850s, long after the introduction of the engine. Similar points apply to other important innovations of this period. The Roberts automatic spinning machine, said by no less an observer than Karl Marx to "open up a completely new epoch in the capitalist system," was a major innovation—the world's first truly automatic power machine. But it diffused slowly; fifty years passed before this machine accounted for a majority of the output of the UK cotton spinning industry.

13.2.4.2 Innovation in Other Sectors

Although industrialization necessarily was associated with a fall in the share of national output flowing from agriculture, British agriculture grew in absolute terms during 1750–1850 and was highly innovative. During this period, key innovations were developed in farm tools, cultivation implements (plows, harrows, mowers), sowing implements, harvesting equipment (reapers, rakes, hoes, scythes, winnowing and threshing devices, etc.), and drainage equipment (for a detailed overview, see Bruland 2004). Agricultural innovation was associated with the emergence by the 1830s of a specialized agricultural equipment industry, which in turn supported the growth of numerous small engineering works and foundries.

Closely linked with technical change in the agricultural sector were innovations in the processing, distribution, and consumption of food, which during the Industrial Revolution (and after) dominated British manufacturing. Technological innovations in food preservation, refrigeration, baking, brewing, and grain milling supported expansion in the scale of production establishments and organizational innovation of production and firms. Baking was the first British industry to develop and use the production line, based on new techniques that supported more accurate timing of operations. Brewing and milling were the first sectors to deploy large, professionally managed enterprises with national distribution systems.

A similarly innovative sector was the glass industry, which manufactured widely used and differentiated products—windows, bottles and containers, lamps, and spectacles. Glass was one of the few large-scale production activities in early industrialization, and relied on experimentation and research to a degree not widely appreciated in many accounts of the role of science in technological innovation during this period. The most knowledge-intensive segment of glass production was optical glass, where developments of the technology deployed optical theory, pioneering the integration of science with production. Although the first Industrial Revolution overall was far from a science-based phenomenon, developments in at least some of the key innovative sectors prefigured subsequent changes in the organization of innovation.

These examples of innovation could easily be expanded to include sectors such as iron and steel, chemicals (alkalis and chlorine), pottery and ceramics, machinery and machine tools, instruments, mining, and paper and printing. The pervasiveness and extent of innovation in these and other industries once again suggests that innovation during the First Industrial Revolution was not confined to "leading sectors" of the economy, but was present in virtually all sectors during the period. We cannot ignore the sectors such as textiles and steam power that have driven so much of the historiography of industrialization; but their role needs to be kept in economic and technological perspective.

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13.2.5 The Organization of Innovation and Learning in Early Industrialization

How was innovation organized during the First Industrial Revolution? Analyses of patent data suggest that virtually all inventions in the late eighteenth and early nineteenth centuries resulted from the efforts of individual inventors. These inventors may have worked alone in individual workshops or in larger enterprises, but the key point was the individuality of inventive and innovative effort, and its integration with shop-floor production. Inventors' skills and knowledge bases were rooted in existing trades, such as watchmaking, carpentry, blacksmithing, metalworking, and woodworking. Textile machinery in particular was fabricated largely within the existing textile-producing firms. A specialized capital goods sector appeared only in the 1820s.

The upsurge in inventive and innovative activity during the Industrial Revolution did not depend in any general way on "science" as we now understand it, although isolated instances of the integration of science and industry during the late eighteenth and early nineteenth centuries are apparent in such areas as glassmaking. The period saw the emergence of formal and informal scientific societies in Great Britain and wide diffusion of scientific ideas (see Uglow 2002), but this early "scientific revolution" produced few practical applications. Although the search and learning processes employed by inventors during this period are best described as "trial and error," this characterization inaccurately minimizes the extent and sophistication of the knowledge required for innovation in early industrialization. Indeed, Mokyr has proposed that a central factor in the Industrial Revolution was an "Industrial Enlightenment," associated with improvement in the quantity and accessibility of knowledge concerning industrial techniques. This "Enlightenment" included the surveying and codification of artisanal techniques in published manuals, handbooks, textbooks, and pamphlets on industrial practices (Mokyr 2002: 34–5). Patterns of learning and knowledge accumulation during the Industrial Revolution may have begun as tacit and practical, but during the late eighteenth and early nineteenth centuries, more and more of this learning was codified, accelerating the diffusion of industrially relevant knowledge across sectors.

13.2.6 Institutions and the Organization of Enterprise during the First Industrial Revolution

Institutional change that affected the organization of firms and production processes played an important role in the upsurge of innovation during early industrialization. This is a vast topic, and we focus on two crucial institutional changes—the development of new forms of company lawand finance that supported
p. 356 the growth of ↳ corporate firms; and the rise of managerial control of production, which transformed workplace organization and scale. These institutional innovations together made possible the subsequent growth in factory production.

Most industrial enterprises operating during the eighteenth century were extremely small. Large-scale factories were uncommon before the early nineteenth century, and the small-scale workshop or production unit was the primary organizational form for most of the period of early industrialization. These small firms were individually owned or were partnerships, locally financed, in which liability for debts was the personal responsibility of owners who usually acted as managers. Two institutional forms made possible an expansion in the scale of enterprises: jointstock (i.e. limited liability) organization and the growth of financial networks.

Joint-stock associations emerged in the medieval period in Britain, but were permitted only via the explicit authorization of the state. A series of piecemeal reforms after 1825 were followed by legislation permitting the creation of companies with separate legal identity, limited liability and tradeable shares. General legislation for the joint stock form was passed in 1844 and consolidated in the statutes of 1856 and 1862 (Mathias 1983: 325; see Harris 2000 for a comprehensive account). Although much industrial financing remained local and small in scale (see Hudson 1986 for an account of local networks' role in financing the woollen industry), these legal reforms enabled substantial growth in the financing and scale of industrial enterprises. But joint stock organization and access to finance were necessary rather than sufficient conditions for enterprise growth. Even more significant was the development of management systems and managerial control.

Managers of these early industrial enterprises confronted serious challenges in the assembly and maintenance of a suitable workforce, the control of work, and the adoption of new techniques and organizational structures for production activities by a restructured workforce. Pollard highlights "two distinct, though clearly overlapping difficulties; the aversion of workers to entering the new large enterprises with their unaccustomed rules and discipline and the shortage of skilled and reliable labour" (Pollard 1965: 160). The emergence of rule-based disciplinary methods, the laborious construction of supervisory systems, and the habituation of workers to an organized and controlled working day emerged slowly but were central developments of early industrialization. New management techniques that appeared during the Industrial Revolution permitted the development of larger, centralized production sites and of the mechanized factory. In turn, such sites permitted the application of power, the adoption of new industrial techniques, and closer managerial control over the organization and pace of work.

These organizational and managerial innovations were defining characteristics of the First Industrial Revolution. In pottery for example, the most important managerial innovator was Josiah Wedgwood, who developed a number of product innovations—new designs, new glazes and finishes, and new basic materials
p. 357 —and pioneered new marketing methods. But his most important innovations were ↳ organizational—the creation of an integrated workforce, the design of a plant organized around a set of production sequences, and above all the creation of a workforce subject to control and discipline (McKendrick 1961; see Box 13.2). Wedgwood's innovations strengthened managerial power over the production workforce, which formed the central context for innovation (and struggle) in the later nineteenth century.

Box 13.2 Josiah Wedgwood and “modern” management in pottery fabrication

In the second half of the eighteenth century, rising incomes and increased coffee and tea consumption accelerated growth in the market for china and other types of glazed, fired clay plates, cups, and related items. This was part of a wider growth in demand for “luxury” consumer goods (Berg and Eger 2003). The production of pottery was concentrated in Staffordshire in central England, and was dominated by small enterprises operated by craftsmen, often producing on a piecework basis. Production was controlled by individual craftsmen, and production rhythms and volumes were haphazard. Josiah Wedgwood transformed the industry by developing factory-based production techniques that supported the creation of an enterprise of unprecedented scale. Wedgwood's success rested on two achievements. First, he successfully lobbied the British government to improve regional transportation infrastructure (a publicly financed turnpike was built in 1763 and a canal, on which Wedgwood sited his factory, was completed in 1771), thereby enabling his factory to serve the British market while reducing formerly exorbitant breakage rates. Second, he introduced radical organizational innovations, developing new techniques for organizing production and managing the workforce (Bruland 1989).

Wedgwood, an acquaintance of Matthew Boulton, the entrepreneur who formed the successful steam-engine firm of Boulton and Watt, modeled his new production organization on Boulton's factory, emphasizing a physical layout that separated and sequentially organized the various operations that went into production of his china (Langton 1984). Consistent with this organization, Wedgwood assigned workers to specific tasks, relying on specialization to enhance skill and consistency in the performance of these tasks. Workmen “were not allowed to wander at will from one task to another as the workmen did in the pre-Wedgwood potteries. They were trained to one task and they had to stick to it” (McKendrick 1961: 32).

Having reorganized the structure of production and jobs within his organization, Wedgwood had to develop techniques to encourage and/or force workers to adapt to this new system. He invested heavily in the retraining of experienced workers (with mixed results) and in the training of new employees, many of whom were young women (women accounted for 25 per cent of his employees as of 1790). Even more important, however, was Wedgwood's emphasis on codification of technical guidelines for the performance of the various tasks in his factory and development of extremely detailed, written rules for worker behavior. Wedgwood also introduced sanctions and rewards for punctuality and absenteeism on the part of workers, going so far as to develop an early prototype of a timeclock for monitoring workers' attendance.

Wedgwood's new methods were significant organizational changes in the production of kitchenware and china, resting on a transformation of the nature and character of work itself. The new methods encountered considerable resistance from experienced workers, but he successfully created a production system without equal in the industry, employing 200 workers. By 1790, less than twenty-five years after its foundation. Wedgwood himself was enormously wealthy, and the firm survived as an independent entity into the twentieth century.

 An essential ingredient in the transformation of economic and innovative activity that characterized the First Industrial Revolution thus was the development of new techniques of economic organization and management. Another wave of institutional change and managerial innovation proved indispensable to the Second Industrial Revolution and an organizational innovation that was at its heart—the industrial research laboratory.

13.3 The Second Industrial Revolution

13.3.1 A Second Phase of Industrialization

In the late nineteenth century industrial technologies began to change, and a range of new technologies and industries emerged. This Second Industrial Revolution took place on the continent of Europe and in the USA. In Europe it was led by the emergence of new industrial regions in France and Germany, such as the Ruhr. It involved a shift away from the basic industries that had developed in Britain before diffusing to Europe and the United States (iron, steel, coal, textiles, and mechanical engineering), to new industrial sectors (such as chemicals, optics, and electricity), and signaled the passing of technological leadership from Britain to the United States and Germany.

The Second Industrial Revolution was characterized by organizational innovations that laid the groundwork for links between industry and formal science that became stronger during the course of the twentieth century. The development of these stronger links transformed the innovation process in several ways: (1) Formal training for would-be inventors became far more important and the role of artisanal ingenuity diminished;[3] (2) the role of institutions external to the firm that p. 359 ↳ conducted such formal training and research increased; and (3) bodies of empirically grounded, codified scientific and technological knowledge internal to the firm became powerful engines for expansion and diversification.

The technological shifts of the late nineteenth century were accompanied by changes in firm structure. Large-scale, vertically integrated enterprises emerged in Germany and the United States that incorporated specialized research and development departments or laboratories. Within such firms scientific work was carried out by teams of researchers and depended on networks of scientific contacts in the education (particularly university) systems. These professionally managed firms of unprecedented size became the agents of Schumpeter's "creative destruction" by the mid-twentieth century, as industrial innovation became a core component of corporate strategy.

13.3.2 Was the Second Industrial Revolution a "Science-Driven" Phenomenon?

Although important scientific breakthroughs and an expanded application of science to industry did emerge in the late nineteenth century, for most of the century these two trends were more loosely coupled to one another than is commonly thought. The construction of a bridge between recent scientific discoveries and technological innovation typically requires considerable time. For example, no significant technological applications followed Faraday's demonstration of electromagnetic induction in 1831, with the exception of the telegraph. Yet this scientific discovery laid the foundations for one of the defining industries of the Second Industrial Revolution, electrical equipment and electric power generation.

As the example of electricity suggests, technological exploitation of new scientific understanding often requires considerable time, since additional applied research is needed to translate a new but abstract formulation into economically useful knowledge. In other important cases, such as Perkin's accidental synthesis in 1856 of mauveine, the first synthetic dyestuff, exploitation of scientific advances required the development of complex process technologies for which no scientific foundation existed. Although chemical science was vitally important to industrial developments during the period, much of the actual timing of innovation, i.e. the translation of scientific breakthroughs into commercial products, depended on advances in manufacturing technologies that remained poorly understood through much of the nineteenth century.

In other industries, the linkage between science and technological innovation remained weak, simply because technological innovation did not require scientific knowledge. This was true of a broad range of metal-using industries in the second half of the nineteenth century, a period during which America took a

p. 360 position of ↳ technological leadership. The development of this new machine technology rested on mechanical skills of a high order, as well as considerable ingenuity in conception and design. It required little or no recourse to the scientific knowledge of the time, and US success in this and other industries, such as chemicals, meatpacking, and consumer goods, relied on access to a large domestic market.

The creation of a truly “national” market in the United States in turn was facilitated by the construction of a reliable national infrastructure for communications and transportation. The enterprises most heavily involved in the creation of this infrastructure were themselves among the largest industrial firms organized in the United States, and the organizational and financial innovations developed by firms such as Western Union and the Pennsylvania Railroad werewidely emulated in other industries as new firms of unprecedented scale were created (Chandler 1977). But few if any of these economically crucial organizational innovations relied on science.

13.3.3 The Origins of Industrial Research

A defining characteristic of the “new industries” of the Second Industrial Revolution was their increased reliance on organized experimentation. The pioneers in this organizational innovation were the large German chemicals firms that grew rapidly in the last quarter of the nineteenth century, based on innovations in dyestuffs. By the first decade of the twentieth century, a number of large US firms had established similar in-house industrial research laboratories. In both nations, the growth of industrial research was linked to a broader restructuring of manufacturing firms that transformed their scale, management structures, product lines, and global reach. But the development of industrial research in the German chemicals and electrical equipment industries also relied on complementary changes in the institutional structure of the nascent “German” innovation system that occurred before and after German unification in 1870.[4]

Scientific advances in physics and chemistry during the last third of the nineteenth century created considerable potential for the profitable application of scientific and technical knowledge in industry. The first in-house industrial R&D laboratories were established by German firms seeking to commercialize innovations based on the rapidly developing field of organic chemistry. Kekule's 1865 model of the molecular structure of benzene, a key component of organic chemistry and synthetic dyestuffs, provided the first scientific foundation for developing new products. But scientifically trained personnel were needed to translate Kekule's breakthrough into new products. The rapid expansion in Germany's network of research and technical universities during the second half of the nineteenth century thus was critically important to
p. 361 the growth of industrial research, particularly in the chemicals industry. ↳ German universities produced a large pool of scientifically trained researchers (many of whom sought employment in France and Germany during the 1860s), university faculties advised established firms, and university laboratories provided a site for industrial researchers to conduct scientific experiments in the early stages of the creation of in-house research laboratories.

The German universities pioneered the development during the nineteenth century of the modern model of the “research university,” in which faculty research was central to the training of advanced degreeholders. In addition, the German polytechnic institutes that had been founded during the 1830s by the various German principalities were by the 1870s transformed into technical universities that played a central role in training engineers and technicians for the chemicals and electrical equipment industries. By the 1870s, according to Murmann (1998), Germany had nearly thirty university and technical university departments in organic chemistry, and seven major centers of organic chemistry research and teaching. And technically trained personnel moved into senior management positions within German industry, in contrast to the situation in Great Britain, further strengthening the links between corporate strategy and industrial research.

The contrast between Germany and Great Britain in the role of universities is especially striking.[5] British universities received far less public funding, supported less technical education, and were less closely linked with domestic chemicals firms than was true in Germany by the 1880s. British university enrollment increased by 20 per cent between 1900 and 1913, far less than the 60 per cent increase in German university enrollment during the same period. Enrollment at the "redbrick" British universities (largely founded during the nineteenth century, this group excludes the ancient English universities of Oxford and Cambridge) grew from roughly 6,400 to 9,000 during 1893–1911, but only 1,000 of the students enrolled in these universities as of 1911 were engineering students, while 1,700 were pursuing degrees in the sciences (Haber 1971: 51). By contrast, the German technical universities alone enrolled 11,000 students in engineering and scientific degree programs by 1911. British government funding of higher education amounted to roughly £26,000 in 1899, while the Prussian government alone allocated £476,000 to support higher education. By 1911, these respective amounts stood at £123,000 and £700,000 (Haber 1971: 45 and 51).

The institutional transformation of Germany's national innovation system was both a cause and an effect of the growth of the chemicals and electrical equipment industries. Werner von Siemens of the Siemens electrical equipment firm was a founder of the German Association for Patent Protection in 1874, and the first national patent law in the new German state was passed in 1877. Although the law did not cover dyestuff products, stronger intellectual property protection increased the ease with which firms could appropriate the returns to their R&D, and many of the largest German chemicals firms established formal in-house R&D laboratories after its passage.

p. 362 The large, profitable firms that emerged in these science-based industries actively lobbied the German government for increased support of higher education (The "Club of German Chemists," drawn largely from senior management of German chemicals firms, lobbied for additional faculty appointments in chemistry) and for other forms of support of research related to their enterprises. Werner von Siemens donated the land for the Imperial Institute of Physics and Technology, located near his firm's headquarters in Berlin and the city's technical university, and the Institute was formally established with public funds in 1887. Similar lobbying by the chemicals industry led to the announcement in 1910 by the German emperor of the foundation of the Kaiser Wilhelm Institute for Chemistry, staffed largely by academic chemists and funded by industry. Both the Institute of Physics and Technology and the Kaiser Wilhelm Institute were dedicated to "mission-oriented" fundamental research, much of which was longer-term in nature than the R&D performed in industry but nonetheless more applied than the work of university faculties (Beyerchen 1988).

The creation by German chemicals firms of in-house industrial research laboratories also was associated with change in the management and structure of these firms (see Box 13.3). Family managers were replaced by professional managers and, eventually, by professional chemists. Their in-house R&D activities
p. 363 produced new products in fields other than dyestuffs, e.g. Bayer's aspirin. And the importance of ↳ close links between research personnel and the users of these new products, as well as the proliferation of new products, triggered expansion in these firms' internal distribution and marketing capabilities. Just as US firms were doing by the end of the nineteenth century, the German chemicals firms expanded their boundaries to incorporate new functions and a much broader and more diversified product line. A similar sequence occurred at roughly the same time in the German electrical equipment industry, as Siemens and AEG, among other leading firms, established in-house research laboratories during the 1870s and 1880s.

Box 13.3 The foundation of R&D laboratories by Bayer and Du Pont

Bayer's foundation of a laboratory was triggered in part by a realization among the firm's senior management that it was unable to compete effectively with Hoechst and BASF (which had founded research laboratories respectively in 1877 and 1878), as well as the growing difficulties that Bayer faced in forming strong linkages with leading university research chemists. In 1883, Carl Duisberg, who later served as the first director of Bayer's in-house research facility and the firm's CEO, was sent by Bayer managers to work with the chemistry faculty at the University of Strasbourg (then a German university), before returning to Bayer to begin work in the firm's R&D laboratory (a small room just off the main production floor in Bayer's plant). At the same time, Bayer sought to strengthen its links with German university chemists through other tactics, including the negotiation of contracts with leading research chemists and the funding of research by new Ph.D. degree holders in university or technical university laboratories.

Duisberg's first laboratory was at best an appendage to Bayer's main production facility, but his success in dyestuff synthesis led to an expansion in his staff. Nevertheless, Duisberg's group had important responsibilities in production engineering and problem-solving, as well as marketing, until roughly 1890. Only in 1891 was a dedicated laboratory established at Bayer and a clear distinction made within the organization between R&D and workaday technical support (see Meyer-Thurow 1982).

The US chemicals firm Du Pont established its first industrial research facility, the Eastern Laboratory, in 1902, and founded the Experimental Station in 1903. Creation of the Eastern Laboratory followed the acquisition of control of the Du Pont Company, founded in the early nineteenth century, by T. Coleman Du Pont, Pierre S. Du Pont, and Alfred I. Du Pont from other family members. The Company's transformation from a loose holding company to a multifunction, diversified industrial corporation began with this 1902 change in control.

Du Pont's Eastern Laboratory was the first laboratory to be physically and organizationally separated from the manufacturing operations of the firm. Its R&D activities were devoted almost entirely to improvements in manufacturing processes for Du Pont's existing product line of dynamite and high explosives. By contrast, the Experimental Station, founded one year later, focused on the development of new products and improved applications of Du Pont's smokeless-gunpowder products. The Experimental Station also monitored and evaluated inventions from sources outside of the Du Pont Company.

A US government antitrust suit against Du Pont forced the divestiture of a portion of its black powder and dynamite businesses in 1913, and the firm used its R&D laboratories to diversify its product lines through R&D and the acquisition of technologies from external sources during and after World War I.

The development of industrial research within US manufacturing firms followed these developments in the German chemicals and electrical machinery industries. Many of the earliest US corporate investors in industrial R&D, such as General Electric and Alcoa, were founded on product or process innovations that drew on recent advances in physics and chemistry. The corporate R&D laboratory brought more of the process of developing and improving industrial technology into the boundaries of US manufacturing firms, reducing the importance of the independent inventor as a source of patents (Schmookler 1957).

But the in-house research facilities of large US firms were not concerned exclusively with the creation of new technology. Just as the German dyestuff firms' laboratories had, these US industrial laboratories also monitored technological developments outside of the firm and advised corporate managers on the acquisition of externally developed technologies.

p. 364 As Pavitt notes in his chapter in this volume, in-house R&D in US firms developed in parallel with independent R&D laboratories that performed research on a contract basis (see also Mowery 1983). But over the course of the twentieth century, contract-research firms' share of industrial research employment declined. The complex and uncertain projects undertaken within many in-house research facilities did not lend themselves to "arm's-length" organization.

As had been the case in Germany, the development of industrial research, as well as the creation of a market for the acquisition and sale of industrial technologies, benefited from a series of reforms in US patent policy between 1890 and 1910 that strengthened and clarified patentholder rights (See Mowery 1995). Judicial tolerance for restrictive patent licensing policies further increased the value of patents in corporate research strategies. Although the search for new patents provided one incentive to pursue industrial research, the impending expiration of these patents created another important impetus. Both American Telephone and Telegraph and General Electric, for example, established or expanded their in-house laboratories in response to the intensified competitive pressure that resulted from the expiration of key patents (Reich 1985; Millard 1990: 156). Intensive efforts to improve and protect corporate technological assets were combined with increased acquisition of patents in related technologies from other firms and independent inventors.

Schumpeter argued in *Capitalism, Socialism and Democracy* that in-house industrial research had supplanted the inventor-entrepreneur (a hypothesis supported by Schmookler 1957) and would reinforce, rather than erode, the position of dominant firms. The data on research employment and firm turnover among the 200 largest US manufacturing firms suggest that during 1921–46 at least, the effects of industrial research were consistent with his predictions. Displacement of these firms from the ranks of the very largest was significantly less likely for firms with in-house R&D laboratories (Mowery 1983).

13.3.4 Innovation in the Interwar Chemicals Industry

As we noted in the previous section, one of the critical science-based industries associated with this Second Industrial Revolution was chemicals. A comparison of US and German innovative performance in this industry highlights many of the points made above concerning the new institutional and organizational underpinnings of innovation during this period. Although German and US chemicals firms had pioneered in the development of a new structure for innovation that relied on in-house R&D and the "routinization of innovation," these two groups of firms pursued somewhat different innovative strategies during the
p. 365 interwar period following the creation of their R&D facilities. These differences highlight the ↳ influence of cross-national contrasts in market structure and resource endowments, factors that receded somewhat in importance after 1945.

One important point of contrast was the quality of scientific research in chemistry (as opposed to technological innovation) of leading firms and universities in the two nations. Through 1939, German scientists received fifteen out of the thirty Nobel Prizes awarded in chemistry, US scientists received only three, and French and British scientists each accounted for six. Between 1940 and 1994, US scientists received thirty-six of the sixty-five chemistry Prizes awarded, German scientists received eleven, British scientists received seventeen, and French scientists received one (*Encyclopaedia Britannica* 1995: 740–7). Although the situation was beginning to change during the 1930s and would change dramatically after 1945, the United States remained a scientific backwater during this portion of the twentieth century.

Technological change in the American chemical industry was shaped by several features: (l) the large size and rapid growth of the American market; (2) the opportunities afforded by large market size for exploiting the benefits to be derived from large-scale, continuous process production; and (3) a natural resource endowment—oil and gas—that provided unique opportunities for transforming the resource base of the organic chemical industry and achieving significant cost savings, if an appropriate new technology could be developed.

The introduction and rapid adoption of the internal combustion automobile in the opening years of the twentieth century in the United States brought in its wake an almost insatiable demand for liquid fuels. This demand in turn spurred the growth of a new sector of the petroleum refining industry that was specifically calibrated to accommodate the needs of the automobile in the first two decades of the twentieth century. Petroleum refining had two important, related features. First, it was highly capital-intensive; by the 1930s it had become the most capital-intensive of all American industries. Second, productive efficiency required that small batch production, so characteristic of other chemical products, such as synthetic organic materials, be discarded in favor of high-volume production methods that required continuous-process technologies. American leadership in petroleum refining provided the critical knowledge and the engineering and design skills to support the chemicals industry's shift from coal to petroleum feedstocks in the interwar years.

The large size of the American market had introduced American firms at an early stage to the problems involved in the large-volume production of basic products, such as chlorine, caustic soda, soda ash, sulfuric acid, superphosphates, etc. The early American experience with large-scale production contributed to the US chemical industry's transition to petroleum-based feedstocks. The dominant participants in this industrial transformation were Union Carbide, Standard Oil (New Jersey), Shell and Dow. But the shift to petroleum benefited as well from the adoption by US petroleum firms, notably Humble Oil (an affiliate of Standard Oil of New Jersey), of new techniques for discovery and exploitation of petroleum deposits. The
p. 366 availability of low-cost petroleum and natural gas, coupled with the ↳ new, large-scale process innovations developed by US firms, enabled significant reductions in manufacturing costs.

By contrast, the German chemicals industry fashioned new technologies that compensated for the absence of such domestic feedstocks. During World War II, German tanks and airplanes were fueled by synthetic gasoline and ran on tires made from synthetic rubber derived from coal feedstocks. Only in the wake of World War II and the creation of a set of multilateral institutions governing international trade and finance did the revival of international trade and US guarantees of access to foreign petroleum sources support a shift by the German chemicals industry to petroleum feedstocks (Stokes 1994). Here as well as elsewhere, the post-1945 revival of international trade and investment flows relaxed somewhat the constraints on technological innovation imposed by reliance on domestic natural resources. As Abramovitz (1994) and other scholars (Nelson and Wright 1994) have pointed out, economic conditions in Europe and elsewhere in the global economy gradually came to resemble more closely those that had given rise to US supremacy in this sector.

13.4 A “Third Industrial Revolution”? R&D and Innovation during the post-1945 Period

13.4.1 The Post-war Transformation

The structure of the innovation process in the industrial economies was transformed after 1945. Global scientific leadership shifted decisively from Western Europe to the United States. A new set of industries, focused on ICT and biomedical innovation, grew rapidly. As global trade and investment flows revived after the 1914–45 period of war and depression, international flows of technology also expanded, and by the 1980s and 1990s enabled economies such as Japan, South Korea, and Taiwan to advance to the front rank as sources of industrial innovation. Developments in the United States illustrate these trends most vividly, and highlight the development of a US “national innovation system” that contrasted sharply with its 1900–1940 counterpart.

The structure (if not the scale) of the pre-1940 US R&D system resembled those of other leading industrial economies of the era, such as the United Kingdom, Germany, and France—industry was a significant funder and performer of R&D and central government funding of R&D was modest. Innovation and R&D during the p. 367 ↳ post-1945 period in the United States were transformed by the dramatic increase in central government spending on R&D, much of which was allocated to industry and academic research. As Lundvall and Borrás point out in Chapter 22 of this volume, this expansion in public R&D funding was motivated primarily by national security and public-health concerns and secondarily by political support for basic research. The post-war US R&D system differed from those of other industrial economies in at least 3 aspects: (l) small, new firms were important entities in the commercialization of new technologies; (2) defense-related R&D funding and procurement exercised a pervasive influence in the high-technology sectors of the US economy; and (3) US antitrust policy during the post-war period was unusually stringent.

The prominence of new firms in commercializing new technologies in the postwar United States contrasts with their more modest role during the interwar period. In industries that effectively did not exist before 1940, such as computers, semiconductors, and biotechnology, new firms were important actors in R&D and commercialization, in contrast to post-war Japan and most Western European economies. Moreover, in both semiconductors and computers, new firms grew to positions of considerable size and market share.

Several factors contributed to this prominent role of new firms in the post-war US innovation system. The large basic research establishments in universities, government, and a number of private firms served as important “incubators” for the development of innovations that “walked out the door” with individuals who established firms to commercialize them. Relatively weak formal protection for intellectual property during the 1945–80 period paradoxically also aided the early growth of new firms. Commercialization of microelectronics and computer hardware and software innovations by new firms was aided by a permissive intellectual property regime that facilitated technology diffusion and reduced the burden on young firms of litigation over inventions that originated in part within established firms. In microelectronics and computers, liberal licensing and cross-licensing policies were by products of antitrust litigation, illustrating the tight links between these strands of US government policy. US military procurement policies also contributed to the growth of new firms in microelectronics and contributed to high levels of technological spillovers among these firms.

13.4.2 Electronics and ICT

Advances in electronics technology created three new industries—electronic computers, computer software, and semiconductor components—in the post-war global economy. The electronics revolution can be traced to two key innovations—the transistor and the computer. Both appeared in the late 1940s, and the exploitation of both was spurred by ColdWar concerns over national security.

p. 368 New firms played a prominent role in the introduction of new products, reflected in their often-dominant share of markets in new semiconductor devices, significantly outstripping that of larger firms. Moreover, the role of new firms grew in importance with the development of the integrated circuit (IC). The US military's willingness to purchase semiconductor components from untried suppliers was accompanied by conditions that effectively mandated substantial technology transfer and exchange among US semiconductor firms. To reduce the risk that a system designed around a particular IC would be delayed by production problems or by the exit of a supplier, the US military required its suppliers to develop a “second source” for the product, i.e. a domestic producer that could manufacture an electronically and functionally identical product. To comply with second source requirements, firms exchanged designs and shared sufficient process knowledge to ensure that the component produced by a second source was identical to the original product. These requirements spurred interfirm “spillovers” of knowledge and knowhow within the semiconductor industry.

The development of the US computer industry also benefited from Cold War military spending, but in other respects the origins and early years of this industry differed from semiconductors. During the war years, the American military sponsored a number of projects to develop high-speed calculators to solve special military problems. The ENIAC—generally considered the first fully electronic US digital computer—was funded by Army Ordnance, which was concerned with the computation of firing tables for artillery. From the earliest days of their support for the development of computer technology, the US armed forces were anxious that technical information on this innovation reach the widest possible audience. The technical plans for the military-sponsored IAS computer were widely circulated among US government and academic research institutes, and spawned a number of “clones” (e.g. the ILLIAC, the MANIAC, AVIDAC, ORACLE, and JOHNIAC—see Flamm, 1988: 52).

Although business demand for computers gradually expanded during the early 1950s, government procurement remained crucial. The projected sale of fifty machines to the federal government (a substantial portion of the total forecast sales of 250 machines) influenced IBM's decision to initiate the development of its first business computer, the 650 (Flamm 1988). New firms played a much more modest role in the early years of the business computer industry, however, in part because established firms such as IBM had developed powerful marketing organizations for electromechanical business equipment sales that were (with some difficulty) adapted to selling computers to their business customers (Usselman 1993). The appearance of new markets for computers that resulted from the development of scientific computers and minicomputers during the 1950s and 1960s and desktop systems during the 1970s and 1980s, however, provided opportunities for entry by many new firms, such as Digital Equipment, Cray Systems, Computer Research Associates, and Apple.

p. 369 The progress of computer technology since the 1950s has been driven by the interaction of several trends: (1) dramatic declines in the price–performance ratios of components, including central processing units and such essential peripherals as data storage devices; (2) resulting in part from(1), the rapid extension of computing technology into new applications; and (3) the increasing relative costs of software. Throughout the brief history of the electronic computer industry, these trends have created bottlenecks that have influenced the path of technological change. The IBM 360 mainframe computer, for example, which cemented IBM's dominance of the US computer industry during the 1960s and 1970s, created a “product family” of computers in different performance and price classes that all utilized a common operating system and other software.

The Intel Corporation's commercialization of the integrated circuit microprocessor in 1971 transformed the structure of the US computer industry during the next twenty-five years. Development of the microprocessor at Intel resulted from a search for an integrated circuit that could be used in a wide range of applications. Rather than designing a custom “chipset” for each application, the microprocessor made it possible for Intel to produce a powerful, general-purpose solution to many diverse applications, breaking a bottleneck that limited technological progress and diffusion.

The microprocessor was the foundation for a new generation of computing technology that transformed the ICT industry. Desktop computers diffused rapidly throughout most industrial economies, and the sheer size of the resulting “installed base” radically changed the economics of the computer hardware and software industries. Computer software, formerly dominated by relatively small independent vendors or subsidiaries of established computer systems producers, became a mass-market industry that supported entry by a flood of new firms, some of which proved to be enormously profitable. Established producers of computer hardware were severely affected by the rise of desktop systems, which encroached rapidly on markets for mainframe and minicomputers. By the end of the twentieth century, only a few of the dominant computer systems firms of the 1970s remained active.

The final dramatic transformation in computing technology, the Internet, depended on the appearance of the desktop computer (see Box 13.4). The development of computer networking and the Internet began during the 1960s and was sponsored by governments in the United States, France, and the United Kingdom. The large-scale and early commitment to deployment of computer networks in the United States, which relied entirely on public funds, as well as the rapid diffusion of desktop computers in the United States during the 1980s, created a huge domestic network by the late 1980s. Although the HTTP and HTML “hypertext” software protocols were invented at the European research center, CERN, in 1991, the first commercial application of these protocols as part of a “Web browser” emerged from a US university in 1993.

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Box 13.4 The Internet

A collection of independent but interconnected networks built and managed by a variety of organizations, the Internet owes its success to institutional as well as technological innovations (Mowery and Simcoe 2002). Research in computer networking was supported by governments in France, the United Kingdom, and the United States during the 1960s. A central goal of Defense Department computernetworking research was to enable more effective use by researchers in universities, government, and industry of the small number of large research computers then available.

Research and early experiments in computer-networking technology in all three nations led to the development of prototype networks. But the ARPANET, deployment of which in 1969 was sponsored by the US Defense Advanced Research Projects Agency, was far larger and linked more diverse groups of researchers than the prototype networks in France and the United Kingdom. Computers attached to the ARPANET "backbone" communicated on the basis of a shared set of protocols (TCP/IP), another outcome of DARPA research. Later policy decisions by the National Science Foundation (NSF) and other federal agencies that shared responsibility for the backbone encouraged standardization of Internet infrastructure. These agencies also promoted expansion of the Internet beyond the science and engineering communities. In 1990, the US Defense Department transferred managerial control over the Internet infrastructure to NSF, and five years later NSF transferred responsibility for the core network to the private sector.

Software protocols and architectural elements critical to the Internet had been placed in the public domain from the beginning. Open standards encouraged expansion by making available the details of core innovations and lowering entry barriers for firms that supplied hardware, software, and networking services. State and federal regulation of telecommunications aided the rapid diffusion of the Internet in the United States by maintaining low, time-insensitive rates. The 1982 settlement of the federal government's antitrust suit against AT&T restructured the US telecommunications industry and encouraged entry by new service providers, spawning further innovation. But through the late 1980s, the Internet was used mainly by researchers from the academic, industrial, and government communities throughout the world.

Key inventions (HTML and HTPP, developed by Berners-Lee) from CERN, the European particle-physics installation, were used by US technology developers (a group of graduate students in computer science at the University of Illinois, among whom the best-known is Marc Andreesen, who moved to Netscape to commercialize a browser based on the MOSAIC technology developed at the University) to produce the first "browser" in 1994, which vastly expanded use of the Internet and led to the "World Wide Web." The large "installed base" of desktop computers in the United States was a powerful impetus to the "user-led" innovation that quickly produced a vast array of new applications and eventually, a speculative bubble in the equity markets. But the "radical innovation" of the World Wide Web in fact represented a culmination of nearly thirty years of research and innovations in networking protocols and software, as well as high-speed data transmission, routers, and computer processing and memory technologies.

 Commercial exploitation of the Internet proceeded most rapidly in the United States during the remainder of the 1990s. Like previous US innovations in ICT, the Internet's development drew on a mix of public and private R&D funding, as well as entrepreneurial new firms seeking to commercialize new applications and an active (and entrepreneurial) community of university researchers. Moreover, the Internet's commercial development, as well as the development of desktop systems and software in the United States, benefited from the enormous size of the US market and the large domestic installed base of desktop computers that was rapidly connected to the Internet. Innovation in the Internet benefited from the participation of millions of users in developing or refining new applications, just as had been the case with desktop computer software during the 1980s. In other words, the development of one of the major industries of the late twentieth and early twenty-first centuries benefited from the large size of the US domestic market, a central feature of US economic development that has been prominent since the nineteenth century.

13.4.3 Innovation in Pharmaceuticals and Biotechnology

World War II initiated a transition in the United States to a pharmaceutical industry that relied on formal, in-house research and on stronger links with US universities that were also moving to the forefront of research in the biomedical sciences. The post-war era in the US pharmaceuticals industry opened with a widespread expectation in the industry that there existed a vast potential market for new pharmaceutical products, and that catering to this market, however costly, would prove to be highly profitable.

The post-war period alsowitnessed a remarkable expansion of federal support for biomedical research through the huge growth in the budget of the National Institutes of Health. Between 1950 and 1965, the NIH budget for biomedical research grew by no less than 18 per cent per year in real terms. By 1965, the federal government accounted for almost two-thirds of all spending on biomedical research. Although NIH funding has continued to grow rapidly, it has been outstripped by growth in privately funded R&D since the 1960s. The US Pharmaceutical Manufacturers Association estimated that foreign and US pharmaceuticals firms invested more than $26 billion in R&D in the United States in 2002, substantially above the $16 billion R&D investment by the National Institutes of Health in the same year (see Pharmaceutical Manufacturers Association 2003, for both estimates).

The identification of the double helix structure of DNA by Watson and Crick in 1953 eventually set off a new epoch of technological change in the pharmaceuticals industry. Biotechnology has created new techniques for drug discovery, as well as new techniques for production of existing drugs, such as insulin (Henderson et
p. 372
al. ↳ 1998). The biotechnology enterprise was supported by huge federal expenditures on R&D, including the Nixon Administration's War on Cancer of the early 1970s. As Mowery and Sampat point out in their chapter (8) on universities in this volume, biotechnology has been a key area of university–industry research collaboration, as well as university patenting and licensing, since the 1970s. And as Powell and Grodal (Ch. 3) note, much of the innovation process in the “new” pharmaceuticals industry that has been triggered by the rise of biotechnology relies on collaboration between the long-established major pharmaceuticals firms, who retain strong capabilities in marketing and management of the complex regulatory process, and new firms that specialize in biotechnology-based drug discovery.

13.4.4 A New “Resource Base” for Innovation

The creation of new industries in the post-war US economy illustrates a fundamental change in the nature of the US resource endowment and its relationship to technological innovation. The trajectory of innovation in the United States for much of the 1900–1945 period was influenced by exploitation of the nation's abundant natural resource endowment. During the post-1945 period, however, a combination of factors shifted US innovation from a natural resource-intensive path of development to one that more intensively exploited a burgeoning US “endowment” of scientists and engineers, derived from both domestic and foreign sources. The scale of US markets remained important, but even this source of national advantage became less significant outside of the ICT sector.

The post-war electronics and biotechnology industries did not rely on domestic endowments of natural resources. But the development of these industries assuredly did benefit from the abundance of scientific and engineering human capital in the post-war United States, as well as an unusual mix of public and private demand for electronics technologies. The creation of an institutional infrastructure during this century that, by the 1940s, was capable of training large numbers of electrical engineers, physicists, metallurgists, mathematicians, chemists, biologists, doctors, and other experts capable of advancing these new technologies, meant that the postwar American endowment of specialized human capital was initially more abundant than that of other industrial nations.

This shift from natural to "created" resource endowments as critical factors in international competition has obviously not been confined to the United States. Indeed, Nelson and Wright (1994) among others (Abramovitz 1994; see also Ch. 19 in this volume by Fagerberg and Godinho) argue that the early post-war economic advantages enjoyed by the United States have been eroded by the widespread investments by governments in education and the development of strong domestic R&D infrastructures. In the post-war
p. 373 era, the resource base for knowledge-based ↳ industries in electronics, no less than in chemicals, pharmaceuticals, or automobiles, has been transformed.

Natural resources *per se* now play a less central role, particularly by comparison with domestic stocks of human capital that can be expanded through public investments in education and training (see Ch. 7 by Edquist in this volume). In addition, many of the historic scale-based advantages enjoyed by US firms in manufacturing industries were eroded during the post-1945 period by the revival of international flows of trade and capital that made it possible for smaller nations to achieve scale economies through the export of their products. Expanded trade and capital flows have also spurred growth in cross-border flows of technology and knowhow (see Ch. 12 by Narula and Zanfei in this volume). This transformation made it possible for nations such as Taiwan and South Korea, with low pre-1945 levels of industrial development (in contrast to Japan, which had created a relatively sophisticated, albeit militarized, industrial base by the 1930s) and relatively modest endowments of natural resources, to "catch up" with the industrial economies (see Ch. 19 by Fagerberg and Godinho in this volume).

13.5 Conclusion

History rarely presents neat lessons for generalization, and the historical study of innovation is no exception. The primary lessons from our historical discussion concern the heterogeneity of the innovation process across time, across sectors, and across countries. Much of the surviving historical evidence that guides the historical study of innovation tends to highlight the formal and obscures the informal processes of knowledge accumulation, learning, and dissemination that underpin technological change and that contribute to its economic benefits. An important area for further research is the enrichment of our historical understanding of the informal processes for knowledge accumulation and diffusion that have been neglected in historical research on the First Industrial Revolution in particular. In addition, as we pointed out in our introductory discussion, a key historiographical mystery remains—why was Northwest Europe the locus of the first transition to sustained, innovation-led growth, rather than Asia or some other region of the global economy?Much of the discussion of this age-old question relies heavily on sweeping generalizations, and more research on the (asserted) failure of non-European economies to make the transition to sustained economic growth during this early period is needed.

p. 374 One of the defining characteristics of innovation through time is change in the structure of the innovation systems that influence the development and dissemination of knowledge and innovations. The "innovation system" characteristic of the First Industrial Revolution relied on a craft-oriented, trial-and-error process, in which familiarity with basic woodworking and metalworking techniques was valuable. Inasmuch as demand factors appear to have influenced the upsurge of innovation on a broad front during this period, the institutional changes that laid the groundwork for growth in incomes and the expansion of markets for consumer goods also were important.

By contrast, the scale and organizational complexity of the innovation system that characterizes the "Second Industrial Revolution" are vastly greater. A new system of innovation emerged, pioneered by German and US firms in the electrical equipment and chemicals industries, characterized by organized innovation activities in large firms interacting with a public R&D infrastructure. The innovation process during this period was institutionalized within large enterprises of unprecedented scale, and the Second Industrial Revolution in the United States relied heavily on the creation of a national market of great size and homogeneity.

The "Third Industrial Revolution" defies summary description, but its characteristic innovation system relied on the state to an even greater extent than the Second Industrial Revolution. The role of the state as R&D funder and (in many cases) "first customer" for the high-technology industries that developed during the Cold War also contributed to another novel feature of the innovation system of the Third Industrial Revolution that is highlighted in Pavitt's chapter in this volume—increased collaboration and interaction among different institutions. State actions also contributed to the spread of innovation-led development to Asia, as the military alliances and economic institutions of the post-1945 period supported the expanded international trade and capital flows that were indispensable to "catch-up." In addition, Asian governments' strategies for technology transfer and industrial development were of great importance (see Ch. 19 by Fagerberg and Godinho in this volume).

Recent historical research stresses the wide distribution of innovation within the industrializing economies of the First Industrial Revolution, in many cases involving sectors overlooked by the previous historical research that has emphasized the "key sectors" of steam and textiles. This characterization of the process of technological innovation has not been sufficiently integrated into conceptual and theoretical work in innovation studies. The integration of recent historical evidence with the broader conceptual frameworks employed in the field of innovation studies represents an important task for future research. More research also is needed on the factors underpinning innovation in sectors other than the "leading industries" of the First Industrial Revolution. Although the patent data indicate that consumer goods were an important focus for such innovation, the factors triggering this upsurge remain poorly understood. Similarly, the
p. 375 development of organized innovation during the ↳ Second Industrial Revolution outside of the electrical equipment and chemicals industries has received far too little attention.

Institutional change in areas ranging from managerial hierarchies and enterprise control to the training of scientists and engineers is of central importance to innovative performance and to change in the structure of innovation systems over time. In many cases, these institutional changes have occurred in response to pressure from innovators and entrepreneurs, and are best characterized as "coevolving" with change in industries and technologies (see Engerman and Sokoloff 2003 for a useful discussion of this point). The transformation of the German and US university systems, as well as the much more limited restructuring of British universities, is but one example of this coevolution; the development of intellectual property rights systems is another. But the conditions under which such political pressure arises, as well as the factors contributing to the success of failure of such pressure, remain poorly understood.

Although it now is widely celebrated as a hallmark of twenty-first-century "knowledge-based economies," science-based innovation is in fact a relatively recent development. Indeed, it appears well after the institutionalization of R&D within industry in the early twentieth century in the United States and Germany. Moreover, even "high-technology" sectors such as biotechnology and semiconductors continue to rely on experimental methods that at their heart are "trial and error" approaches (see Pisano 1997; Hatch and Mowery 1998).

Our approach has been limited both in time and geographical coverage. Perhaps the two most important omissions from this account are the spread of industrialization beyond Germany within nineteenth-century Europe, and a full account of the rise of the Asian economies after 1945 (see Ch. 19 by Fagerberg and Godinho in this volume for a fuller account of the process of economic "catch-up" in Asia). In the first of these cases it is important to remember that the smaller European economies, now among the wealthiest in the world, have benefited from the import and adaptation of technology during the nineteenth-century, and that Ireland since 1970 has enjoyed rapid growth from similar sources. The post-1945 growth of Japan and Korea was originally based on altogether different scales and types of innovative industrialization—adaptation of foreign technologies, largely in such mature industries as automobiles, steel, and shipbuilding (see also Ch. 19 in this volume). But both of these episodes highlight the importance of broad institutional change, rather than the "strategic importance" of any single industry or technology, in much the same way as do the three "Industrial Revolutions" described in this chapter.

Notes

1. Chapter 2 by Lazonick in this volume also discusses the role of the institutional environment in contributing to firm-level innovative capabilities.

2. See Peer Vries (2002) for an overview and critique of the literature in this field.

3. "[S]cientific explanations proved to be reliable guides to the commercial development of new processes and products. Unlike the unrestrained inventions of myth and fable, they could not be ignored by industrial firms except at the risk of being displaced by rival firms. But to understand and apply scientific explanation required years of training in the theology of an invisible pantheon of scientific entities. That requirement professionalized industrial science and diminished the role of artisan invention" (Rosenberg and Birdzell 1986: 253).

4. This discussion draws on Beer (1959), Murmann (1998), and Murmann and Landau (1998).

5. See Murmann (1998, 2003) for a more detailed discussion.

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