3

The United States: Engines of economic growth in the capital-intensive and knowledge-intensive industries

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As emphasized in the previous chapter, a nation's economic growth and competitive strength rest on more than natural resources, labor and managerial skills, available capital, or even the size of internal markets. The wealth of nations during the past hundred years has been based more on organization and technology – on how technologies of production have been created or improved. It rested on the ability of industrial enterprises to adopt and to develop these technologies and to devise administrative structures to coordinate the flow of materials from the raw materials through the processes of production and distribution to the final consumer.

The United States story is a place to begin a study of the impact of "big business" in the form of the large industrial enterprise on the economic performance and growth of nations. During the century from the 1880s to the 1980s the United States was the world leader in terms of per capita income, output per worker, and, most important of all, technical change. In the United States large industrial firms developed – that is, brought to market – the products and processes of more new technologies in a broader variety of industries than in any other nation. As the world's leader, the history of its large industrial enterprises provides an essential introduction to those of other nations. And according to Angus Maddison, "We can get some idea of the changing pace of technical change only by close inspection of performance in the lead country." This chapter divides into three historical periods that follow the chronology of economic growth worldwide outlined in Chapter 1.

The first covers the years from the 1880s to 1914, when unprecedented capital accumulation in the new capital-intensive, scale-dependent technologies helped to propel the United States into a position of world leadership. In this period, firms made the investments large enough to utilize fully the productivity of the new technologies and recruited workers and managers essential for that utilization. These firms became the initial learning bases for the development of product-specific skills and organizational capabilities in these new technologies and the seedbeds of related industrial activities.

The second period covers the interwar years, when such learning continued and led to further augmentation of capital – that is, the more intensive use of existing equipment and facilities – in the industries created before World War I. In these years too, science-based industries became increasingly a major source of commercializing new products and processes closely related to their initial core technologies. The most important source of new capital accumulation and technical progress during the interwar years, however, was the new set of technologies based on the internal-combustion engine, particularly in motor vehicles. Again, those new firms that made the largest investment in tangible goods and most rapidly embodied the needed skills and capabilities into their organizational routines quickly dominated their industries, became essential sources of learning as well as cores of networks of small, medium, and large firms in ancillary industries.

In the third period, from the end of World War II until the 1980s, as the bias of technical progress shifted from the accumulation of tangible capital to that of intangible capital, the primary sources of growth came in new, knowledge-intensive, science-based technologies. In those the essential large-scale investments in both tangible and intangible capital were made not by new enterprises as they had been in the past, but primarily by well-established firms whose existing learned organizational capabilities were critical in developing and commercializing the potential of the new technologies on a global scale. This was true of aerospace, polymer chemicals, antibiotics, telecommunications, consumer electronics, and mainframe computers. And those that made the largest investments, particularly in intangible capital, quickly dominated the commercializing of these new technologies. Large industrial enterprises also played a major role in the exploitation of the two major postwar technologies, those based on electronic integrated circuits and recombinant DNA.

This review only outlines the historical narrative, identifying the beginning and continuing existence of the major players in the capital-intensive and increasingly knowledge-intensive industries. I make little attempt here to detail the processes by which intangible capital came to embody physical capital and how the resulting organizational capabilities were developed

through "learning by using" and "learning by doing." I do, however, point out the continuing interaction between tangible and intangible capital as being absolutely essential to economic growth through technical progress.

CAPITAL-INTENSIVE, SCALE-DEPENDENT INDUSTRIES BEFORE WORLD WAR I

First wave – chemical processes

The exploitation of the new capital-intensive technologies had to wait until the completion of modern transportation and communication networks – those powered by steam and electricity. Only as the railroad, steamship, telegraph, and cable systems were nearing completion in the late 1870s were manufacturing establishments assured the steady, scheduled, high-volume flows of materials *in* and finished products *out* that were essential to maintain close to the potential minimum efficient scale of each new technology. Such firms initially appeared primarily in technologies where the transformation processes were primarily chemical – such industries as primary metals, glass, paper, rubber, and oil. In these industries, as pointed out in Chapter 2, the economies of scale were much greater in terms of daily throughput and value-added than they were in the mechanical industries. There the ratio of machine tenders to machines remained much the same. Only in tobacco and some food-processing industries did high-speed mechanical processes come quickly.

In tobacco, continuous production came with the development in the 1880s of two machines – one producing cigarettes and the other simultaneously packing them. Those machines immediately reduced production costs to one-sixth of their previous level. In 1890 the four firms acquiring these machines joined the first mover, James B. Duke, to form the American Tobacco Company, which immediately competed in Europe and Asia with Wills, the first user of this production technology in Britain and the dominant leader in the 1901 merger that formed Imperial Tobacco. In 1911 American Tobacco was broken up by antitrust action into four firms. These four plus one other continued to be the American industry's leaders at least until 1964 when the report of the U.S. Surgeon General on the health hazard of cigarette smoking pushed these companies into new lines of products.

In the processing of grains, vegetables, fruit, and dairy products, comparable integrated mechanical processes appeared in the same decade of the 1880s. In grains new technologies, both European and American, were embodied in the "automatic, all-roller, gradual-reduction" mills into which carloads of wheat and oats entered and bags of flour or boxes of cereals emerged. Here the first firms to use this technology, such as Pillsbury in flour and Quaker Oats in cereals, remained leaders throughout most of the next century. The invention of high-speed canning equipment in the 1880s and comparable machinery in bottle making somewhat later led to the quick rise of such large food-processing firms as Heinz, Campbell Soup, California Packing (Del Monte), Corn Products Refining, Borden (powdered milk), and also such brewers as Anheuser-Busch and such soft-drink makers as Coca-Cola. In the same decade of the 1880s the modern meat-packing industry was created and was dominated until after World War II by Swift, Armour, and three smaller firms. These leaders built large "disassembling plants" next to stockyards in Chicago and other mid-western cities and shipped their chilled products over their own national and international refrigerated transportation networks throughout the United States and Europe.

These large food firms, unlike those in tobacco, rarely drove out smaller ones. The rapid growth of markets, the multitude of farmers that provided the supplies, and the seasonal and perishable nature of the products provided continuing opportunities for the smaller producers. In 1921, the first time the U.S. Census listed the number of establishments in food and related products (SIC 20), that group had 51,502 establishments, far more than any other two-digit SIC classification. But those firms that did make the investment in capital-intensive, high-volume production and in national distribution networks quickly moved into international markets. By World War I such firms as Quaker Oats, Heinz, and Coca-Cola, had built factories abroad, while Armour's and Swift's meat-packing plants dominated their industry in Argentina and Uruguay.

In glass the new capital-intensive, chemically processed technology – the Siemens continuous-process, gas-heated, electrically controlled tank furnaces – transformed the production of heavy plate and lighter window glass, but not of tableware or specialty glass. The development of the Owens bottle-making machinery in the next decade did the same for glass bottles. In plate glass, the first to make essential investments in the new technology, Pittsburgh Plate Glass formed in 1893, quickly dominated. In 1911 Michael Owens, the inventor of the bottle-making machine, developed a new process for producing flat glass. In the 1920s, each firm used its learned capabilities to move into the other's product markets.

Before World War I, Pittsburgh Plate Glass had established plants in Europe, and Libby-Owens did so in 1921. In abrasives the new scale-dependent electrolytic production technologies required a more massive amount of energy. So the two firms, Norton and Carborundum, that built plants at Niagara Falls in the 1890s followed the same route as the glass-makers. By 1910, Carborundum had plants in Germany and Britain, and Norton in Germany. On the other hand, in the production of SIC 32 products other than glass and abrasives – these included bricks, tiles, ceramics, pottery, chinaware, kitchenware, and stone products – labor-intensive, customized, small-batch processes of production continued to thrive.

The transformation of the paper industry came in the 1880s and 1890s with the adoption of a German-developed technology that made paper from wood rather than rags, one that required a great amount of energy and wood pulp. The first companies to commercialize these new processes merged in 1900 to form International Paper Company. But the merged enterprise failed to rationalize its activities by consolidating production facilities and creating a single national marketing organization. So smaller challengers were able to become firmly established before International Paper carried out the rationalization essential to obtain the scale economies required to maintain its competitive position. Because the production processes required a steady flow of pulp, 80 percent of the producers of newsprint, paperboard, and other paper packaging products had their own pulp mills by 1930. Those that did not integrate backward were nearly all producers of stationery and other high-grade paper, using specialized, more labor-intensive processes of production.

In primary metals, the new Bessemer Steel making technology was introduced in the 1860s, but the potential of scale economies came only after the several processes of production were placed within a single works that included coke ovens, blast furnaces, and rolling and shaping mills that turned out rails, beams, bars, and structural steel. Andrew Carnegie became the new American steel industry's first mover in the 1880s when he completed a carefully designed "greenfield" works in Pittsburgh that went into full production in 1879 when its battery of blast furnaces was completed. Carnegie then acquired and reshaped two other nearby works. In one he placed the first open-hearth furnaces to be operated in the United States. In 1894 the output of these three establishments was 1.7 million tons of steel – more than was produced in all of the United States six years before.

The massive increases in output drove down costs and prices. Between

1880 and 1889 the price of steel rails at Pittsburgh plummeted from $67.50 to $29.25 a ton. By 1898 it was $17.63. By the mid-1890s the four works of Carnegie's leading competitor, Illinois Steel, had an annual output of two million tons, even larger than Carnegie's. Such vast increases in throughput brought backward and forward integration. The two scale-dependent giants purchased coal mines and then large ore deposits, primarily in Lake Superior's Mesabi Range. The two also quickly built marketing organizations to sell to railroads, building contractors, machinery makers, and other industrial customers.

At the end of the century came a series of mergers that culminated in combining Carnegie Company with Federal Steel, the successor of Illinois Steel, and with a number of producers of secondary products – wire, tin plate, hoops, and sheet steel – into a huge combination, the United States Steel Corporation, the world's first billion-dollar firm. However, like International Paper, the Steel Corporation failed to rationalize its facilities quickly. Moreover, its explicit policy of not utilizing scale economies to reduce prices (generated by fear of federal antitrust actions), gave independent firms the time to make investments in facilities and personnel to assure them the benefits of scale economies. After 1910 these leaders competed oligopolistically, not on price, but functionally and strategically. In this competition U.S. Steel continually lost market share.

In nonferrous metals the coming of an electric generator powerful enough to provide for the electrolytic reduction of smelted copper and refined aluminum completely transformed the processes of production in the first and in the second turned a semiprecious metal into a mass-produced one. In 1891 five new electrolytic copper smelters went on stream. Their minimum efficient scale was so high that only twelve more copper smelters were built in the United States during the next ninety years, and seven of these were in operation by 1910. Four American firms and one German firm dominated global as well as U.S. copper markets from the 1890s until well after World War II. In 1896 the predecessor of the Aluminum Company of America built a plant at Niagara Falls to provide the electric power needed to mass-produce aluminum and formed a marketing organization to distribute and sell a wide range of new products – tubes, rods, castings, wire and cable, containers, foil, and kitchenware. The result was that Alcoa completely dominated the U.S. aluminum industry until World War II.

In the 1880s rubber and oil were still new industries. Both had come into full production after the civil war. The initial products of the rubber industry provide an early example of the cost advantages of the economies of scope in the utilization of physical capital (i.e., the economies gained by producing a number of different products in a single manufacturing establishment using the same raw materials and many of the same intermediate processes). The use of different admixtures and accelerators in the vulcanizing process, and of different machines to mold, extrude, and further process the finished rubber, made possible the production within a single plant of a wide variety of apparel (boots, gloves, and rainwear) and of industrial goods (hoses, belting, flooring, and insulating materials). By 1899 the average number of workers in a rubber establishment was 125 as compared to 9 in the production of apparel made from natural fibers. By that time the rubber apparel industry was dominated by B. F. Goodrich and industrial rubber by United States Rubber Company (created by a 1893 merger). In 1905 as Goodrich moved into the production of industrial rubber, U.S. Rubber expanded into apparel. In a few years, however, the coming of the motor vehicle enormously expanded the demand for rubber and altered the structure of the firms so that they could exploit the economies of scale as well as those of scope.

John D. Rockefeller's Standard Oil Company has long been identified as the classic example of a giant integrated multinational enterprise of that era. From the start, its process of refining was one of close to steady flow. Then the building of pipelines permitted crude oil to flow from the oil fields to the refineries. In the twentieth century pipelines came to carry the refined product to distribution centers throughout the nation, and those pipelines acted as inventory reservoirs as well as conduits of flow. By the time the Standard Oil Company consolidated its control over the oil industry by acquiring its major competitors, that industry had achieved the nation's highest ratio of capital to labor. (See Table 2.4.)

Standard Oil achieved its initial dominance in the early 1870s by building the nation's largest refinery in Cleveland and by vastly increasing the company's throughput (a word first used in the oil industry). During the 1870s the throughput of Standard's refineries rose from 500 to 2,000 barrels a day, thus reducing the cost of a gallon of kerosene from 5¢ to 3¢ and then to 2½ ¢. As the lowest-cost producer by far, Standard Oil acquired about 90 percent of the industry during that decade. And from 1879 to 1881 Standard Oil and other companies it controlled built over 4,000 miles of pipelines to replace railroads as shippers.

In 1881 Rockefeller and the heads of the acquired companies formed the Standard Oil Trust to consolidate into a single enterprise the many companies' operating units. Their aim was to capture the cost potentials of the oil-refining technology by rationalizing their industries – their rationalization became the model for comparable mergers in capital-intensive industries, particularly at the turn of the century. Between 1881 and 1886 the trust reduced the number of its refineries from fifty-six to twenty-three, concentrating production of its primary product, kerosene, in three 6,000-barrel refineries and converting other refineries into production of such specialties as lubricants, paraffins, wax, and vaseline. By 1884 the cost of refining a gallon of kerosene had dropped from 1.5¢ to 0.45¢. In that same year the purchasing of crude oil was centralized into a single department. By the end of the decade Standard Oil had completed its nationwide marketing organization at home, had built a comparable one abroad, had begun to own and operate oceangoing tankers and scores of railroad cars, and was beginning to integrate backward into the production of crude oil in the newly opened fields on the Ohio–Indiana border.

By then its middle managers at corporate headquarters, 26 Broadway in New York, were supervising and coordinating the several functional activities and the flow of products. Its top managers monitored the work of the operating departments and planned the strategies and allocated the resources to maintain and expand the operations of this global empire. By then Standard's competition consisted mainly of two or three small U.S. competitors, the powerful Nobel and Rothschild enterprises in Europe, and Royal Dutch Shell in Asia.

Nevertheless, with the opening of the huge Texas and California oil fields at the turn of the century and, at almost the same moment, the coming of the swiftly growing markets created by the automobile, challengers immediately appeared. The U.S. industry was quickly transformed into a modern oligopoly. Before 1911, when the U.S. government dismembered the Standard Oil Company of New Jersey (the successor to the trust), for violations of the antitrust laws, seven other integrated oil companies were listed among the nation's largest 200 enterprises.

By 1899 the industries based on the first wave of the new technologies, primarily those using chemical processes of production, became the most capital-intensive in the nation and already accounted for approximately 40 percent of the value-added in U.S. manufacturing, as stated earlier. The relatively few firms which made the large investments needed to capture the scale economies had contributed a substantial share of the capital accumulation in these industries that drove economic growth at the turn

of the century. By embodying the physical facilities of the new technologies with the human skills needed to exploit their potential, these firms became the initial learning bases from which much of the new organizational capabilities and new organizational structures would evolve.

Metalworking and machinery-making industries

Raising output, adding value, and increasing productivity by speeding up the flow of materials through the processes of production and distribution came more slowly in the metalworking and machinery-making. Here the increase in output per worker was more the result of capital augmentation than of capital accumulation. For in these same years these industries were still a locus of small shops making custom-ordered goods or a single line of equipment in small batches or small-bulk production processes, or making different products from the same set of individual craft skills. But, as the demand for specific products grew with the nation's expanding industrialization, machinery-making firms increasingly focused on producing standardized equipment for those markets. Here firms moved toward volume output by fabricating and assembling standardized parts in large batches and in some cases by what became close to continuous sequential line production. As they concentrated production in large capital-using works, the coordination of flows within and to and from the production establishment came to be increasingly essential to competitive strength and continuing profits. Such coordination required the development of complex skills and capabilities in the allied activities of purchasing, marketing, and distribution.

The metalworking industries grouped by the Census in SIC 34 (fabricated metals) remained far less concentrated and more labor-intensive and continued to rely much more on craft and small-batch production methods than did the machinery industries classified in SIC 35, 36, 37, and 38. (The United States Standard Industrial Classifications are listed on Table 2.9.) In 1937, SIC 34 had 493,000 production workers in 8,688 establishments for an average of 56.7 workers per establishment. In 1948 only 6 of the 200 largest U.S. firms were listed in SIC 34. Only in the making of metal cans and canning machinery, standardized plumbing and heating equipment, and safety razors (Gillette) did the cost advantages of scale bring large integrated enterprises in SIC 34.

In nonelectrical machinery (SIC 35), more enterprises had moved into higher-volume production of standardized machines through fabricating and assembling of standardized parts, making for greater accumulation of capital and greater employment. In 1937 the number of production workers in nonelectrical machinery (654,000) was 31 percent more, and the capital expenditures of $4,097 million were closer to twice the amount than in fabricated metals. Although the number of establishments in nonelectrical machinery, 7,327, was only a little less than in fabricated metals, those small establishments were concentrated in two three-digit subindustry categories, called metalworking (SIC 354) and unclassified industrial machinery (SIC 359).

In the other SIC 35 three-digit categories, companies during the last decades of the nineteenth century had begun to move toward producing standardized machinery used in major labor-intensive industries – textiles, shoes, lumbering, woodworking, printing, mining, and construction. Others concentrated on one major line of products such as pumps and other hydraulic equipment, steam boilers, conveyors and transmission equipment, or even elevators – that is, things used in many industries and businesses. Here products were produced in large batches or in large-bulk units with their final forms shaped to customers' needs. These machinery companies built extensive sales forces that included engineers and other trained personnel to install and help maintain the industrial equipment sold and to make arrangements with customers for financing purchases. But they made little attempt to acquire either their suppliers or the makers of their own capital equipment. By 1914 such leaders as United Shoe Machinery, Mergenthaler Linotype, Babcock & Wilcox, Otis Elevator, Chicago Pneumatic Tool, Worthington Pump, Crown Cork & Seal, and Westinghouse Air Brake, had built plants abroad to support their international marketing activities. Indeed, by that time SIC 35 included more American multinationals than any other SIC category.

It was, however, in the light-machinery industries with the most standardized products that the processes of manufacturing moved closest to the continuous process developed in the chemically processed industries. In harvesters, reapers, and other agricultural equipment; in typewriters, cash registers, adding machines, and other business equipment; and in sewing machinery, American companies had acquired a near monopoly in international markets by 1914. They were operating some of the largest manufacturing works in Britain, Germany, France, and Russia.

Their factories were designed to facilitate sequential line production. Materials moved from the foundry and the receiving areas to the departments making the different parts and then to the final assembly process, so as to assure a smooth and continuing flow of throughput. The production process was not yet fully continuous. The movement of materials through the factory remained relatively slow, and the final finishing and assembling of parts still required their individual filing and other hand work by fitters. Parts were standardized but not yet fully interchangeable.

As these light-machinery producers moved into volume production, they created national and then worldwide wholesale organizations. They quickly discovered that existing jobbers were unable to assure that the retailers who sold their products to the final customers provided essential marketing services including demonstrations and after-sales service and repair. Nor were the jobbers able to supply the retailers with the credit needed by housewives, farmers, and small businessmen to pay for the products. Moreover, independent jobbers were slow in forwarding payments from the retailers to the company's corporate office – payments that were needed to meet current operating costs. In the management of the costs of production the coordination of financial flows was as critical as the coordination of materials. Therefore, most of these companies used their wholesale organizations to provide these services through a network of exclusive franchise dealers – retailers who handled their products exclusively but could also sell related products made by other companies. Thus, a McCormick Harvester dealer sold plows, seeders, and mowers of other companies, lines which McCormick did not produce.

Of the three other machinery groups (SIC 36, 37, and 38), transportation equipment (SIC 37) was still relatively labor-intensive in the early part of this century, producing locomotives, ships, and wooden horsedrawn vehicles. Its capital-intensive, scale-dependent technologies would come with the development of the internal-combustion engine. SIC 38, instruments and related products, also was small, in fact still in its infancy with only 85,000 employees in 1909. Employment in the third (SIC 36, electrical equipment) in 1909 had not yet become large. But its high ratio of capital investment to labor (see Table 2.4) and its technological sophistication indicate its importance for economic growth through technological progress.

The new science-based industries – electrical equipment and chemicals

In the years before World War I, the electrical equipment industry had a far more profound impact on American industry and American life, especially urban living, than had the other science-based industry, chemicals. In SIC 36, the processes of production were technologically far more sophisticated than those in other industries and its marketing and distribution more complex. Its manufacturing works produced systems made up of the many products essential to the generation, transmission, and uses of electric power, and these products were made by different methods. Turbines, generators, and transformers were large, indeed massive, pieces of equipment. They and large electrical motors, streetcars, and subway trains were made by large-batch processes and then customized to purchasers' needs. On the other hand, smaller equipment such as small motors, connectors, circuit breakers, switches, relays, fuse boxes, sockets, light bulbs, and other lighting fixtures lent themselves to more coordinated sequential volume production. Thus, production was concentrated in a very small number of large works designed so that the different shops or factories within the works benefited both from the economies of scope, by using the similar materials and machines, and the economies of scale, by maintaining a steady throughput in the making of small standardized products. Here the coordination of flows to assure delivery of whole systems on schedule was therefore more challenging than in volume-produced light machinery.

The first companies to make the large investment in plant and equipment and to recruit the substantial number of workers and managers required to produce electric-power systems quickly dominated the industry. By the mid-1890s, little more than a decade after Thomas Edison completed the nation's first central electric power station at Pearl Street in New York in 1882, four enterprises – two American and two German – already dominated world markets and would continue to do so until well after World War II. The American firms were General Electric (GE), an 1892 merger of Thomson-Houston and Edison General Electric, and Westinghouse. The German ones were Siemens and Allgemeine Elektricitäts Gesellschaft (AEG).

A marketing organization was more essential to this new industry than to any others, for the installation and initial operations of electrical equipment by untrained workers could bring death or serious injury by electrocution. Thus, the first movers immediately created the national sales forces not only to market but also to install and service. Thomson-Houston, even before its merger with Edison General Electric in 1892, had built production plants in Britain and France. Westinghouse followed with works in Britain in 1899 and then in France, Germany, and Russia.

Because its products were so costly, General Electric, following the model of Siemens and AEG, formed a credit company – Electric Bond & Share – to take payment in shares of the new utility companies it equipped.

The technology of producing of electrical equipment, based as it was on physics and mathematics, was so sophisticated that it quickly led to the creation of the nation's first industrial research and development organization. General Electric, after setting up laboratories at its primary works in Lynn, Massachusetts, and Schenectady, New York, established in 1901 a research laboratory headed by an MIT professor, Willis R. Whitney. Within a decade Whitney's team developed vacuum tubes, tungsten filaments for better lighting, x-ray equipment, improved plastics for insulation, and metal alloys for better-performing equipment. All became major lines in the company's product portfolio, thus providing a foretaste of the potential of the economies of scope in the science-based industries where a firm would commercialize new products on the basis of its learned organizational capabilities.

By the turn of the century, the science-based electrical equipment industry was already a driving force in the growth and transformation of the American economy. Not only did new works create a multitude of new jobs, but as the industry grew, smaller regional and niche firms began to produce specialized equipment, replacement parts, or both. The products of the first movers provided a brand-new source of light (replacing kerosene) and power (replacing steam) in many of the mechanical and chemical processes of production; a new form of urban transportation (streetcars and subways); and the new electrolytic process of producing chemicals, aluminum, and abrasives.

Also in the last two decades of the century another electrical product, the telephone, began to transform communications. The telephone industry was quickly dominated by a single enterprise – Bell Telephone and its successor, American Telephone & Telegraph (AT&T) – which built a huge production plant outside Chicago and set up a research organization comparable to that of GE. By 1914 its manufacturing subsidiary, Western Electric, had plants in Great Britain, Germany, France, Austria, Italy, Russia, and Canada.

In this same initial period of rapid growth, the other major science-based industry, chemicals, was on the rise. The rapid expansion of the chemical-processed industries – glass, paper, primary metals, oil, and rubber – had brought comparable expansion and output for the chemicals used in their production. This swelling demand led to more continuous-process methods and the resulting scale economies to the production of chemicals themselves. However, modern capital-intensive, scale-dependent chemical industry only began in the United States with the introduction of the new electrolytic process. Dow, American Cyanamid, and forerunners of Union Carbide and Allied Chemical had their start at the turn of the century producing inorganic chemicals with this high-volume process. It required so much energy that Niagara Falls became for the making of those chemicals (and also aluminum and abrasives) what the Merrimack River had been sixty years earlier for the mechanized production of textiles.

By World War I the major players in the capital-intensive industrial oligopolies had established themselves. Many of these firms remained the leaders in their industries for the next half century. Some would disappear by merger, and others would drop off the list of the top 200 as new technologies brought new industrial leaders to the top. Because of continuing oligopolistic competition, rankings in terms of sales, market share, and profit within an industry rose and fell. Nevertheless the first movers, those that made the large initial investment in capital equipment, continued during the following decades to make large-scale investments in physical capital, in most cases funded by retained earnings, and to be among the nation's major employers of industrial workers. The barriers to entry became so high that few challengers entered the oligopoly. These enterprises thus became learning bases for further development of products and processes. They remained at the core of a network of suppliers, dealers, and other related firms.

CAPITAL ACCUMULATION AND AUGMENTATION, 1914–1950

During the years from 1914 to 1950 – the period when global wars, depressions, and international turmoil dissipated the opportunities for continuing growth and productivity in Europe – such opportunities continued in the United States until the coming of the Great Depression in 1930. Continuing capital accumulation and "learning by doing" increased output per worker and value-added in manufacturing in the capital-intensive and scale-dependent industries that had been created earlier. But the major dynamic for growth through technical progress during the interwar years came from the new and improved technologies based on the internal-combustion engine. The motor vehicle industry had the most profound impact.

The impact of the internal-combustion engine

As the twentieth century opened, the gasoline-driven internal-combustion engine was just beginning to be a source of energy that competed with steam and the new electric power. Its most immediate and most profound effect was on transportation and on the mechanical processes of production. After 1900, the year Ransom E. Olds demonstrated the commercial viability of the automobile by producing and selling 500 of his Oldsmobiles, the auto industry grew exuberantly. A decade later, in 1911, 200,000 passenger cars were sold; by 1919, 1.5 million; by 1929, 4.5 million. Then, with the Depression, the industry suffered a staggering sales drop to 1.1 million in 1932. It recovered to 3.9 million in 1937 and fell back to 2.9 million in 1939. The three-digit SIC industry, motor vehicles and equipment (SIC 371) had not been listed in 1899. By 1914 it was still fifteenth among all three-digit classifications in number of workers, seventh in wages, sixth in value-added, and ninth in value of products. By 1935, however, it ranked first in all but number of workers, where it ranked third.

This massive growth marked the culmination of the capital-augmenting sequential production line that had begun with the processors of grain and the makers of agricultural equipment and other light machinery in the 1880s. The moving assembly line that went into operation at Henry Ford's Highland Park plant in the summer of 1913 incorporated the most advanced materials, metalworking machinery, and plant design developed during the two previous decades. With the completion of the assembly line, throughput soared. Work hours expended on the production of an automobile fell from 12 hours and 8 minutes in 1913 to 1 hour and 35 minutes in April 1914. By then Highland Park was producing 1,000 cars a day. The resulting scale economies of throughput permitted Ford to sell his cars at far lower prices than any competitor, to pay the highest wages in the industry, and to acquire within a decade an enormous personal fortune.

In distribution Ford followed the earlier light-machinery companies by setting up exclusive franchise dealers supported by the company's international wholesale network. That organization scheduled deliveries of cars and monitored dealers' service and repair facilities, advertising, and payments to the corporate office. In distribution the Ford Motor Company carried out another impressive innovation, the branch assembly plant which assembled "knocked-down kits," thus reducing shipping costs while maintaining the cost advantages of scale. By 1913 Ford had already built thirteen assembly plants in the United States and one in Manchester, England. Other manufacturers soon followed Ford's example in both production and distribution. By 1929 over 6,500 franchised dealers were selling the output of the leading automobile manufacturers.

In the 1920s two companies – General Motors and Chrysler – began to challenge Ford's dominance. They did so by developing a full line of cars and commercial vehicles – in the terms of General Motors' advertising slogan, a vehicle for "every purse and purpose." This strategy permitted the companies to exploit the economies of scope by having their different end products and their parts and accessories made of much the same materials and by much the same machinery. In time this strategy also drove single-line, middle-price producers out of business – companies such as Packard, Studebaker, Hudson, and Nash. In 1935 the "Big Three" held 90.9 percent of the domestic market. By then Ford's share had dropped to 28 percent. General Motors had risen to 39.2 percent and Chrysler 23.7. Well before that date the U.S. manufacturers dominated world markets. In 1928, 72 percent of all cars exported from one country to another were American, 6 percent French, 5 percent British, and 1 percent German. In the 1930s the subsidiaries of General Motors and Ford were major producers in Britain, Germany, and Japan.

The "Big Three" concentrated on cars and light commercial vehicles. In the production of heavier, more specialized trucks and trailers, both the output and value of production were much smaller (882,100 units produced in 1929 as compared with 4.5 million cars and value-added of $62 million as opposed to $2,790 million). Here sequential, usually large-batch, production remained the mode. Here too niche companies throve, but by exploiting the economies of both scale and scope, some truck companies did become large. By World War II, White Motors, Mack Truck, and Fruehauf Trailer were listed among the 200 largest U.S. industrial enterprises.

The industry producing motor vehicle parts and accessories (SIC 3714) became one of the nation's largest four-digit industries. This occurred because of the zooming requirements of the truck and automobile firms and also because the makers of agricultural, industrial, construction, and mining machinery needed comparable equipment. By 1935 the number of employees hired and the amount of wages paid in SIC 3714 were even greater than in the production of the motor vehicles alone (SIC 3711). The leading parts makers – Borg-Warner, Bendix, Dana, and Thompson Products – were among the nation's largest companies.

During the 1930s the internal-combustion engine became the source of motive power for ships and railroads, and reshaped agricultural and construction equipment. It also became the essential ingredient in the creation of the aircraft industry. One of General Motors' major achievements in the 1930s was the commercialization of the diesel locomotive, which within a decade made the steam locomotive obsolete. In the early 1920s both International Harvester and John Deere had developed all-purpose farm tractors. Caterpillar Tractor commercialized and continued to improve the tracked (as differentiated from wheeled) tractor for highway and building construction. These companies and a handful of smaller competitors quickly diversified into each others' markets as well as remaining leaders in international markets.

The new demands created by the internal-combustion engine made existing capital-intensive industries still more capital-intensive and often brought an increase in the number of players in their respective oligopolies. For example, the unprecedented demand for gasoline and lubricating oil brought a series of technological innovations that increased refinery output by 270 percent between 1919 and 1929, while the number of refining establishments was rising only 22 percent and the number of employees 29 percent. By the 1930s the petroleum industry was by far the most capital-intensive in the United States and the third largest (after food and primary metals) in expenditures for capital goods. Increased throughput brought more vertical integration. By 1939 the twenty largest companies in the industry held 96.5 percent of the U.S. crude oil stocks. The opening of new fields at home and abroad, as well as the huge new markets created by motor vehicles, enlarged the size of the global oil oligopoly. But the reduction of demand during the Great Depression reduced the number of major players. By the coming of World War II the so-called Seven Sisters – five American firms, one British, and one Anglo-Dutch – dominated global markets. Over the past half century this pattern of oligopoly has changed little.

In rubber (SIC 30) the swift expansion of demand for pneumatic tires turned production from exploiting the economies of scope to those of scale. In tires (SIC 301), production per man-hour rose 433 percent, between 1914 and 1935, the largest increase of any three-digit industry. By World War I two new tire makers, Firestone and Goodyear, together with the existing leaders, U.S. Rubber and Goodrich, dominated the industry. They all went abroad in the 1920s where they competed with a French firm, Michelin; a British firm, Dunlop; and a German firm, Continental.

In glass and primary metals the impact of motor vehicle production was less, as that new market took a smaller portion of their industries' total output than was the case with oil and rubber. Nevertheless, by creating a huge new demand for glass, the industry added two more members to the international glass oligopoly. And the new demand for primary metals stimulated innovations in light metals and alloys and the development of hot (and also cold) continuous-strip steel mills. The independents quickly took up these innovations and so strengthened their market positions vis-à-vis U.S. Steel.

The science-based industries – electrical equipment and chemicals – 1914–1950

Second only to the internal-combustion engine in contributing to increased productivity and growth through technical progress during the war and interwar years was the rapid expansion of the two major American science-based industries, electrical equipment and chemicals. They led the way both in the employment of highly skilled nonproduction workers and the creation of large research and development organizations. In chemicals (SIC 28), scientific personnel in 1921 accounted for 30.4 percent of total scientific personnel employed in U.S. manufacturing, followed by primary metals with 8.2 percent and electrical equipment with 7.2 percent. By 1946 the figure for chemicals remained almost exactly the same, 30.6 percent. Electrical had risen to 15.5 and metals had dropped to 5.3.

During these years the electrical industry moved along the trajectory it had begun before 1900, and the chemical industry for the first time came into its own. Both benefited from the forced departure of the German first movers from global markets during the four years of World War I, then followed by five years of military occupation of the industrial Rhineland and Ruhr and explosive inflation.

With the removal of the Germans, General Electric became the industry's dominant firm in global competition, with Westinghouse a good bit behind. In 1929 GE's Associated Electrical Industries was the second largest electrical manufacturer in Britain. It held 25 percent of the voting shares of Germany's AGE and had a controlling interest in leading electrical manufacturers in France, Mexico, South Africa, and Japan. At home its research and development laboratories gave it first-mover advantages in x-rays and other medical equipment, in electrical household appliances and radio, and made it a major player in the production of alloys, plastics, and other man-made materials. The new product lines required substantial investment in both new production facilities and marketing organizations. In appliances, where rapid growth came through the use of assembly-line production, the company set up a separate "merchandising" department. Of particular importance was the development, production, and distribution of radio receiving and transmitting equipment carried out by the Radio Corporation of America (RCA), which had been formed in 1919 as a joint venture of GE, Westinghouse, and AT&T's Western Electric. In 1930 these owners sold off their interests in RCA, which then set up its own laboratories, which, besides improving radio and other electronic products, pioneered in the development of television.

In these same years the R&D departments at GE, Westinghouse, and Western Electric continued to improve existing products and develop new ones. At GE, for example, the number of product lines (the ones whose operating results were accounted for separately) rose from 10 in 1900, to 85 in 1920, to 193 in 1930, to 281 in 1940. In these years GE, Westinghouse, and AT&T's Bell Laboratories laid much of the technological base for the electronic technologies that so transformed their industry after World War II.

In chemicals the dislodgment of the Germans who had dominated the organic chemical branch since the 1880s permitted the leading American firms to move into the production of dyes, pharmaceuticals, agricultural and other chemicals. These firms included the previously mentioned leaders in inorganic chemicals produced through the highly capital-intensive electrolytic processes. They also included Du Pont, which, after an industry-wide merger in 1903, dominated the explosives industry. After World War I all these firms built large research and development organizations following the example of Du Pont, which had established the industry's first formal R&D department in 1902.

During the 1920s each of the major producers of chemicals improved its existing products and commercialized new ones on the basis of the highly product-specific organizational capabilities that had evolved from the production and distribution of its initial product line. Du Pont, for example, used its strength in nitrocellulose organic chemistry to move into the production of rayon, cellophane, photographic film, refrigerants, and pigments, as well as making synthetic ammonia by new high-pressure technology. For the new automobile market, the firm began producing quick-drying paints, antifreeze, and ethyl gasoline additives. Another company, Dow, grew by exploiting its inorganic electrochemical capabilities to produce, based on chlorine, the following: bleaches, chloroform, carbon tetrachloride, insecticides, and fungicides. Union Carbide, a 1917 merger, used its learned skills based on carbides to produce carbon electrodes and metal alloys, and then moved to the production of organic products derived from waste gas of oil refineries. American Cyanamid at its Niagara Falls plant was the first American firm to produce a synthetic fertilizer. Allied Chemical, created in a 1920 merger, concentrated more on products based on coal tar and coke-oven gas – byproducts from iron and steel making. Monsanto grew rapidly by producing saccharine and then caffeine, vanilla, and other fine chemicals based on German intermediates and plant equipment. It was able to grow more rapidly than it had before the war by producing its own intermediates and obtaining equipment from U.S. suppliers. The exploitation of the economies of scope in this knowledge-based industry that permitted the development of new lines of products laid the groundwork for the polymer/petrochemical technologies whose impact on American production after World War II was second only to that of the new electronic technologies.

For the pharmaceutical industry the pattern was much the same. Growth of the leading U.S. producers came with the exploitation of German-developed coal-tar pharmaceutical technologies that produced aspirin and other barbiturates, serums for diphtheria, cholera, and other deadly diseases, and novocaine and other pain killers. The capabilities learned in developing these products through systematic research and development helped to lay the base for the antibiotic technologies that transformed the U.S. pharmaceutical industry during and after World War II.

During the 1930s the economic growth propelled by the coming of the internal-combustion engine, particularly the motor vehicle, came to an end. Although the science-based industries continued to commercialize new products and processes, the collapse of the automobile market and with it the demand for steel, glass, petroleum, and rubber was a significant factor in bringing on the Great Depression and with it the sharpest drop in gross national product to occur in the twentieth century. Nevertheless, during those interwar years, the capital accumulation and learning base were laid for the commercializing of new technologies that would drive economic growth after World War II. For, unlike the two earlier periods, the years after World War II would see the commercializing of basic new technologies not by newly formed companies but by established enterprises that used their learned capabilities to bring the resulting new industries on stream.

THE KNOWLEDGE-BASED INDUSTRIES AFTER WORLD WAR II

The military demands of the two-front global war jump-started the American economy. It quickly brought full employment and a high level of capital utilization. Even more important in terms of long-term growth, the demands of the high-tech war provided the necessary large-scale investment and the "learning by doing" essential to commercialize new technologies that drove technical progress in the postwar years. The demands for military planes created the modern aviation industry. In 1939, only 5,865 planes were built in the United States, but in 1943 there were 85,433, and in 1944 there were 95,272. This expansion brought basic innovations in the design of aircraft bodies and engines, including jet engine propulsion, and in the processes of production. Crash programs in the development and production of high-octane gasoline and synthetic rubber helped to reshape the chemical industry on the basis of the new polymer/petrochemical technologies. The government-sponsored development of penicillin and sulpha drugs led to the therapeutic revolution that so transformed the pharmaceutical industry. Finally, the large-scale production of radio, radar, sonar, fire control equipment, and other electronic devices created new technologies that were central to the postwar information revolution.

The leaders in these transformed high-tech industries quickly replaced those of older industries on the list of the largest 200 U.S. industrial firms. Between 1948 and 1988 the large majority of new entries to that list came in chemicals (SIC 28) and electrical equipment (SIC 36). The number in chemicals rose from 23 in 1948 to 28 in 1973 then to 40 in 1988. Pharmaceuticals (SIC 283) added the most, going from 3 in 1948 to 7 in 1973 and to 12 in 1988. Of the 40 chemical firms on the list in 1988, all but one, a 1980s Wall Street concoction, had prewar roots. Most had been established before 1920. In electrical equipment the count in the top 200 went from 7 in 1948 to 16 in 1973, and then to 21 in 1988, and 4 more were ranked between 200 and 213. However, it was only in electrical equipment that postwar start-up firms began to be listed among the nation's biggest industrial firms. By 1973 two of them had made the top 200, and by 1983 eight more were found among the top 215. Of these ten firms, all but one (Xerox) was based on the new integrated circuit technologies. During these years the number of transportation equipment (SIC 37) firms remained about the same, but several of the leaders in the motor vehicle and related industries were replaced by aircraft and aerospace firms.

In 1987 the 200 largest industrial companies accounted for 43 percent of all value-added in U.S. manufacturing and 47 percent of new capital expenditures. Of the 200 in 1988, 86 were in high-tech categories – SIC 28, 36, 37, and 38 (scientific instruments). Except for the electronics firms, all these companies had been established before 1941 and a sizable number before 1914, a testimony to the significance of the large industrial firm as an instrument for capital accumulation and the acquisition of new product-specific knowledge.

Because of space limitation, I say little about aircraft and aerospace and instead concentrate on the contributions the leading firms in chemicals and electronics made to economic growth through technical progress. As to aircraft, I need only to point out that the first movers continued to maintain their competitive strength. Boeing had built the first all-metal airliner in 1933 and the first over-the-water commercial plane, the Clipper, in 1935. It became the largest producer of bombers during the war and was the first to build a commercial jet, the Boeing 707. Douglas, which merged with an aerospace firm, McDonnell, in 1967, produced the DC-3 in 1935. Its postgenerations of DCs remain Boeing's major competitor. Pratt & Whitney (now part of United Technologies) and General Electric, the first firms to commercialize the jet engine (in the 1940s), still dominate global markets for aircraft engines.

Polymer/petrochemical revolution

The polymer/petrochemical revolution that so reshaped the chemical industry reflected a simultaneous and dramatic shift in sources of supply and product markets. On the supply side crude oil and natural gas replaced coal as a cheaper and more versatile raw material. The U.S. chemical companies completed the shift by the mid-1950s. On the demand side, polymers – long-chain molecules usually having a carbon backbone – became the basis for a cornucopia of new products, opening up huge new markets. As a result, by 1970 the chemical industry's fixed assets per production worker, though well behind oil, was substantially higher than that of any other two-digit SIC category. It had the largest annual new capital expenditures, $3,111 million, of any of the two-digit groups.

The petrochemical and polymer revolution had prewar roots. Oil and chemical companies had begun to move into oil-based chemicals in the 1930s. Four oil companies – Jersey Standard (Exxon), Standard of California, Shell, and Phillips – had followed Union Carbide into the small-scale production of solvents and a few other products from petrochemicals. But it was the long-established chemical companies that pioneered in the development of the new basic polymer intermediates and the initial polymer end products. During the 1930s Union Carbide led the way in commercializing polyvinyl chloride (PVC). At the same time Dow's research on styrene pioneered in the development of a basic monomer, liquid styrene, and then a polymer, polystyrene (PS), and an end product, Styrofoam. The same company developed another oil-based chemical, vinylidene chloride, with Saran as an end product having many uses. The wartime programs in high-octane gasoline and synthetic rubber created an unprecedented demand for both PVC and PS as well as such oil-based feedstocks as styrene, ethylene, and chlorine. During the war, in 1943, Du Pont began the production of polyethylene, a polymer discovered at Imperial Chemical Industries (ICI) which Du Pont received through its Patent and Process Agreement with its long-time British ally. By the mid-1950s two more versatile polymers had been commercialized, high-density polyethylene (HDPE) and polypropylene (PP).

The commercialization of finished products such as Styrofoam and Saran from these intermediates began shortly before World War II. Du Pont in 1939 started producing nylon, an artificial silk, the first fiber that was wholly chemically made; and neoprene, a substitute for rubber. After the war came a stream of other polymer-based fibers (at Du Pont these included Dacron, Orlon, and Lycra spandex) that replaced natural fibers or blended well with them, as did acrylic-based fibers produced by Monsanto and Rohm and Haas. By 1985 man-made fibers pouring out of these and other chemical companies accounted by one estimate for 71.6 percent of the total fibers produced in the United States.

As one type of polymers was replacing natural fibers, another type, the so-called engineering plastics, was replacing metals, glass, paper, and other substances. These included strong impact-resisting materials that were more easily shaped and more cheaply fabricated than metals; also materials with unprecedented insulating, adhesive, and mechanical properties; certain packaging and wrapping materials; improved coatings and finishes; and lighter and stronger substitutes for glass, such as plexiglass and Lucite. By the 1980s the production of plastics had become a major American industry, taking markets from the producers of both primary and fabricated metals. For example, the plastic usage in an automobile rose from 12 pounds in 1950 to roughly 200 pounds by the 1970s.

For agricultural markets came new fertilizers, herbicides, pesticides, growth regulating and other crop-control products. New biological chemicals brought new medicines for humans and animals. Moreover, all of these new end products required, and often were the result of, reshaping existing intermediates and developing new ones. The production of such intermediate chemicals became a major industry of its own. All these new product markets expanded rapidly during the 1950s and well into the 1960s and in some cases beyond. Between 1950 and 1970 the overall chemical market grew at annual rates of about 2.5 times the growth rate of the gross national product.

The huge growth of markets and the availability of cheap, low-cost raw materials intensified the need for technological innovation to increase minimum-efficient scale of chemical plants. At first, throughput of existing plants was expanded on the basis of existing technology by adding another set or "train" of production processes. But merely enlarging the capacity of plants by building parallel units reduced unit costs only slightly. By means of the knowledge acquired in increasing the production of gasoline before and during the war, facilities were reshaped into "single train" plants. The construction and further improvements of such facilities, carried out by independent engineering firms, soon became a niche global industry in its own right.

During these years of growth some leaders, such as Du Pont, Monsanto, and Rohm and Haas, concentrated on the production of end products. Others, including Dow, Union Carbide, and Hercules, focused on expanding the high-volume commodity production of polymer intermediates. All continued to produce nonpolymer products that they had commercialized earlier in the century. Those concentrating on commodity polymers integrated backward to take control of refineries and even oil fields. The same concern for assured supplies caused those companies that focused more on specialty end products to maintain their production of the intermediates needed in their production processes.

As the new "single train" works came on stream and capacity soared, competition became intense. Overcapacity ruled, because minimum-efficient scale had become so much higher. So unit costs rose as the new plants operated at well below that scale. Then came the global oil crises. In 1973 the price of a standard Arabian crude rose to $11.65 a barrel (it had been $1.80 in 1970), and in 1979 it was a staggering $34.

Fierce competition, higher production unit costs, and the sharp rise in raw material costs led to one of the most significant restructuring of companies and industries that occurred in the United States during the 1970s and 1980s. Many chemical companies, whose organizational capabilities had been shaped by commercializing new products and processes, sold off their commodity polymer businesses, while oil companies, whose capabilities had always been in the exploitation of scale economies inherent in massive continuous-process production, expanded their investment in commodity polymers.

In reshaping their product lines these companies not only retained a heavy R&D commitment to the most technologically advanced products, but also focused on maintaining other lines where their long-established organizational capabilities gave them competitive strength. Thus Du Pont purchased Exxon's carbon fiber business and Hercules' Olefin Fiber Carpets Division while trading its acrylic fiber business to ICI for the latter's nylon operations. It also acquired Shell's Agricultural Chemical Division and Ford's North American Automotive Paint Division. Such product-portfolio-realigning transactions carried out by major chemical companies ran into billions of dollars.

This reconstruction strengthened the chemical industry's competitive position in international markets. By the late 1980s the industry had a surplus of exports over imports of $15.4 billion and was second only to aircraft and aerospace in that respect. Of more importance in terms of revenue earned, by 1990 a number of the leaders were reporting that 30 to 50 percent of their sales were made in foreign markets, largely from their foreign subsidiaries. In international markets the primary competitors of the U.S. chemical industry were comparable long-established German, British, and Swiss firms with roots in the nineteenth century. By then the Japanese were only beginning to enter European and American markets.

By the late 1980s the chemical companies, often using the funds received from divestitures, were expanding their output of specialty polymers and other intermediates and of such end products as additives for gasoline and food, industrial coatings, enzymes, electronic chemicals, new fibers, fiber and metal composites, new engineering plastics, ceramics, imaging equipment, electronic materials, pharmaceuticals, and medical equipment. By 1986, petroleum refining (SIC 291) still had the nation's highest fixed assets and new capital expenditures per worker. Nevertheless, total capital expenditures of the three largest three-digit SIC industries, industrial organic chemicals (SIC 286), plastics materials and synthetics (SIC 282), and inorganic chemicals (SIC 281) totaled twice the capital expenditures of petroleum refining. In value-added in manufacturing, organic chemicals with $14.7 billion and plastics with $14.1 billion were even greater than petroleum refining with $13.7 billion.

The therapeutic revolution

The development of antibiotics during World War II led the way in transforming the United States drug industry. In 1940 the first sulpha drugs had only begun to be produced commercially and penicillin had just been discovered in Britain. In the United States a government crash program was instituted to produce both. In 1942 Merck brought out the first industrially made penicillin. Pfizer, Squibb, and other established drug firms quickly followed. By the end of the war both sulpha and penicillin were produced in volume. After the war, these drug companies developed a broad range of antibiotics (such as Aureomycin and Terramycin), antihistamines, steroids, and other pharmaceuticals.

Before the war, American drug companies had carried on three businesses. They produced drugs in bulk, which were sold to pharmacists to be retailed or to be mixed into doctors' prescriptions. They made, packaged, and sold "ethical" or prescription drugs. Their third business included pills, powders and liquid patented (therefore "proprietary") medicines sold over the counter without prescriptions, as well as cosmetics, toiletries, and health care products sold over the same retail counters. With the coming of antibiotics and other related products, prescription drugs became their primary business. Production became a complex chemical process rather than a simple mixing or bottling one. Marketing shifted from selling in bulk or over the counter to contacting the doctors who wrote the prescriptions and the hospitals where they were used. Research became far more science-based and much more costly.

Those companies that made the transformation successfully in the late 1940s and 1950s are still the industry's leaders in the 1990s. By 1988, for eight of the twelve drug companies listed among the top 200 U.S. industrials, prescription drugs accounted for more than half their revenues, and for most more than two-thirds. Although income from exports was small, the revenue from foreign subsidiaries ranged from 30 to 50 percent for several of the leaders. As in chemicals, the competitors were European companies with comparable roots in the nineteenth and early twentieth

centuries. Again, Japanese firms have made very few inroads into international markets.

These same 70- to 100-year-old U.S. leaders played a critical role in commercializing a most significant post–World War II technological paradigm, that based on recombinant DNA. The companies began investing in the new technology in the late 1970s, expanding their commitments in the following years. They also supported entrepreneurial start-ups, essentially research enterprises established by geneticists and biologists. The established firms provided these new research enterprises with essential production facilities and marketing outlets, as well as funding their continuing research and costly clinical trials. The new biotech concerns first licensed their products and then formed alliances with the large pharmaceutical companies that permitted them to develop their own production and, most important of all, the marketing organizations and capabilities essential to becoming full-line pharmaceutical competitors. In turn, such alliances permitted the established companies to develop their capabilities in the new technology more quickly than if they had begun the initial research in their own laboratories. The major beneficiaries of this symbiotic relationship have been the long-established enterprises. In 1994, only four of the twenty-five leading U.S. biopharmaceutical companies posted a profit – Amgen, Genetech, Chiron, and Genzyme. Two of these, Genetech and Chiron, were controlled by full-line century old pharmaceutical firms.

The electronics revolution

The foregoing review of the transformation of the chemical and pharmaceutical industries documents the central role that large enterprises have played in the technological progress of the knowledge-intensive industries of the late twentieth century. With few exceptions the new technologies were exploited by long-established large firms whose learned R&D capabilities gave them a powerful advantage over start-ups, or firms whose capabilities rested on the commercializing of less closely related technologies. The history of the electronics sector documents this point from a different perspective, for the technological innovations that drove growth in that industry came after World War II. The new semiconductor or "chip" technologies based on the transistor patented in 1948 and the integrated circuit patented in 1959, required the creation of a new set of capabilities and so provided more opportunities for start-ups and younger firms than existed in chemicals and pharmaceuticals. Nevertheless, an even smaller number of large enterprises came to dominate global markets even more powerfully than had been the case in the commercializing of new capital-intensive, scale-intensive technologies earlier in the century.

In consumer electronics the leading U.S. firms lost out to large Japanese enterprises, in good part because they failed to move quickly into the new transistor technology. As late as the 1960s, RCA, Zenith, and others were relying more on vacuum tubes than transistors or integrated circuits to power their products. In contrast, one of Japan's first major postwar exports was the transistor radio. The critical loss of the U.S. industry, however, came in the late 1960s and early 1970s when its leader, RCA, after developing and then dominating color television, failed to maintain its distinctive learned capabilities.

First it turned to commercializing a very different new electronic product, the large general purpose digital computer. It entered the market in 1965 shortly before IBM's large multiproduct System 360 came on stream. After spending half a billion dollars and five years of research effort, RCA gave up the project in 1970. The appearance of IBM's second-generation System 370 made it clear that RCA could not catch up with the industry's first mover.

RCA then began a strategy of unrelated diversification. That growth strategy, then popular in American industry, quickly dissipated RCA's funds and managerial and technical capabilities – as it did in other U.S. companies. RCA purchased car rental, frozen food, and carpet-producing companies and others providing financial and legal services. By 1975 only 25 percent of its revenue came from electronics. In the meantime, RCA's smaller U.S. competitors were finding it impossible to compete in price and performance with the high-volume Japanese electronic companies. By the 1970s, Matsushita, Sanyo, Sony, and Sharp were rapidly conquering American and European markets. Only Holland's Philips was able to hang on.

If the history of U.S. consumer electronics provides an example of the dissipation of organizational capabilities, the history of the computer – or, more properly, the electronic data-processing industry – provides an example of the successful creation of such capabilities. Success, however, came to the long-established makers of business machinery and not to electrical equipment manufacturers. Both types of companies had pioneered in computers during the 1950s on the basis of government

contracts, primarily from the Department of Defense. The business machinery makers were International Business Machines (punch cards); Remington-Rand (typewriters); National Cash Register; Burroughs (adding machines); and Honeywell (heat regulators). IBM surged ahead of the rest by a strategy of almost continuous product development. It commercialized machines for two nondefense markets, one for business and commerce that called for a variety of uses but did not demand complex computation tasks, and the other for university and engineering enterprises where computing power was more important than a broad range of applications. By 1960 IBM had produced fifteen different nonmilitary computer systems. No other company had developed more than three or four. Within seven years it had transformed itself from being the world's leader in punch cards for record-keeping to becoming the world's leader in the new electronic computing technology.

IBM's fifteen systems used different types of components, peripherals, and other auxiliaries. In 1961, however, IBM senior managers made one of the boldest strategic moves in U.S. industrial history. The company would build a new generation of computers, covering a broad range of price and performance markets, for which all the hardware and software would be compatible. IBM would make its own hardware – printers, disk drives, and other peripherals, as well as semiconductors. The latter would not be based on transistors, but on the just invented, still untested integrated circuits. As Kenneth Flamm (the industry's historian) points out, the new System 360 benefited from the economies of scale in research, development, and production – and from the economies of scope in software and also in research.

Bringing the new products on stream and integrating them at different levels of price and performance proved to be enormously costly and risky. It was also an unparalleled learning experience. The cost of developing the new SIL chips went way beyond all estimates. By 1964 more money was spent on software development than had been originally planned for the entire project. The year of crisis was 1966, when there was over $600 million in the inventory of work in process. By 1967, the multitude of products began to pour onto the market. By 1969 IBM had captured 70 percent of the world market for general purpose computers. The System 360 provides a classic example of the embodiment of human with physical capital so essential to technological advance. And no other company in the world had the resources and experience required to accomplish such a task.

While IBM was in the throes of creating a System 360, new entrepreneurial firms entered the market at its low and high end. At the low end came the makers of minicomputers – small high-powered systems for university and engineering use. The first of these companies, Digital Equipment Corporation (DEC), was formed in 1957 by Kenneth Olsen, an MIT engineer who had been involved in developing defense computers and worked for a while at IBM during the 1950s. Its first successful products, the PD6 and the PD8, both using integrated-circuit technologies, appeared in 1965. Then came Data General established in 1968 by Edson de Castro, who had headed the PD8 project at DEC. In the early 1970s two Massachusetts firms, Prime Computer and Wang, had moved into the production of minicomputers, and so did Hewlett-Packard, the California instrument maker, and then IBM itself. By 1980 minicomputers accounted for 30 percent of the total computer market. At the high end of the price-performance scale, Control Data built the first supercomputer, a very fast powerful mainframe computer capable of handling highly complex problems. This was announced in 1962 but the first shipment came only in 1966. In 1972 Seymour Cray, Control Data's top designer, left to start his own supercomputer firm, Cray Research.

In 1965 General Electric as well as RCA began to compete directly with the IBM 360 in mainframe products, but in 1970, after IBM's announcement of the improved System 370, GE, like RCA, decided it could not catch up with the first mover and left the market. RCA had spent over half a billion dollars, and GE had planned to spend even more, in an attempt to compete in a technology where neither had developed the necessary learning base and the resulting organizational capabilities.

IBM's stiffest competition in the 1970s came from its own products made by other companies, some under license, but more often not. (Under a U.S. Department of Justice antitrust consent decree in 1956 IBM had agreed to license its innovations to all comers.) Control Data led the way in producing IBM-compatible equipment or clones by building a full line of peripherals, first for its own use and then for selling to other companies. By retroengineering and making slight changes, it stayed abreast of IBM's products without incurring development costs. Even before the growth of a replacement market, smaller companies quickly began to make IBM System 360 disk drives, printers, add-on memories, boards, and the like.

The first to attempt to clone the 360 itself came when Gene Amdahl, one of the key engineers in its development, left IBM in 1970 to form his

own company. In 1972, when Amdahl needed funds to complete his project, he turned to the leading Japanese computer maker, Fujitsu. That firm, with other Japanese companies and the government agency, MITI, was then attempting to develop competitive computer technology, and was delighted to oblige. It acquired 24 percent of Amdahl's equity in exchange for technical information. Three years later Fujitsu announced that it would make computers in Japan for Amdahl to sell in the United States. As Kenneth Flamm notes: "This was the turning point for the Japanese computer industry. At last it had acquired the ability to produce computers competitively with the latest IBM models" (p. 195).

Fujitsu, working with Hitachi, developed the "M-Series" of IBM-compatible computers and peripherals. By 1976 Fujitsu had committed an additional $54 million to Amdahl, and in 1979 it increased its controlling share of the American company to 49 percent. As Marie Anchordoguy, the historian of the Japanese computer industry noted in 1989, "The M-Series today remains the mainstay of Fujitsu's and Hitachi's offerings" (p. 115). By the mid 1980s the leading European producers were getting their mainframes from Japan to sell under their own labels. Fujitsu made those sold under the labels of Siemens and Britain's ICL; Hitachi made those sold through BASF and Olivetti, and NEC made those sold by France's Bull.

Thus no learning base existed in Europe to nurture capabilities essential for continuing product and technological development. As Flamm pointed out in 1987, "The market for large business machines in Europe is now mainly competition between IBM and other American and Japanese computers." Millions spent on research by European governments and companies remained disembodied, wasted.

The history of the IBM 360/370, besides underlining the essential need for such a learning base if a national industry is to remain viable, emphasizes the importance of new technologies as a source of capital accumulation. Worldwide revenue of the U.S. computers and their related products rose from $1.0 million in 1960 to $2.5 *billion* in 1965 to $10 billion in 1970, to $21 billion in 1971, and to $37 billion in 1979, giving a compound annual growth rate of 33.5 percent. The capital value of the general purpose systems rose from much less than a billion dollars in 1960 to $5 billion in 1965, $18 billion in 1970, $30 billion in 1975, and $50 billion in 1979. By 1971, 45 percent of computers made in the United States were sold abroad for a value of $3.5 billion. By the mid-1970s U.S. firms, largely IBM, produced most of the computers sold in France and

West Germany, and at least two-thirds of those in Britain and still close to 40 percent sold in Japan.

Finally, as the computer production soared, so too did the production of related products. In this way the few companies producing mainframes and minicomputers became the core of an increasingly global network of producers, not only of peripherals but also of semiconductors and other components, software, and a wide variety of consumer computer services. For example the revenue from services rose in the United States alone from an estimated $500–$700 million in 1965 to $1.0 billion in 1973, $3.2 billion in 1975, and $5.5 billion in 1975. Revenue from software went from $400 million in 1968 to $1.1 billion in 1976 and to $2.1 billion in 1980.

The huge increase in output of computers and computer services transformed the production of chips and software. The shift to standardized chips and packaged software had parallels to the shift to high-volume production in light machinery in the 1880s and 1890s and automobiles after 1915. The transformation in software from customized to standardized application packages soared after IBM "unbundled" its software from its hardware in 1969 under antitrust pressure. By selling it to any user, IBM saw its software quickly become the worldwide standard to which applications software makers shaped their packages. Thus in 1968, of the $400 million in the U.S. revenues in software, $300 million came from customized programming. But in 1978 when the total was $1.5 billion, $1 billion of it came from packaged software and only $500 million from customized products.

With the shift from customized to standardized, mass-produced chips, the cost of a fabricating plant soared from $2 million in the early 1970s to $80 million by the end of the decade and to $300 million by the mid-1980s – and to over a billion in the early 1990s. Semiconductors quickly became one of the country's most capital-intensive industries. These rising costs of facilities reflected the complex technology of producing chips and the increasing need for careful supervision of the coordination of the processes involved. As minimum-efficient scale and output rose, per unit costs and prices dropped dramatically.

The U.S. firms that were the hardest hit by this increasingly scale-dependent technology were the small, specialized, customized producers concentrated in California's Silicon Valley. More successful in developing the new production technologies were older enterprises – Texas Instruments (TI), formed in 1931 in Houston, Texas, and Motorola, a maker

of car radios established in 1927. TI, where Jack Kilby had patented the integrated chip in 1959, quickly expanded production in the United States and built a global marketing network. By the late 1960s it had fifteen wholly owned operating plants abroad. Motorola followed the same pattern on a somewhat smaller scale. By the late 1970s TI and Motorola together, in almost equal proportions, enjoyed by one estimate 70.7 percent of the U.S. market, and were as well the largest producers worldwide. Even though new mass-production technology quadrupled Silicon Valley's technological employment, the market share of the California companies was much smaller. Among those companies, Fairchild (where Robert Noyce had also patented the integrated chip in 1959) had by the same estimate 8.3 percent of the U.S. market, National Semiconductor had 7.5, and Intel 5.9.

The most successful embodiers of the new mass-production technology, however, were the giant Japanese integrated computer and consumer electronic firms, all of which produced semiconductors for their own use as well as for the merchant market. In the late seventies, they moved in strength into the U.S. market, particularly with Dynamic Random Access Memory (DRAM) chips. By the early 1980s, except for a few specialized devices, they had driven the American firms out of the production of DRAMs. If it had not been for the microcomputer revolution, the U.S. companies might have also lost out in the far more powerful new chip, the microprocessor.

The microcomputer revolution of the 1980s transformed the electronic data-processing industry as profoundly as the System 360 had done two decades before. The transformation rested on the two highly significant developments of the 1970s. One was the above-noted worldwide proliferation in the production of semiconductors, peripherals, software packages, and other related products that assured their availability and the dramatic reduction of their costs and, therefore, their price. The other was the commercialization of the microprocessor. That "computer on a chip" sharply increased the processing power of the chip even as the large-scale production decreased its cost. By the mid-1970s amateur "hobbyists" were assembling cheap, readily available components into small inexpensive computers and selling kits from which they could be constructed.

The availability of low-cost parts led to the spontaneous beginnings of the microcomputer industry. In the single year 1977 three firms in different parts of the country introduced their initial offerings – Apple Computer in California, Radio Shack (the leading retailer of consumer electronics) in Texas, and Commodore (a maker of hand-held calculators) in Pennsylvania. Others soon followed. But the industry was still in its embryonic stage when in the spring of 1980 IBM's management decided to enter it.

With a brilliant strategy, brilliantly executed, IBM almost immediately brought the industry to young adulthood. But that very act gave life to a product that in time would destroy the worldwide dominance of the mainframe, in which IBM and its clones were the leaders. IBM's management fully realized that the availability of parts and the new processing power made for a far different challenge from that of developing the System 360. Its first decision was to form an autonomous business unit to design, produce, and market its microcomputer, the personal computer or PC. In the summer of 1980, IBM's Management Committee charged a project team with building a global enterprise within a year. The team erected a plant in Boca Raton, Florida, made contracts with outside suppliers of peripherals, components (Intel was chosen), and software (Microsoft but only as second choice) and organized a global marketing and distribution network and did so on schedule. By the fall of 1981 the Boca Raton plant was producing one machine every forty-five seconds. In 1984, the third year of full production, the revenues of IBM's PC unit were $4 billion – revenues comparable to the seventy-fifth-largest U.S. industrial company. In 1985 they levelled off at $5.5 billion!

Companies – established and start-ups – swarmed into this huge and totally unanticipated market. Cloning the IBM PC was simplicity itself, compared with cloning a mainframe; and the minimum-efficient scale of production was too low to create effective barriers to entry. In 1984 and 1985 there was a shake-out in the industry, but when demand recovered in 1986 some 200 enterprises were producing IBM PC clones. The founders of the most successful of these, Compaq, had established their company in 1983 with the express intent of laying the foundations for a large global enterprise by careful financial planning, building a worldwide marketing network, and developing strong organizational capabilities. In the words of one founder, "Above all, we want team players not individualists." By the end of the decade IBM's market share had dropped to 22.3 percent of the personal computer market worldwide. By 1992 it had 17.2 percent followed by Apple with 12.3 and Compaq with 9.2 percent. The other five U.S. firms in the list of the largest fifteen worldwide held between 4.1 percent and 1.7 percent. By then the production of microcomputers was no longer concentrated.

On the other hand, the production of semiconductors and software for the personal computer quickly became as concentrated as any in the United States. All the producers of clones used Intel (or cloned Intel) microprocessors and Microsoft operating systems. Intel's franchise from IBM gave it a powerful competitive advantage based on the economies of scale. The franchise not only permitted Intel to outpace Motorola and other American firms but also to obtain and maintain a dominance in microprocessors that the Japanese firms have had difficulty in challenging. By 1991 Intel with revenues of $4.8 billion accounted for three-fourths of the output of microprocessors by U.S. companies. By then the cost of its new plant was $1.3 billion. In this highly capital- and knowledge-intensive and scale-dependent technology, the economies of scale had created higher barriers to entry in as short a time as had ever occurred in the commercializing of earlier technologies.

At the same time, Microsoft's franchise from IBM gave it powerful competitive advantage based on the economies of scope, not only in the production of software operating systems for personal computers but also in applications software for them where it became the leader. By 1991, 51 percent of Microsoft's revenues of $1.84 billion came from applications software and 36 percent from operating systems. (The rest came from hardware, books, and miscellaneous items.) By then Microsoft was making serious inroads into the markets of the nation's leading applications software producers including Lotus, Novell, Word Perfect, and Oracle. By then Microsoft's R&D expenditures were running into the hundreds of millions of dollars. The development of one operating system, NT, cost millions and five concentrated years of work. As in the case of Intel, the Japanese producers are not yet major competitors.

The electronics story thus differs from that of the other post–World War II high-tech industries in that a much smaller number of large companies dominated major markets. Few companies dominated their industries worldwide as powerfully as RCA and IBM did at the end of the 1960s. In consumer electronics the failure of RCA to maintain the needed organizational capabilities helped to assure the loss of the United States consumer electronics industry to Japan. More than a quarter of a century later, in the middle 1990s, there seems only a faint hope that U.S. firms could again become viable competitors.

On the other hand, in the electronic data-processing industries IBM's achievement in integrating both tangible and intangible capital in the creation of the System 360 gave it unprecedented worldwide dominance. After the Japanese firms acquired this technology, largely through the services of Amdahl, they continued to improve their products and processes and to enhance their organizational capabilities so as to compete effectively in world markets with the U.S. firms. The failure of the European companies in electronics, except possibly for Philips, dramatically emphasizes the necessity for developing and, even more important, maintaining a base that permits the embodiment of intangible and tangible capital within large industrial enterprises. The fact that seven of Japan's eight largest industrial enterprises in terms of capital assets in 1987 were four electronic and three automobile firms further emphasizes this point.

As important as the internal evolution of the electronic data industry has been for technological progress, its impact on other industries and other sectors of the economy may have been even more significant. In nearly all industries the new computer-aided design (CAD) and computer-aided manufacturing (CAM) (including computer-controlled machine tools and devices for automating the processes of\production) have sharply increased the ratio of capital to production workers, sped up flows through the processes of production, and increased value-added in manufacturing in both the chemically processed and the machinery industries.

The new data-processing technologies may have had an even greater impact on the service sector productivity than on manufacturing. The huge growth of software applications and computer services of the 1970s continued during the 1980s. Every category in the service sector was affected. In distribution the point-of-sales cash register and the bar code permitted mass retailers to coordinate the flows of goods into their stores by direct contact with manufacturers, thus squeezing or even eliminating the wholesaler. The new software technologies increased productivity in the operations of chains of hotels, restaurants, and food stores. They had an even greater effect on banking, insurance, and other financial services. They helped to transform the provision of services in transportation, particularly airline travel, and in health care. All aspects of the entertainment business – products, productions, and distribution – were profoundly affected. The high level of productivity in the U.S. service sector in good part reflects the massive use of the new electronic hardware and software technologies in the United States since the 1960s.

CONCLUSION

If "technical progress" is the most essential characteristic of economic growth, then as the twentieth century draws to a close, the United States

would seem to be in as strong a position in maintaining continuing economic growth as it was when the century began. In the first decades of rapid economic growth before World War I, the United States led the way in commercializing many of the new capital-intensive, scale-dependent technologies. In the second half of the century as the bias of growth turned toward the more science-based, knowledge-intensive, and what might be termed scope-dependent industries, the United States still maintains powerful competitive strength. This is in good part because the new technologies were largely commercialized and continued to be dominated by enterprises that were first movers in exploiting the earlier capital-intensive, scale-intensive technologies. They had the product-specific and industry-specific organizational capabilities and the funds from retained earnings that were essential to continue to commercialize the new technologies on a global scale. As was true of the earlier capital-intensive, scale-dependent technologies, unless organizational capabilities were developed and maintained, the critical learning base often disintegrated. Once lost, it was rarely regained. This was probably even more true in the knowledge-intensive, scope-dependent industries of the second half of the century than it was for the capital-intensive and scale-dependent industries of the first period of modern economic growth.

In these postwar knowledge-based industries the United States remains the leader in chemicals, pharmaceuticals, and aerospace. In electronics the United States and Europe have lost out to Japan in radios, TVs, VCRs, and other consumer electronics as well as in bulk semiconductors and certain other components. Both the United States and Europe retain strength in telecommunications, and the United States is at the forefront in such leading-edge electronic technologies as microcomputers and software. With the United States, Japanese companies are strong in information-processing equipment and with both the U.S. and European companies in telecommunications. But they have not developed a strong global presence in higher value-added chemicals and pharmaceuticals nor in aerospace. In sum, during the postwar years the European companies have maintained their competitive strength with the Americans in the older science-based industries but missed the most dynamic of the postwar technologies – those based on the transistor and the integrated circuit.

This essay has reviewed the role of the large industrial enterprise in making the United States the leader in technological change during the twentieth century. Its firms did not necessarily so become by inventing or even pioneering in the new technologies. During the first wave most of the initial innovations came from Europe, in the interwar years from both Europe and the United States, and after World War II more from the United States. The U.S. industries became worldwide technological leaders in Maddison's terms by commercializing these innovations on a scale made possible by the size of national and global markets. It was this large-scale commercialization that created the initial learning base and then the core of a larger industrial nexus, each of which, in turn, became a dynamic element in continuing learning and growth. But, as the rise and decline of companies and even industries such as consumer electronics indicate, in these high-tech industries, and also in medium technology ones such as motor vehicles and steel, the initial advantages did not insure continued strength. Learned product-specific organizational capabilities had to be maintained and enhanced. Once capabilities disintegrated, competitive power rarely returned.

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