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Technological Interdependence in the American Economy

NATHAN ROSENBERG

One of the things which all knowledgeable people supposedly "know" is that technological change has been the critical variable in accounting for the spectacular long-term growth of the American economy and our resulting present affluence. And yet, when scholars of a quantitative turn of mind have attempted to link the story of the growing productivity of the American economy to some of the better-known facts and landmarks of our technological history, that story has turned out to be a remarkably difficult one to tell.

There are many reasons why this has been a difficult exercise. It is, for one thing, an extremely complicated methodological matter to separate out the contribution of technological change from other changes in human behavior, motivation, and social organization. Although this is generally realized, there is less awareness that the productivity contribution of a new technology is also linked to other, less obvious technological forces, to which I will shortly return. Moreover, the public image of technology has been decisively shaped by popular writers who have been mesmerized by the dramatic story of a small number of major inventions—steam engines, cotton gins, railroads, automobiles, penicillin, radios, computers, etc. In addition, in the telling of the story, overwhelming emphasis is placed on the specific sequence of events leading up to the decisive actions of a single individual. Indeed, not only our patent law but also our history textbooks and even our language all conspire in insuring that a single name and date is attached to each invention.

The growing interest in the diffusion of technology in recent years has functioned as a partial corrective to the heroic theory of invention. Inventions acquire their economic importance, obviously, only as a function of their introduction and widespread diffusion. But I want to go farther and suggest that the social and economic history of technology can only be properly written by people possessing a close

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familiarity with the actual technology itself. At the same time, as I would also insist, people who know little beyond the technology in a narrow sense are not likely to rise above the level of antiquarianism. Indeed, one of the main themes of this paper is that it is absolutely essential not to develop too narrow a focus in the study of technology, because a narrow focus severs the links between a given technology and many of the factors which will, inevitably, determine its effectiveness and significance. A larger purpose in what follows will be to show how our appreciation for the functioning of technology in the growth of the American economy can be expanded by focusing attention on the network of larger technological relationships in which specific inventions are always embedded.

I do not want to concern myself here with the conceptual, methodological, and statistical problems involved in attempting to quantify the contributions of technological change to long-term economic growth in America. These problems have been extensively discussed elsewhere. Rather, I want to confine myself to certain aspects of the problem which are of greatest interest to an audience which is committed to the subject of the history of technology. Specifically, I would like to concentrate on certain intrinsic characteristics of the process of technological change which, I will argue, are central to the difficulties experienced when we attempt to measure the growth in productivity flowing from it. The central theme, on which I wish to elaborate, is that technological improvement not only enters the structure of the economy through the main entrance, as when it takes the highly visible form of major patentable technological breakthroughs, but that it also employs numerous and less visible side and rear entrances where its arrival is unobtrusive, unannounced, unobserved, and uncelebrated. It is the persistent failure to observe the rush of activity through these other entrances which accounts for much of the difficulty in achieving a closer historical linkage between technological history and the story of productivity growth. I will briefly explore these neglected factors under three main headings.

Complementarities

Inventions hardly ever function in isolation. Time and again in the history of American technology it has happened that the productivity of a given invention has turned on the question of the availability of complementary technologies. Often these technologies did not initially exist, so that the benefits potentially flowing from invention A had to await the achievement of inventions B, C, or D. These relationships of complementarity therefore make it exceedingly difficult to predict the flow of benefits from any single invention and commonly lead to a postponement in the flow of such expected benefits. Technologies depend upon one another and interact with one another in ways which are not apparent to the casual observer, and often not to the specialist.

A serious difficulty in tracing out the social payoff to invention is that these linkages are both numerous and of varying degrees of importance and therefore difficult to measure with any pretense of precision. Thus an invention reducing the cost of power generation differentially affects different industries. In the past such cost reductions were critical to the expansion of the aluminum industry, an intensive user of electricity. They played a major role in the cheapening of commercial fertilizers and the increasing intensity with which such fertilizers were used in food production. Their significance for the production of ballpoint pens or umbrellas was probably very small. In the event that innovations in power generation were to bring about a massive reduction in power cost (a consummation devoutly to be wished!) further innovations, which are known to be technically feasible but economically unattractive at present, might move into the realm of economic feasibility (e.g., various methods of desalination).

Consider, alternatively, the economic payoff to an innovation which reduced the cost of transportation, for example, the impact of the railroad on the American economy in the mid-19th century.[1] Part of the economic payoff consisted of an increase in the productivity of agriculture, as bulky farm products could now be exchanged over larger geographic areas than was formerly possible. As a consequence it became possible to engage in a greater degree of regional specialization than before and to participate more fully in the increased productivity resulting from the improved opportunities for devoting heterogeneous agricultural resources to their best possible uses. Any estimate of the social payoff from the railroad would need to include an estimate of the reduction in transport costs attributable to it, the effect of cheaper transport on possibilities for regional specialization, and the size of the benefits specifically attributable to this increased specialization, a specialization which makes possible a much finer adaptation of the productive process to the geographic distribution of resources. Furthermore, reductions in transport costs also bring about greater productivity by making it possible to concentrate output in a smaller number of more efficient units. For example, reductions in the cost of transporting coal from the mine to electric generating facilities, due to the development of the unitized train shipment of

[1]See Albert Fishlow, *American Railroads and the Transformation of the Ante-Bellum Economy* (Cambridge, Mass., 1965); and Robert W. Fogel, *Railroads and American Economic Growth* (Baltimore, 1964).

coal and other transportation improvements,[2] have made it possible to close down less efficient coal mines which had previously survived because of their proximity to markets and to rely increasingly on a smaller number of more efficient mining operations. Finally, reductions in transport costs generally make possible the more intensive exploitation of economies of scale, wherever these economies may be significant.[3] In a world of high transport costs, the size of operation of an individual plant will be constrained by the prohibitively high cost of transport as the product is moved to more distant markets. Reductions in transport costs expand the market available to a firm in any given location and thus increase the possibilities for the exploitation of scale economies.

On an even wider geographic scale, the social payoff resulting from railroads and associated reductions in transport cost was increased by the iron steamship, which reduced the cost of transoceanic shipping, and refrigeration, which in turn raised the productivity of *both* the railroad and the steamship. With these complementary innovations there began to emerge, by the end of the 19th century, a truly world-wide agricultural division of labor.[4] This unique division of labor was the combined result of reductions in the cost of land and water transport and the newly acquired ability to utilize the railroad and the steamship for the long-distance shipment of meat. By the 1880s and 1890s, as a result of refrigeration techniques, the rapidly growing populations of western Europe were becoming heavily dependent upon a wide range of overseas food products, including not only the North American midwest but also large quantities of lamb from New Zealand and Australia and beef from the Argentine.[5]

This emphasis on complementarities serves to make explicit one of the main points of this paper: the social payoff of an innovation can rarely be identified in isolation. The growing productivity of industrial economies is the complex outcome of large numbers of interlocking, mutually reinforcing technologies, the individual components of which are of very limited economic consequence by themselves. The

[2] U.S. Department of Labor, *Technological Trends in Major American Industries* (Washington, D.C., 1966), p. 20.

[3] Innovations leading to the reduction in high-voltage transmission costs have exactly the same effect. They make it possible to shut down relatively small, older plants and to exploit the economies of large-scale power generation in a limited number of localities.

[4] By 1903 ". . . freight rates in general were down to about 20 percent of the 1877–8 level, and the actual costs of ocean shipment had fallen by an even greater percentage due to reductions in the cost of insurance" (A. J. Youngson, "The Opening Up of New Territories," in *The Cambridge Economic History of Europe,* vol. 6, *The Industrial Revolutions and After,* ed. H. J. Habakkuk and M. Postan [Cambridge, 1965], pt. 1, p. 171).

[5] Ibid., pp. 172–73.

smallest relevant unit of observation, therefore, is seldom a single innovation but, more typically, an interrelated clustering of innovations. The early industrial revolution can only be understood in terms of the interactions of a few basic technologies which provided the essential foundation for other technological changes in a series of ever-widening concentric circles, at the heart of which were a few major innovations in steam power, metallurgy (primarily iron), and the large-scale utilization of mineral fuels. One can identify similar kinds of clusterings around electrification beginning in the late 19th century, the internal combustion engine in the early 20th century, and plastics, electronics, and the computer in more recent years. In each case a central innovation, or small number of innovations, provided the basis around which a larger number of further cumulative improvements and complementary inventions were eventually positioned.

The importance of these complementarities suggests that it may be fruitful to think of each of these major clusterings of innovations from a systems perspective. The systems nature of a body of technology is well displayed in the case of the electric light. Indeed, it is clear that the most successful inventor-innovators in the development of the electric light were successful—in good part at least—because they consciously and deliberately approached the industry from a systems framework. Incandescent lighting constituted a system of several major components. Economic success in the innovation process was contingent on considering all aspects of the system in the delivery of light to domestic residences. Many of the numerous instances of entrepreneurial failure can be attributed to the fact that a would-be entrepreneur failed to consider the relevant conditions of interdependence between the component with which he happened to be preoccupied and the rest of the larger system.[6] This system can be considered as consisting of four significant components: (1) the generation of electricity at a central power station, (2) a conductor network for the transmission of power, (3) a meter to measure household consumption of electricity, and (4) a lamp. Successful inventor-innovators in incandescent lighting, such as Thomas A. Edison and George Westinghouse, consciously thought in terms of the entire system, the purpose of which was to deliver cheap illumination into

[6]Passer points out, for example, that "the relatively poor performance of the United States [Electric Lighting] company can be partly attributed to the fact that its technical personnel, while competent, did not realize the importance of developing an entire incandescent-lighting *system,* rather than certain components" (Harold C. Passer, *The Electrical Manufacturers, 1875–1900* [Cambridge, Mass., 1953], p. 148, emphasis Passer's; see also pp. 176–77).

millions of domestic residences. "Both set out to develop an entire system, and both took a personal interest in the invention of the system components."[7] In Edison's case:

> The parallel between Edison's work on the dynamo and on the incandescent light is apparent. In each case, he perceived the function of the component in the system. He then determined the characteristic of the component which would result in a system with the lowest production cost of light. The next step was to apply the electrical principles and to conduct numerous experiments until the desired end was reached.
>
> The transmission network which connected the dynamo and the lamps was a third main component of the Edison lighting system. As in the lamp and the dynamo, Edison's contribution was to invent a cost-reducing component.[8]

It is characteristic of a system that improvements in performance in one part are of limited significance without simultaneous improvements in other parts, just as the auditory benefits of a high-quality amplifier are lost when it is connected to a hi-fi set with a low-quality loudspeaker. (For example, after the introduction of steel rails made possible the use of longer trains with heavier loads traveling at higher speeds, making them much more difficult to stop, Westinghouse "providentially" developed the air brake. The improved design of automobile engines and greater speeds were likely to be disastrous without a better braking system and better engineered roads.) Similarly, improvements in power generation will have only a limited impact on the delivered cost of electricity until improvements are made in the transmission network and the cost of transporting electricity over long distances. This need for further innovations in complementary activities is an important reason why even apparently spectacular breakthroughs usually have only a gradually rising productivity curve flowing from them. Really major improvements in productivity therefore seldom flow from single technological innovations, however significant they may appear to be. But the combined effects of large numbers of improvements within a technologi-

[7]Ibid., p. 192; see also Arthur A. Bright, Jr., *The Electric Lamp Industry* (New York, 1949), pp. 67–69, 76.

[8]Passer, pp. 177–78. See also the subsequent discussion of the fourth component, the meter. The meter was an extremely important component in the system. Before General Electric developed a satisfactory meter around 1900, meters were likely to be both very expensive and unreliable, and flat-rate contracts were common. Consumers had no incentive to economize in the use of electricity. In the absence of a meter, therefore, electrical utilities had to undertake excessively large investments in generating and transmitting equipment, and operating expenses were very high. The meter, therefore, was a major contributor to the improved efficiency in resource use.

cal system may be immense.[9] Moreover, there are internal pressures within such systems which serve to provide inducement mechanisms of a dynamic sort. One invention sharply raises the economic payoff to the introduction of another invention. The attention and effort of skilled engineering personnel are forcefully focused on specific problems by the shifting succession of bottlenecks which emerge as output expands.[10]

The role of complementarity relationships may be further observed, in finer detail, in the history of individual innovations. Sometimes a particular innovation has to await the availability of a specific complementary input or component; sometimes the evident need for the input is sufficient to lead to its invention; and sometimes the input, when it is fully developed, is found to have uses and applications of a totally unanticipated—or at least unintended—sort. Thus, many innovations have had to await the development of appropriate metallurgical inputs with highly specific performance characteristics. The compound steam engine had to await cheap, high-quality steel. Higher pressures (and therefore greater fuel economy) in power generation required high-strength, heat-resistant alloy steels.[11] Hard alloy steels, in turn, were of limited usefulness until appropriate new machine tooling methods were developed for working them. The jet engine required, and eventually contributed to, numerous metallurgical improvements. Similarly, the transistor required major improvements in techniques for purifying metals and eventually contributed richly to a wide range of productive activities which also required metals of a high degree of purity. In agriculture, the introduction of techniques for the mechanical harvesting of crops has been sharply accelerated by the advances in genetic knowledge which permit a redesigning of the plant itself to accommodate the specific needs of machine handling. Thus, midwestern corn is now almost

[9]Bright cites an estimate for the reduction in residential lighting costs which "... takes into account the reductions in energy cost, the reductions in lamp price, the increases in lamp efficiency, and the increase, if any, in lamp life. . . . Lighting costs in 1945 were 1.3 percent of what they were in 1882; they were 13 percent of what they were in 1906; and they were 45 percent of what they were in 1923. About 60 percent of the saving since 1923 is attributable to increases in lamp efficiency; and about 10 percent is attributable to reductions in lamp prices" (p. 362).

[10]For further discussion of the role of bottlenecks in inducing technological changes, see Nathan Rosenberg, "The Direction of Technological Change," *Economic Development and Cultural Change* 17 (October 1969): 1–24.

[11]On high-pressure steam engines, Usher stated: "Undoubtedly, the limiting factor was not the concept, but the practical difficulty of dealing with steam pressures. Neither boilers nor cylinders could then be made that would resist the pressures needed for effective working" (A. P. Usher, *A History of Mechanical Inventions* [Boston, 1959], p. 356).

entirely of a specially bred, stiff-stalked variety which remains conveniently upright well into the fall; mechanical tomato harvesters have been available for many years but were not adopted until it became possible to breed a new, tough-skinned variety which was less susceptible to bruising and ripened more uniformly; similarly, in cotton, breeding has been directed toward the development of plants which lend themselves more readily to mechanical picking.[12]

The Cumulative Impact of Small Improvements

I turn now to a second significant aspect of technology. That is, a large portion of the total growth in productivity takes the form of a slow and often almost invisible accretion of individually small improvements in innovations. The difficulty in perception seems to be due to a variety of causes: to the small size of individual improvements; to a frequent preoccupation with what is *technologically* spectacular rather than *economically* significant; and to the inevitable, related difficulty which an outsider has in attempting to appreciate the significance of alterations within highly complex and elaborately differentiated technologies, especially when these alterations are, individually, not very large.

It is useful here to think in terms of the life cycle of individual innovations. Major improvements in productivity often continue to come long after the initial innovation as the product goes through innumerable minor modifications and alterations in design to meet the needs of specialized users.[13] Widely used products like the steam engine or the electric motor or the machine tool experience a proliferation of changes as they are adapted to the varying range of needs of ultimate users. Consumer durables have typically gone through parallel experiences with special emphasis on expanding the quality range in catering to different income categories.[14] Such modifications are achieved by unspectacular design and engineering activities, but they constitute the substance of much productivity improvement and increased consumer well-being in industrial economies.

The view of technological change as consisting of a steady cumula-

[12]See Clarence Kelly, "Mechanical Harvesting," *Scientific American* (August 1967), pp. 50–59; Wayne Rasmussen, "Advances in American Agriculture: The Mechanical Tomato Harvester as a Case Study," *Technology and Culture* 9 (October 1968): 531–43.

[13]Marx pointed out that there were no less than 500 different types of hammers being produced in Birmingham (Karl Marx, *Capital* [New York, n.d.], p. 375).

[14]Brady provides extensive documentation for individual products (see Dorothy Brady, "Relative Prices in the Nineteenth Century," *Journal of Economic History* [June 1964], pp. 146–47, 155–56, 164, 75–82, and passim).

tion of innumerable minor improvements and modifications, with only very infrequent major innovations, was nicely embodied by S. C. Gilfillan in his book, *Inventing the Ship*.[15] Although Gilfillan was primarily concerned with the social rather than the economic aspects of the process, his book provides an invaluable "close-up" view of the gradual and piecemeal nature of technological change, drawing heavily on small refinements based on experience and gradually incorporating a succession of improved components or materials developed in other industries. His analysis of the evolution of marine engines (chap. 2) is that of a slow sequence incorporating the growing strength and steam-raising capacity of boilers, the increasing reliance on steel components as steel became cheaper, and the adoption of petroleum lubricants:

> To the ship's motive plant were added further important cut-off arrangements and valve gear for them, feed-water heaters (e.g., from the condenser), superheaters (in the 60s, saving 10 percent of the fuel), steam jackets, better air-pumps, evaporators, tricks of tinning the copper condenser tubes, changing to brass after learning how to manufacture the brass, protecting the tubes from galvanic action, forced draft, and various improvements of grates and methods of feeding with coal and air, instead of iron (a large improvement for weight-saving), and a limitless number of betterments too minor for us to mention here.[16]

The introduction of screw propulsion (chap. 3) was largely a matter of determining, through experience and experiment, the optimal design form of the propeller as well as simply exploiting new construction possibilities provided by improvements in metalworking as they occurred elsewhere: "The propeller admits of strangely wide variations in form without much difference of efficiency, if only certain gradually learned mathematical principles be respected, chiefly that of adapting the blade angle at every separate point to the speeds of ship, engine and thrown water. It was in learning such principles that the real invention of the propeller largely took place."[17] Shipbuilding for the past century has been involved in a long sequence of gradual improvements: improvements in engine efficiency which save fuel space; changes in hull design; exploitation of scale economies which permit reductions in crew requirements per ton of cargo; changes in

[15]S. C. Gilfillan, *Inventing the Ship* (Chicago, 1935). See also his companion volume, *The Sociology of Invention* (Chicago, 1935), and A. P. Usher's earlier and authoritative *A History of Mechanical Inventions*.

[16]Gilfillan, *Inventing the Ship*, p. 131.

[17]Ibid., p. 137.

cargo handling techniques, such as containerization, which also sharply reduce "turn-around time," etc.[18]

Louis Hunter's observations on the history of the steamboat on western rivers in the antebellum period are worth quoting here because his description of technological change in connection with the steamboat would also apply, with only minor changes, to a broad range of technological change elsewhere and in later periods.

> The history of the steamboat is also the history of foundry and machine-shop practice, of metalworking techniques and machine tools, and of the practical art of steam engineering. The story is not, for the most part, one enlivened by great feats of creative genius, by startling inventions or revolutionary ideas. Rather, it is one of plodding progress in which invention in the formal sense counted far less than a multitude of minor improvements, adjustments, and adaptations. The heroes of the piece were not so much such men as Watt, Nasmyth, and Maudslay, Fulton, Evans, and Shreve—although the role of such men was important—but the anonymous and unheroic craftsmen, shop foremen, and master mechanics in whose hands rested the daily job of making things go and making them go a little better. The story of the evolution of steamboat machinery in the end resolves itself in large part into such seemingly small matters as, for instance, machining a shaft to hundredths instead of sixteenths of an inch, or devising a cylinder packing which would increase the effective pressure a few pounds, or altering the design of a boiler so that cleaning could be accomplished in three hours instead of six and would be necessary only every other instead of every trip. Matters such as these do not often get into the historical record, yet they are the stuff of which mechanical progress is made, and they cannot be ignored simply because we know so little about then.[19]

Much of the technological change which goes on in an advanced industrial economy is, if not invisible, at least of a low-visibility sort. It includes a flow of improvements in materials handling,[20] redesigning

[18]"Container ships may reduce terminal loading costs by 90 percent and 'turn-around' time from 84 to 13 hours. The gang that was capable of loading 25 tons 'loose stow' in 1 hour can load 300 tons of containerized cargo in the same time. Use of pallets and containers increases productivity by 3 to 4 times . . ." (U.S. Dept. of Labor, *Technological Trends in 36 Major American Industries* [Washington, D.C., 1964], p. 78).

[19]Louis Hunter, *Steamboats on the Western Rivers* (Cambridge, Mass., 1949), pp. 121–22.

[20]For example, in the construction industry "there are a plethora of materials handling improvements. They range from hoists of all types, to conveyors, to higher line speeds, to powered concrete buggies, to more handleable packages on the part of suppliers. These improvements have been continuous and probably no single change is individually significant. We do have an estimate of the use of one type, the tower crane,

production techniques for greater convenience, and reducing maintenance and repair costs (as in modular machinery design).[21] In iron and steel, reductions in fuel requirements have been achieved by rearrangement of plants so as to eliminate the need for successive reheating of materials.[22] In metalworking, new and harder materials continue to be introduced in cutting edges, making possible a considerable acceleration in the pace of work.[23] In electric-power generation, where the long-term rate of growth of total factor productivity has been higher than any other American industry,[24] the slow, cumulative improvements in the efficiency of centralized thermal power plants have generated enormous long-term increases in fuel economy. A stream of minor plant improvements, including the steady rise in operating temperatures and pressures made possible by metallurgical improvements (such as new alloy steels) and the increasing sophistication of boiler design and resulting increased capacity, have sharply raised energy output per unit of input. The size of this improvement may be indicated as follows. It required almost 7 pounds of coal to generate a kilowatt-hour of electricity in 1900, but the same amount of electricity could be generated by less than 0.9 pounds of coal in the 1960s.[25] But even this figure understates the full

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which has changed the construction skyline in recent years. Not used in this country in 1958, 150 European tower cranes had been imported by 1962 and the number [is] increasing . . ." (A. D. Little, Inc., *Patterns and Problems of Technical Innovation in American Industry* [report to National Science Foundation, September 1963], p. 132).

[21] Innumerable such examples may be found in U.S. Department of Labor, *Technological Trends in 36 Major American Industries* (1964), and *Technological Trends in Major American Industries,* Bulletin no. 1474 (Washington, D.C., 1966).

[22] The reduction in fuel requirements from *all* sources—a trend going back well into the 19th century for the steel industry—shows no sign of abating. In 1949 it required almost 1,900 pounds of coke to produce a ton of pig iron; in 1968 it required only 1,200 pounds (see Bureau of Mines, Department of Interior, *Mineral Facts and Problems* [Washington, D.C., 1970], p. 40).

[23] "From 1935 to 1955 the machine tool industry made rapid progress in increasing metal-cutting speeds. Whereas in 1935 cutting speeds were 150–200 feet per minute with high-speed tools, by 1955 they had reached 600–800 feet per minute with carbide tools and more than 1,000 feet per minute with ceramic tools. The effect of speed on the cost of cutting is easily calculable: doubling the speed halves the time and the cost. However, there is another consideration. Tool life decreases with increased speed; consequently, tool maintenance and replacement costs increase. The most economical cutting speed, for a given set of conditions, therefore, represents a compromise between the two rates. . . . The industry was able to reduce the productive cost of metal cutting by as much as 75% during this 20 year period . . ." Little, p. 99).

[24] John Kendrick, *Productivity Trends in the United States* (Princeton, N.J., 1961), pp. 136–37.

[25] Hans H. Landsberg and Sam H. Schurr, *Energy in the United States* (New York, 1968), pp. 60–61.

improvement in the utilization of energy sources: "During the 50-year period 1907–1957 reduction of the total energy required or lost in coal mining, in moving the coal from mine to point of utilization, in converting to electric energy, in delivering the electric energy to consumers, and in converting electric energy to end uses have increased by well over 10 times the energy needs supplied by a ton of coal as a natural resource."[26]

In the construction industry, often regarded as a stronghold of traditionalism and conservatism, there have been innumerable minor changes of great cumulative significance, but it may be that the organizational changes have been even more significant:

> During the last thirty years, the U.S. building industry has undergone a radical change of character. Project and corporate size has increased greatly. Equipment, materials, design and planning practices, are in many ways different than those employed before the Depression. Nevertheless, while the industry as a whole has undergone major change, this change has proceeded in the small segments of the industry through many small increments. There has been no radical change, of great technical and economic significance, which is associated with a single invention or family of inventions. Nothing is to the building industry as synthetic fibers and finishes are to textiles or as numerical controls are to machine tools. In the building industry, change has been evolutionary—like the many small process changes accounting for increased productivity in machine tools and textiles—and much of the most important change cannot be described as technical at all. It has had to do, rather, with methods of managing and organizing the building process.[27]

A more general source of small, low-visibility innovations of great cumulative significance has been the multitude of ways in which main-

[26]U.S. Department of Commerce, *Historical Statistics of the United States,* p. 501. See also William Hughes, "Scale Frontiers in Electric Power," in *Technological Change in Regulated Industries,* ed. William Capron (Washington, D.C., 1971).

[27]Little, p. 119. The availability of superior materials has been particularly important to construction: "Improvements in construction materials make possible more efficient utilization. Paints, for example, require less on-site preparation and less effort in their application. Adhesives are being more widely used to save time and reduce wall costs. Plastics offer the advantage of ease of handling and ability to be molded to extremely close tolerances. The development of high-strength and rust-retardant steels allows construction in which the steel is exposed to the weather. Labor and other cost savings of 25 percent can be realized by the use of prestressed concrete beams in place of structural steel in some areas. Prestressed concrete also makes possible wide spans where column-free construction is desirable. Brick construction has benefited by the development of high-strength mortar" (U.S. Department of Labor 1964, pp. 12–15).

tenance and service requirements for capital goods have been reduced and the useful life of capital goods prolonged. The substitution of new materials (e.g., aluminum and rust-resistant steels) for old ones, improved techniques of friction reduction (lubrication and roller bearings) have led to a considerable extension of the useful life of a wide range of capital equipment. The replacement of untreated railroad ties with ties impregnated with creosote was estimated roughly to double the expected life of a tie—from fourteen to twenty-eight years. Sludge removers and chemically treated feed water extended the life of locomotive boilers and reduced the frequency with which they once had to be taken out of service and washed out.[28] The substitution of heavier for lighter rails increased the life of a rail by a percentage far in excess of the weight increase.

The emphasis placed on technological change of the form emphasized here suggests the extremely great usefulness of research which attempts to link productivity change with specific technological changes at the level of the individual firm. Ideally, studies conducted at the firm level, and with sufficient access to appropriate technological and economic information, should be able to accomplish what has not been done at the highly aggregated level: to separate out the contribution of technological changes from the variety of other forces contributing to the growth of productivity. One such microeconomic analysis was Samuel Hollander's study of the du Pont rayon plants,[29] in which he attempts to determine the extent to which observed reductions in unit costs of production at particular plants are the result of changes in the techniques of production. Hollander's findings are of great interest in the present context. Unit costs declined strikingly in the du Pont plants which he studied. Furthermore, he finds that the contribution of technical change in accounting for these reductions

[28]Harold Barger, *The Transportation Industries, 1889–1946* (New York, 1951), pp. 100–111. For some useful estimates of the impact of improved maintenance procedures on employment requirements for American railroads, see William Haber et al., *Maintenance of Way Employment on U.S. Railroads* (Detroit, 1957). The story of the response of the railroads to rising timber prices is told in Sherry Olson, *The Depletion Myth* (Cambridge, Mass., 1971). It is interesting to note that chemical techniques for the preservation of wood also had the important result of making it possible to use "inferior species" of wood for crossties—i.e., kinds of wood which decayed very rapidly without chemical treatment and which were not used until chemical treatment became widespread. In this respect such techniques not only increased the useful life of crossties but expanded substantially the wood supplies upon which it became possible to draw. "Untreated, the mixed hardwoods, sappy pines, and Douglas fir had small value as ties or bridge timber. Treated, their service value for ties and many items of car lumber was roughly equal to the best white oak" (ibid., p. 132).

[29]Samuel Hollander, *The Sources of Increased Efficiency: The Study of du Pont Rayon Plants* (Cambridge, Mass., 1965).

was "of overwhelming importance."[30] And, most significant for our present purposes, is his finding that the cumulative effect of minor technical changes on cost reduction was actually greater than the effect of major technical changes.[31]

Hollander is, of course, aware that there is an interdependence between minor and major technical changes and that "without some preceding major change the potential stream of minor changes will be exhausted."[32] Nevertheless, his findings lend powerful support to the view that the economic importance of minor technical improvements has been vastly underestimated.

Hollander's findings for rayon are closely paralleled by those of Enos in his study of technological change in petroleum refining. Enos studied the introduction of four major new processes in petroleum refining: thermal cracking, polymerization, catalytic cracking, and catalytic reforming. In measuring the benefits for each new process he distinguished between the "alpha phase"—or cost reductions which occur when the new process is introduced—and the "beta phase"—or cost reductions which flowed from the later improvements in the new process. Enos found that the average annual cost reductions which were generated by the beta phase of each of these innovations considerably exceeded the average annual cost reductions which were generated by the alpha phase (4.5 percent as compared with 1.5 percent). On this basis he asserted that "the evidence from the petroleum refining industry indicates that improving a process contributes even more to technological progress than does its initial development."[33]

[30]Ibid., pp. 192–93.

[31]Ibid., p. 196.

[32]Ibid., p. 205.

[33]John L. Enos, "A Measure of the Rate of Technological Progress in the Petroleum Refining Industry," *Journal of Industrial Economics* (June 1958), p. 180. In their study of the operation of the steamboat on western rivers in the antebellum period, James Mak and Gary Walton also emphasize the quantitative importance of later improvements in the steamboat as compared to the cost reductions which had been achieved by the initial innovation. Thus, "The introduction of the steamboat, 1815–20, led to a significant fall in real freight costs, but the absolute as well as the relative decline in real freight rates was greatest during the period of improvement, 1820–60" (James Mak and Gary Walton, "Steamboats and the Great Productivity Surge in River Transportation," *Journal of Economic History* [September 1972], p. 625). Not all of the improvement in productivity, of course, was attributable to technological change. For example, significant reductions in cargo collection times and passage times were unconnected to such changes. However, technological changes brought about increases in cargo-carrying capacity per measured ton and an extension of the navigation season. A cumulation of minor design changes on the steamboat had the effect of substantially increasing the length of the navigation season for each steam boat size class. By steadily reducing the

Albert Fishlow's incisive study of productivity growth and technological change in the railroad sector makes a notable contribution at the industry level to the goal of sorting out the relative importance of the separate factors contributing to that growth.[34] Fishlow calculates the growth in productivity of American railroads between 1870 and 1910. That growth was extremely large. He finds that the incremental expenses which would have been required to meet the demands of 1910 traffic loads with the technology available back in 1870 would have amounted to about $1.3 billion. The technological sources of productivity growth included a series of important inventions specific to the railroads—air brakes and automatic couplers—the substitution of steel for iron rails, and the gradual improvement in the design of locomotives and rolling stock. Fishlow finds that the economic contribution of the air brake and the automatic coupler was minor. The higher speed and greater safety due to these inventions translated into operational economies of $50 million. The substitution of steel rails for iron, however, was of major importance, and such rails were rapidly adopted in spite of their much higher price. Steel rails were first used by the Pennsylvania Railroad during the Civil War, and they accounted for 80 percent of all track mileage by 1890. Steel rails were far more durable, lasting more than ten times as long as iron rails, and they could bear far greater loads than iron rails. Indeed, the old iron rails of 1870 were simply incapable of supporting the 1910 locomotives and would have been crushed under their average weight of 70 tons. Fishlow calculates that the combined effects of increased longevity and greater strength effected a saving of $479 million.

But the largest cost saving by far was due to a succession of im-

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draft in relation to tonnage and cargo-carrying capacity, steamboat designers and builders brought about major improvements in the productivity of capital by enabling steamboats to operate a longer portion of the year. In fact, as a rough average, "The navigation season was extended from approximately six months, before 1830, to about nine months, during the last half of the ante-bellum period" (ibid., p. 634). Here, too, the greatest overall increase in total factor productivity came in the years following the initial introduction of the innovation. According to Mak and Walton, "The major factor causing the reduction of input requirements per payload ton was the more than threefold increase in the ratio of carrying capacity to measured tonnage. If utilization and the ratio of carrying capacity to measured tonnage had remained unchanged over the period, we would have observed little change in the input requirements of capital, labor, and fuel per payload ton (where we consider only a single voyage)" (p. 626).

[34]Albert Fishlow, "Productivity and Technological Change in the Railroad Sector, 1840–1910," in *Output, Employment, and Productivity in the United States after 1800,* National Bureau of Economic Research Studies in Income and Wealth no. 30 (New York, 1966), pp. 583–646.

provements in the design of locomotives and freight cars, even though the process included no readily distinguishable or memorable innovations. Nevertheless, "Its cumulative character and the lack of a single impressive innovation should not obscure its rapidity. Within the space of some forty years—from 1870 to 1910—freight car capacity more than trebled. The remarkable feature of the transition was its apparent small cost; capacity increased with only a very modest increase in dead weight, the ratio changing from 1:1 to 2:1. Over the same interval, locomotive force more than doubled as powerful engine types, such as the Mogul, the Consolidation, etc., replaced the familiar and faithful American 4-4-0."[35]

This combination of prosaic, unremarkable improvements, leading to more powerful locomotives and more efficient freight cars, accounted for a reduction of $749 million in operating costs, well over half of the cost savings of $1.3 billion achieved over the period 1870–1910.[36]

Finally, the immense cumulative importance of individual improvements has been pointed to in that most modern of industries, the computer industry. Kenneth Knight, reporting on his own research on the computer industry, asserts that ". . . most of the developments in general-purpose digital computers resulted from small, undetectable improvements, but when they were combined they produced the fantastic advances that have occurred since 1940."[37]

Interindustry Relationships

The measurement—even the perception—of the economic payoff to technological innovation is obscured by the difficulties involved in completely identifying the growth in productivity associated with a given innovation. A critical aspect of these difficulties appears to be the prevalence, in modern industrial economies, of a special kind of

[35]Ibid., p. 635.

[36]Here again we find that these two streams of improvement—in freight car and locomotive—stood in a strongly complementary relationship to each other: "Had the powerful twentieth century engines been developed without that simultaneous remarkable advance in freight-car construction, much more of the increased power would have been dissipated in the nonproductive task of hauling dead weight. A higher ratio of dead weight requires either more or heavier trains to deliver the same payload, both involving additional expense. If 1910 tonnage had to be moved in 1870 freight cars, it would have required about 3.3 of them to equal one 1910 car, and at twice the weight. With identical load factors under both technologies, the same loads would have been carried in four trains of identical weight (but with 3.3 times as many cars) as were actually transported in three" (ibid., p. 641).

[37]Kenneth Knight, "A Descriptive Model of the Intra-Firm Innovation Process," *Journal of Business* 40 (October 1967): 493.

external economy. Specifically, many of the benefits of increased productivity flowing from an innovation are captured in industries *other* than the one in which the innovation was made. As a result, a full accounting of the benefits of innovation must include an examination of interindustry relationships. In part this is due to the fact that industrial development under a dynamic technology leads to wholly new patterns of specialization both by firm and by industry, so that it is impossible to compartmentalize the consequences of technological innovation even within conventional Marshallian industrial boundaries.

One component of these changing patterns of industrial specialization is the emergence of specialized firms and industries which produce no final product at all—only capital goods. In fact, much of the technological change of the past two centuries or so has been generated by these specialist firms.[38] The main beneficiaries of technological change in these capital goods industries are, in the first instance, the buyers of these goods in other industries, but the total benefits may be very widely diffused in an economy of increasingly specialized productive units and high rates of interindustry purchases. The inability to take these interindustry relationships fully into account is a fundamental limitation of most of the recent literature on technological innovation.

It is one of the cardinal merits of input-output analysis that it corrects some of these deficiencies; it breaks open the "black box" in which the primary factors of production, capital, and labor are somehow transformed into a flow of final output and displays a wealth of information on the sectoral flow of intermediate inputs. The technique makes it possible to study the process of technological change by examining changing intermediate input requirements, by looking, that is, ". . . at the coal and ore and steel and chemicals and fibers and aluminum foil; sausage casings, wire products, wood products, wood pulp, electronic components, trucking, and business services that establishments furnish to each other. . . ."[39] Many aspects of technological change are visible only at this intermediate level. These take the form of new materials, new machines, new components, or technical processes which never show up in conventional measures of final product for the simple reason that they are not final product.

[38]See Nathan Rosenberg, "Technological Change in the Machine Tool Industry, 1840–1910," *Journal of Economic History* (December 1963), and "Capital Goods, Technology and Economic Growth," *Oxford Economic Papers* (November 1963), pp. 217–27; and Edward Ames and Nathan Rosenberg, "The Progressive Division and Specialization of Industries," *Journal of Development Studies* (July 1965), pp. 363–83.

[39]Anne P. Carter, *Structural Change in the American Economy* (Cambridge, Mass., 1970), p. 4.

Thus, since highly aggregated approaches jump directly in their reasoning from primary inputs at the beginning of the productive process to final outputs at the end of the process, an enormous amount of interesting information is completely lost from view.[40] The great virtue of input-output analysis, for our present interests, is that it helps us to understand the structural interdependence of the economic system, and the *changes* over time in this structural interdependence, by providing quantitative measures (input-output coefficients) of the interindustry flow of goods and services. Anne Carter has shown that technological change has been associated with an increasing reliance on general sectors—producers of services, communications, energy, transportation, and trade. This has been offset by decreases in other sets of coefficients, most conspicuously in the general, across-the-board declines in the contributions of producers of materials. Technological change has been forcefully associated with a significant expansion in the kinds and qualities of materials and in improvements of design generally. Carter demonstrates how technological change has been expanding the range of substitutability among materials in addition to bringing about an absolute reduction in input requirements per unit of output. The traditional dominance of steel in many uses, for example, has been successfully challenged by aluminum, plywood, and prestressed concrete. The growing importance of plastics and chemicals, and the changes in product design associated with such new and versatile materials, have been clearly quantified. Moreover, technological changes in the crucial area of capital goods, and their increasing complexity and sophistication, have brought a decline in the relative importance of general metalworking and a sharp increase in the role of electrical, electronics, and instrumentation sectors. It is a significant contribution of input-output analysis that such changes can be examined in quantitative terms.

In spite of its usefulness, even input-output analysis can capture only a small portion of the kinds of interindustry relationships which

[40]"In earlier days of national income accounting, intermediate production was eliminated to avoid 'double counting.' This is reasonable if one is primarily concerned with measuring an economy's 'success'—the net amount the nation has managed to produce, whatever its methods. Yet this duplicative portion of economic activity is precisely the focus of our present analysis. For it is the composition of interindustry sales that mirrors most directly the effects of changing technology and the organization of production. Intermediate inputs are the specific goods and services used to produce the gross national product. As methods of production change, more of one kind of input will be required and less of another—more chemicals, less steel, and so on—and the interdependence of individual supplying sectors will be changed accordingly" (ibid., p. 33).

are relevant to an examination of the payoff to technological innovation. One would need to include also all the consequences to the customer industry when technological changes in the supplying industry bring about a reduction in the price of the intermediate good. Here, indeed, input-output analysis can at least provide some preliminary guidance on the direction and relative magnitudes of specific innovations. Input-output information enables us to predict that cost-reducing technological changes in some sectors are likely to have wider-range repercussions than similar changes in other sectors. It highlights the pervasiveness of cost reductions in such sectors as transportation, energy, services, and communications, and makes it possible to identify and assess the relative significance of such cost reductions in different sectors of the economy. But the problems are far more subtle and complicated and revolve around the essential fact that technological progress in one sector of the economy has become increasingly dependent upon technological change in other sectors. That is to say, technological problems arising in industry A are eventually solved by bringing to bear technical skills and resources from industry B, C, or D. Thus, industries are increasingly dependent, in achieving a high rate of productivity growth, upon skills and resources external to, and perhaps totally unfamiliar to, themselves.

This situation is not a new one, although it is a phenomenon the relative importance of which has been plainly increasing. It is clearly a function of the growing specialization of industrial activity. In the early stages of the industrial revolution, textile firms produced their own machines. As the size of the market for such machinery grew and as such machines became increasingly complex, the making of textile machinery became the unique responsibility of an increasingly independent set of specialized machinery producers, from whom the textile firms subsequently purchased their equipment.[41] As the textile industry expanded in the nineteenth century, it generated other input requirements which were far beyond its own technical competence and which drew upon the skills of the chemical industry as well as machinery makers. As David Landes has graphically expressed it in connection with the British textiles industry: "The transformation of the textile manufacture, whose requirements of detergents, bleaches, and mordants were growing at the same pace as output, would have

[41]Nathan Rosenberg, "Technological Change in the Machine Tool Industry, 1840–1910," pp. 418–19. The process continues in the 20th century. Chemical firms used to design their own plants, and still do to some extent. Increasingly, however, they rely on specialized plant contractors for the construction of new plants (see, for example, C. Freeman, "Chemical Process Plant: Innovation and the World Market," *National Institute Economic Review* [August 1968], pp. 30–31).

been impossible without a corresponding transformation of chemical technology. There was not enough cheap meadowland or sour milk in all the British Isles to whiten the cloth of Lancashire once the water frame and mule replaced the spinning wheel; and it would have taken undreamed-of quantities of human urine to cut the grease of the raw wool consumed by the mills of the West Riding."[42]

The ways in which technological changes coming from one industry constitute sources of technological progress and productivity growth in other industries defy easy summary or categorization. In some cases the relationships have evolved over a considerable period of time, so that relatively stable relationships have emerged between an industry and its supplier of capital goods. Equipment makers are a major source of technological change in many industries—for example, the aluminum industry.[43] On many occasions the availability of new and superior metals has played a major role in bringing performance and productivity improvements to a wide range of industries—railroads, machine tools, electric-power generation, and jet engines, among others. Since the 1930s the building industry has been the recipient of numerous new plastics products which have found a wide range of uses, not the least of which has been cheap plastic sheeting which made possible an extension of the construction year by providing protection on the building site against inclement weather.[44] The sharp increase in the utilization of commercial fertilizer inputs in American agriculture, so important to the growth of agricultural productivity, can be entirely explained by the decline in fertilizer prices. This decline, in turn, was to a considerable extent the result of technological change in the fertilizer industry.[45]

[42]David Landes, *The Unbound Prometheus* (Cambridge, 1969), p. 108.

[43]Merton J. Peck, "Inventions in the Postwar American Aluminum Industry," in *The Rate and Direction of Inventive Activity* (Princeton, N.J., 1962), pp. 279–98; esp. p. 285, table 1.

[44]"In the past thirty years, one new major class of materials has been introduced into the building industry: plastics. Polyvinyl chloride dates from 1936; Polystyrene, from 1938; Melamines, from 1939; Polyethylene, from 1942; Polyesters, from 1952; and Urethanes, from 1953. All of these products have been developed within the chemical industry, many of them as synthetic products for wartime use. The growth of plastics has been rapid. The Census of Manufacturers reports a 1937 volume of $67 million, a 1950 volume of $791.8 million, and a 1958 volume of $1.8 billion. . . . De Marco of Monsanto Chemical Company estimated . . . that in 1959 approximately 5 billion pounds of plastic were produced with about 18% going to the construction industry. It is further estimated that the construction industry's consumption rose from 501 to 866 million pounds between 1956 and 1959. About 40% of these plastics were in paints, 20% in laminates and floor coverings, and another 20% in wire coatings and electrical devices and controls . . ." (Little [n. 20 above], pp. 120–21).

[45]See Zvi Griliches, "The Demand for Fertilizer: An Economic Interpretation of a Technical Change" (*Journal of Farm Economics* [August 1958], pp. 591–606), where a

Often, however, an innovation from outside will not merely reduce the price of the product in the receiving industry but will make possible wholly new or drastically improved products or processes. In such circumstances it becomes extremely difficult even to suggest reasonable measures of the payoffs to the triggering innovation, because such innovations, in effect, open the door for entirely new economic opportunities and become the basis for extensive industrial expansion elsewhere. In the 20th century the chemical industry exercised a massive effect on textiles through the introduction of an entirely new class of materials—synthetic fibers.[46] Their great popularity, especially in clothing, is attributable to the possibility of introducing specific desirable characteristics into the final product, often as a result of blending (including blending with natural fibers). Thus, materials used in clothing can now be designed for lightness, greater strength, ease of laundering, fast drying, crease retention, etc.

Technological change in the chemical industry has exercised a similar triggering function in industries other than textiles. In metallurgy, for example, thermochemical and electrothermal developments have considerably widened the range of available metal products by making possible the reduction of the ores of metals with high melting points. The most important instance was, of course, aluminum, but there were others, including manganese, chromium, and tungsten. These latter materials were particularly important in the major materials innovations associated with the development of alloys. In the case of the electrical industry, the chemicals industry played a vital role in the innovation process through the provision of such essential items as refractory materials, insulators, lubricants, coatings, and, with the increasing importance of conductors, through the provision of metals of a high degree of purity. All these profound effects of chemicals innovation have had a relatively limited visibility because of the intermediate good nature of most of the products concerned. One could document in detail the manner in which transistors in recent years have been exercising triggering effects similar to the experience of chemicals.

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distributed lag model is employed; see also Gian S. Sahota, *Fertilizer in Economic Development: An Econometric Analysis* (New York, 1968).

[46]"In the period immediately following World War II there was a major invasion of the textile industry by the chemical industry, as the synthetic fibers and finishes were introduced. From the point of view of technical and economic significance, these have been the major innovations of the last 30 years. In the 50's, then, came a series of innovations involving fabric, yarn, and machinery. Almost all of these (except compacting and tufting) have depended on the chemical innovations of the 40's. The 50's have been a time of minor innovation exploiting the major chemical innovations of the 40's" (Little, p. 56).

The transmission of technological change from one sector of the economy to another through the sale of intermediate output has important implications for our understanding of the process of productivity growth in an economy. Specifically, a small number of industries may be responsible for generating a vastly disproportionate amount of the total technological change in the economy. Government policy directed at stimulating technological change generally, for example, or for stimulating the output of certain categories of goods or services, will need to be based on the clearest possible understanding of the interindustry relationships which have been discussed in this section. For example, although electric-power generation has one of the very highest rates of technological change and productivity growth of any sector of the economy, the industry has had virtually no R & D expenditures of its own. Rather, technological change in electricity power generation has flowed from the research expenditures of the equipment industry, the metallurgical industries, and various other federally supported research projects. Clearly, any attempt to analyze the economic effects of R & D expenditures must be based on a far better understanding of such relationships than is presently available. For, even though only a few industries are research-intensive, the interindustry flow of new materials, components, and equipment may generate widespread product improvement and cost reduction throughout the economy. This has clearly been the case in the past among a small group of producer-goods industries—machine tools, chemicals, electrical and electronic equipment. Industrial purchasers of such producer goods experienced considerable product and process improvement without necessarily undertaking any research expenditure of their own. Such interindustry flow of technology is one of the most distinctive characteristics of advanced industrial societies.[47] Indeed, it might even be more appropriate to say that such technology flows have radically reshaped industrial boundary lines, and that we still talk of "interindustry" flows because we are working with an outmoded concept of an industry:

> Any consideration of the textile industry would be artificial which did not include the chemical, plastics, and paper industries. Consideration of the machine tool industry must now take into account the aerospace, precision casting, forging, and plastics forming industries. These industries are now complex mixtures of

[47]The emergence of the machine-tool industry in the United States in the 19th century and the precise role which it played in the development and the interindustry diffusion of new industrial techniques are examined in Nathan Rosenberg, "Technological Change in the Machine Tool Industry, 1840–1910."

> companies from a variety of SIC categories, some functioning as suppliers to the traditional industry, some competing with it for end-use functions and markets. "The industry" can no longer be defined as a set of companies who share certain methods of production and product-properties; it must be defined as a set of companies, interconnected as suppliers and market, committed to diverse processes and products, but overlapping in the end-use functions they fill. We can talk about the "shelter" industry and the "materials forming" industry, but we cannot make the assumptions of coherence, similarity and uniformity of view which we could formerly make in speaking of "builders" or "machine tool manufacturers." Similarly, companies are coming to be less devoted to a single family of products and manufacturing methods, and more a diverse conglomerate of manufacturing enterprises, stationed around a central staff and bank, and to some extent overlapping in the markets and functions they serve. These changes are part and parcel of the process of innovation by invasion.[48]

I have emphasized that the benefits of innovation were difficult to identify comprehensively because such benefits were frequently captured by industries other than the one in which the innovation was originally made. The benefits of an innovation may be both highly diffuse and difficult to identify because its availability permits a large number of *other* alterations (including innovations) in the productive process to take place. Consider the case of electricity. The reduced cost of power alone did not exhaust the productivity benefits of electricity. The social payoff to electricity would have to include not only lower energy and capital costs but also the benefits flowing from the new-found freedom to redesign factories with a far more flexible power source than was previously available under the regime of the steam engine. To appreciate this, it is necessary to cast a much wider net.

Although the rise of electricity began in the 1890s, the industry commenced its rapid growth only after the steam turbine had been brought to a level of efficiency sufficiently high to create the thermal power station and the highly centralized generation of electric power.[49] It was the rise of this new power source which challenged the dominance, at the beginning of the 20th century, of the coal-using steam engine in industry. The steam engine had always presented

[48] Little, p. 181.

[49] Utilities were producing more than half of all electricity in the United States by 1914 (see *Historical Statistics of the United States* [n. 26 above], p. 506).

serious problems. Its minimum size was too large for small plants. Furthermore, it was highly inefficient in those frequent situations where a large steam engine had to be operated in order to supply small quantities of power. In addition, the steam engine required clumsy belting and shafting techniques for the transmission of power within the plant. These methods were not only responsible for high energy losses; they also imposed serious constraints upon the organization and flow of work, which had to be grouped, according to their power requirements, close to the energy source.

With the advent of the "fractionalized" power made possible by electricity and the electric motor, it now became possible to provide power in very small, less costly units and also in a form which did not require the generation of excess amounts in order to provide small or intermittent "doses" of power. Although the direct, energy-saving and capital-saving effects (including, it should be noted, a vast saving of floor space) were great, the flexibility of the new power source made possible a wholesale reorganization of work arrangements and, in this way, made a wide and pervasive contribution to productivity growth throughout manufacturing. "Shortly after steam power began to yield to electricity, installation of electric motors called attention to the obvious restraints placed on efficiency by the steam engine. Its systems, practices, and factory organization became almost visibly redundant. Thus, as 'unit drive' electric power grew in plant after plant, thoroughgoing reorganization of factory layout and design took place. Machines and tools could now be put anywhere efficiency dictated, not where belts and shafts could most easily reach them. To these advantages were simultaneously added those of revamped industrial processes, leading to mass-production and batch-processing techniques."[50]

Electric power was rapidly adopted by industry. Electric motors accounted for less than 5 percent of total installed horsepower in American manufacturing in 1899. By 1909 their share of manufacturing horsepower was 25 percent, by 1919 55 percent, and by 1929 electric motors accounted for over 80 percent of total installed horsepower in manufacturing.[51] The sharp productivity rise in the Ameri-

[50]Richard B. Du Boff, "The Introduction of Electric Power in American Manufacturing," *Economic History Review* (December 1967), p. 513.

[51]Landsberg and Schurr (n. 25 above), pp. 52–53. They also make the following observations on the efficiency of electric motors: "Installation of electric motors resulted in higher thermal efficiency—a higher yield of mechanical work per unit of primary energy employed in the plant. Instead of less than 10 percent in the case of belt-driven machinery powered by steam engines—or a waste of 90 percent and more

can economy in the years after World War I owed a great deal, directly and indirectly, to the electrification of manufacturing.

But even this account does not exhaust the ways in which electricity contributed to the overall growth in productivity. New patterns of specialization and division of labor became feasible, with important implications for industrial organization. For

> . . . electricity did more than change the techniques and decor of the factory: by making cheap power available outside as well as inside the plant, it reversed the historical forces of a century, gave new life and scope to dispersed home and shop industry, and modified the mode of production. In particular, it made possible a new division of labour between large and small units. Where before the two had almost inevitably been opposed within a given industry—the one using new techniques and thriving, the other clinging to old ways and declining—now a complementarity was possible. Both types could use modern equipment, with the factory concentrating on larger objects or standardized items that lent themselves to capital-intensive techniques, while the shop specialized in labour-intensive processes using light power tools. And often the complementarity became symbiosis: the modern structure of sub-contracting in the manufacture of consumers' durables rests on the technological effectiveness of the small machine shop.[52]

And finally, within the household itself, cheap electricity and small, versatile electric motors were the vital technological breakthroughs which made possible a wide array of household appliances.[53] Although electricity was introduced into the household in its early years almost entirely for purposes of illumination, it soon provided the basis for much else, which eventually transformed the operation

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between energy input and final utilization—efficiency was 70 to 90 percent in the case of electric motors. With energy losses on the way to the machine practically eliminated, a smaller amount of energy was needed to accomplish the same amount of work (though this was somewhat offset in the economy as a whole by the fact that thermal power generation for its part at then prevailing heat rates, wasted 70 to 80 percent of the fuel's inherent energy)" (pp. 62–63).

[52]Landes, p. 288.

[53]The electric-power companies worked very hard at increasing the demand for their output by becoming aggressive salesmen of electricity-using innovations inside the household (see Raymond C. Miller, *Kilowatts at Work* [Detroit, 1957], chap. 11). The value (in millions of current dollars) of electrical household appliances and supplies for selected years was as follows: 1899, 1.9; 1900, 2.4; 1910, 16.3; 1920, 82.8; 1930, 160.0; 1937, 341.0 (*Historical Statistics of the United States*, p. 420).

of domestic households: refrigerators, electric ranges, water heaters, vacuum cleaners, dishwashers, clothes dryers, freezers, etc.[54] Indeed, one might therefore well argue that the women's liberation movement is essentially due to the combination of declining fertility (in turn partly attributable to a more effective technology of contraception), on the one hand, and the electrification of household chores, on the other. One need not be a technological determinist to argue that the social benefits of the new-found freedom of women in American society are, in large measure, the product of technological innovation.

[54]In an absorbing account of the mechanization of the household, Siegfried Giedion points out that many household appliances—the vacuum cleaner, clothes-washing machine, dishwashing machine—had made their first appearances as early as the 1850s and 1860s. Such devices "belonged to those shelved inventions whose release awaited the coming of the small electric motor" (*Mechanization Takes Command* [Oxford, 1948], p. 553; see also the article by Cowan in the same issue).