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David C. Mowery and Nathan Rosenberg
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Introduction

An examination of technological innovation in the 20th-century U.S. economy must naturally begin in the 19th century. An appropriate starting point is Alfred North Whitehead's observation, in *Science and the Modern World*, that "The greatest invention of the 19th century was the invention of the method of invention" (p. 98). Whitehead understood that this invention involved the linking of new scientific knowledge to the world of artifacts. But he also understood that this linkage was not easily achieved, because a huge gap typically exists between a scientific breakthrough and a new product or process. The sentence just quoted is well known, but equally important is the less famous observation that immediately followed it:

> It is a great mistake to think that the bare scientific idea is the required invention, so that it has only to be picked up and used. An intense period of imaginative design lies between. One element in the new method is just the discovery of how to set about bridging the gap between the scientific ideas, and the ultimate product. It is a process of disciplined attack upon one difficulty after another.

Whitehead's statement serves as a valuable prolegomenon in at least two respects to this volume's discussion of technology in the 20th century. First, a distinctive feature of the 20th century was that the inventive process became powerfully institutionalized

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and far more systematic than it had been in the 19th century.[1] This institutionalization of inventive activity meant that innovation proceeded in increasingly close proximity to organized research in the 20th century. Of course, this research was not confined, as Whitehead appreciated, to the realm of science, much less to scientific research of a fundamental nature. But Whitehead's observation is apposite in another respect as well. For all its reorganization and institutionalization, the realization of the economic impacts of 20th-century scientific and technological advances have required significant improvement and refinement of the products in which they are embodied. This process of incremental learning, modification, and refinement, along with the often prolonged process of adoption of these new technologies, means that even in this technologically revolutionary century, realization of the economic effects of new technologies requires considerable time.

This point needs to be emphasized because there is not always time or space to develop it in detail within the scope of a short volume. Inventions, when they are first introduced or patented, are typically very far from the form that they embody when they eventually achieve widespread diffusion; or, to put it differently, it is the improvements that they undergo that finally lead to widespread diffusion. The Wright brothers' achievement of heavier-than-air flight at Kitty Hawk in 1903 was a great technological accomplishment, even though the clumsy contraption was held together with struts, baling wire, and glue, and the total distance traveled was just a couple hundred yards. It required thousands of improvements, small and large, over fully a third of a century, before regularly scheduled intercity flights became common with the introduction of the DC-3 in 1936. The first digital electronic

[1] Schumpeter (1942) noted that "innovation itself is being reduced to routine. Technological progress is increasingly becoming the business of teams of trained specialists who turn out what is required and make it work in predictable ways" (p. 132).

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computer, the ENIAC, was over 100 feet long and required the simultaneous functioning of no less than 18,000 vacuum tubes when it was introduced in 1945. Today an instrument with vastly superior capabilities can easily be held in one's hand or even carried in a pocket.

Moreover, many intermediate steps must be completed before the commercialization of such innovations. In many cases, ancillary inventions or improvements, frequently from other industries, are needed; new products must be redesigned for greater convenience, and cost-reducing changes are necessary to render them more affordable; further adaptations are necessary as consumers discover new unanticipated uses; production facilities need to be reorganized to adapt to the idiosyncratic production requirements of the new product. The time required for all these complementary developments to emerge is measured typically in years and not infrequently in decades.

Although considerable time is typically required for the economic effects of technological innovation to be felt, these effects are profound. Not until the 20th century had run more than half of its course did economists develop a fuller appreciation of the extent to which economic growth was a consequence of the process of technological change. One important reason for this delay was a simple one. An *economic* approach to economic growth is feasible only after certain magnitudes have been reduced to quantitative expression. The measurement of economic growth itself requires a conceptual framework and a methodology for aggregating the myriad of activities that make up the daily life of a large economy. The development of national income and national product accounts were products of the 1930s and 1940s, when a number of scholars developed estimates of long-term changes in the inputs to economic activity as well as the estimates of output. The availability of such data set the stage for the "discovery" in the 1950s of the contribution of technological change to long-term economic growth in the United States.

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Once reasonably reliable estimates of the growth of inputs and outputs were available, it seemed natural to ask how much of the long-term growth in output could be accounted for by the estimated growth in inputs. The two most influential studies, by Abramovitz (1956) and Solow (1957), employed different methods, examined different time periods, and measured the economy's output in different ways. But these studies agreed on a very important conclusion: No more than 15% of the measured growth in U.S. output in the late 19th century and the first half of the 20th century could be accounted for by the growth in measured inputs of capital and labor. The strikingly large "residual" of 85% suggested that 20th-century American economic growth was overwhelmingly a matter of extracting more output from each unit of input into economic activity, rather than merely utilizing more inputs.

A prime candidate in accounting for the residual was technological change, although the residual necessarily captured all the growth in output that could not be attributed to growth in measured inputs of capital and labor. Incautious analysts drew the conclusion that the growth in the stock of capital did not make an important contribution to economic growth. But the contributions of technological change to economic growth rarely are independent of investment, because most new technologies need to be embodied in the capital goods that are the vehicles for their introduction. Most new technologies enter the stream of economic life only as the result of an investment decision. At the same time, however, the character of technological change, especially any factor-saving or -using bias associated with it, influences the demand for physical and human capital investment.

There is another connection between technological change and 20th-century U.S. economic growth. Kuznets pointed out in 1930 that technological innovation frequently creates entirely new industries devoted to the production of new products (see also Burns 1934). These new industries typically grow rapidly in their early stages and then experience retardation in their growth rates as their

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markets reach saturation. Because older final goods are likely to face lower demand elasticities, further cost-reducing process innovations have relatively small effects on demand for the product. The rate of growth of the entire economy is the summation of the growth rates of its component industries, which means that a high rate of aggregate growth requires that declining rates of growth in mature industries be offset by the more rapid growth rates of new industries associated with new technologies. In other words, sustained economic growth reflects a continuous shift in the economy's product and industry mix.[2]

Although insightful, Kuznets's statement tends to understate the importance of the adoption of new technologies by mature industries, which has sparked productivity growth and even the appearance of new products (e.g., synthetic-fiber radial tires) in these industries. In fact, many older industries have experienced significant productivity growth as a result of the *intersectoral flow of new technologies*. This intersectoral flow is a fundamental characteristic of 20th-century innovation in the U.S. economy – for example, innovations in the chemicals and electronics industries have been truly pervasive, being incorporated into a staggering array of consumer and capital goods. In addition, the rise of the automobile and commercial aircraft industries significantly increased the demand for advanced products (e.g., jet fuel, composite materials, gasoline) from other industries, thereby creating additional incentives for increases in scale and efficiency. The importance of this intersectoral flow of technologies is one reason

[2] "[A] sustained high rate of growth depends upon a continuous emergence of new inventions and innovations, providing the bases for new industries whose high rates of growth compensate for the inevitable slowing down in the rate of invention and innovation, and upon the economic effects of both, which retard the rates of growth of the older industries. A high rate of over-all growth in an economy is thus necessarily accompanied by considerable shifting in relative importance among industries, as the old decline and the new increase in relative weight in the nation's output" (Kuznets 1959, p. 33).

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that we focus the discussion in this book on a few broad classes of technologies that have influenced innovation and growth throughout the U.S. economy.

The international flow of technology has also been important to U.S. economic growth. No treatment of technological change in the 20th-century United States can overlook the importance of this economy's technology imports and exports. Although the United States was overwhelmingly an importer of foreign technology during its early history (Rosenberg 1972), by 1900 it had become a considerable exporter of industrial and agricultural technologies. In fact, the United States had begun to export specialized machine tools as early as the 1850s. A collection of such tools was shipped to the Enfield Arsenal in Great Britain, where they laid the basis for the large-scale manufacture of firearms made of interchangeable parts – a technology that the British referred to as "the American system of manufactures."

At the same time, however, the United States imported a range of industrial technologies that, as of 1900, had not been mastered in this country. For example, German industry dominated the manufacture of organic synthetic dyes in the late 19th century. Indeed, the technological position of the U.S. economy before the Second World War bore more than a superficial resemblance to the situation of Japan in the 1960s and 1970s. During this period, U.S. firms had few equals in their ability to exploit (and often, improve) technologies that had been invented abroad. But until the Second World War, America's role in the world of science was in no way on a par with the leadership position that it had established earlier in the century in numerous realms of industrial and agricultural technology.

The general point is that, even at the beginning of the 20th century, the world economy was already well on its way toward globalization. Indeed, by some measures (such as the share of gross national product [GNP] accounted for by exports) the U.S. economy at the turn of the century (1900–10) was more open to international

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influences than at any time during the 1910–70 period (see Davis et al. 1972). By 1900, United States–based multinational firms, such as Singer Sewing Machine and International Harvester, were already playing a significant role in the international transfer of new technologies. The great improvements in the realms of transportation and communication were, of course, the main technological facilitators in the increasing flow of technological knowledge, as well as goods and capital, across political borders. Two disastrous world wars, the most severe depression in history, and the protectionist policies that separated those wars served to interrupt the trend toward globalization for several decades.

Since World War II, new international institutions, such as Bretton Woods and General Agreement on Tariffs and Trade (GATT), and, more recently, the World Trade Organization (WTO), have reduced barriers to the exchange of goods and technological knowledge. Indeed, the last third of the 20th century has witnessed the emergence of an increasingly dense network of interfirm relationships – international joint ventures and strategic alliances of all sorts – that contribute to more rapid international flows of technology (see Mowery 1988). The spectacular improvements in the information technologies that unite this international network have lent to the term "globalization" a vastly expanded significance over its meaning at the beginning of the century.

The discussion in the preceding paragraphs has been rather abstract, with its references to technological change in the context of "inputs," "outputs," and growth. In fact, technological change in the present century has produced a wide range of new products and manufacturing processes. The last decade of the 20th century differs from the last decade of the 19th, not primarily in terms of larger quantities of goods that already existed in the 1890s; rather, the distinctive differences consist in the present availability of goods for which there was no close equivalent a century ago.

An attempt to describe the new technologies of the 20th century would quickly take on the dimensions of a full shelf of

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Sears Roebuck catalogues and trade journals – and even then these two abundant sources of information would fail to disclose much of what was distinctive about 20th-century technology. We focus instead on three clusters of innovation that have dominated American technology in the 20th century, using their development as the basis for a more general treatment of the central features of 20th-century U.S. innovation and its economic impacts. The three clusters are the internal combustion engine, chemistry, and electricity and electronics (we consider electricity and electronics as a single cluster).

These clusters have a number of common characteristics. They are pervasive – in fact, their economic impact has been more pervasive than is generally realized. Moreover, they are highly research-intensive, particularly if the term "research" is interpreted broadly and not confined to fundamental research at the frontiers of science. This is really no more than an acknowledgment that we employ the term to include all the components of what is now commonly referred to as *R&D* (*research and development*). Major new technologies have by no means always been dependent on new scientific knowledge. Innovation has throughout this century drawn on existing technological knowledge as much as it has on "science," and in some celebrated cases, technological innovations have appeared in advance of the scientific theories that explain their performance or design. Moreover, realization of the economic consequences of these technological advances has typically required considerable refinement and improvement of the crude early versions of the products that incorporate them.

The development within the United States of at least two of these three technology clusters, chemicals and the internal combustion engine, has also been influenced by this nation's unique geographic structure and resource endowment. The vast distances that goods and travelers must cover within the United States gave an impetus to the development and adoption of technologies that could shorten travel times, reduce transportation costs, and increase

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reliability of communication – in the 19th century, these were the telegraph and railroad (plus the older technology of canals), and in the 20th they were the automobile and the airplane.

The U.S. resource endowment, with its abundant supplies of raw materials – in particular, petroleum – also meant that the development of the internal combustion engine and the U.S. chemicals industry followed a resource-intensive trajectory. This characteristic of U.S. technological innovation reflects a more general phenomenon, the path-dependent nature of the innovation process. The initial conditions under which an innovation appears and is refined for economic exploitation exert a powerful influence over the types of knowledge required for its exploitation, the types of knowledge generated from its exploitation, and the evolutionary path followed by the technology.

Another distinctive feature of the history of innovation in the 20th-century American economy is the institutionalization of the innovation process that occurred during this period. In the late 19th century, industrial enterprises began to organize systematic programs of in-house R&D. The emergence of these industrial research laboratories in the U.S. economy occurred in parallel with the growth of new engineering and applied science disciplines in the universities. Indeed, all of our technological clusters are characterized by a shifting "division of labor" among private industry, universities, and government in R&D performance and funding. The structure of the U.S. R&D system that has spawned these waves of innovations underwent dramatic change during the first eight decades of this century, and since 1989, the end of the Cold War and economic globalization have triggered yet another wave of restructuring.

Before turning to our detailed discussion of 20th-century innovation, a general observation is in order. We have emphasized, so far, the role played by technological change in generating long-term growth in productivity and, therefore, in incomes. But the

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relationship between income and technological change is obviously a two-way street, even though the following pages travel on only one side of that street.

As a society's income rises, the composition of demand changes, and along with those changes in demand the profitability of inventions in different sectors of the economy changes as well. The vast commitment of resources in the United States today to the development of technologies aimed at recreational and leisure-time activities would have been inconceivable, or at least intolerable, during Thomas Jefferson's presidency, when the American workforce was overwhelmingly employed in food production. Similarly, if one is to account for American leadership, early in the 20th century, in the exploitation of the automobile, it is not sufficient to invoke the "wide open spaces" of a huge continental nation; the income levels that created a huge potential market for a "personalized" form of transportation were also essential.

Schmookler (1962, pp. 226–227) expressed this point well:

> It seems almost obvious, to this writer at least, that the automobile came when it did more because of economic and social changes than because of technological change as such. In the first place, in the automobile, prestige, flexibility, privacy, recreation, and utility are combined in ways which only an individualistic high-per-capita-income society could afford or develop. (The so-called bicycle craze of the 1890s was part of the same phenomenon.) The automobile, after all, did not and has not revolutionized life in low-income India or China. Its effects have been confined primarily to the United States and other industrialized countries, roughly in proportion to income. A good case can be made for the contention that among the indispensable conditions for the coming of the automobile age were relatively high levels of income, at least for the middle-income classes, and an individualistic society.

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