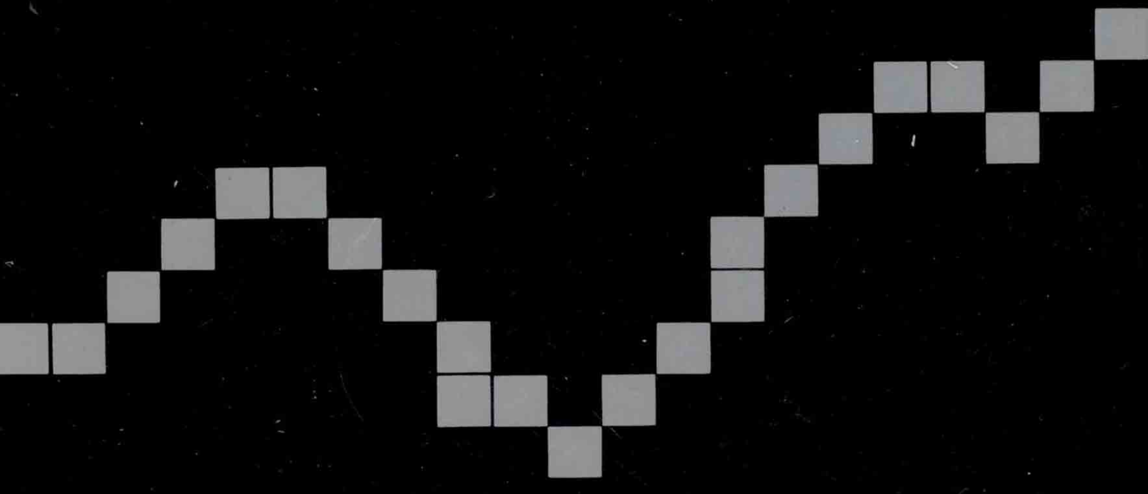
INSIDE THE BLACK BOX: TECHNOLOGY AND ECONOMICS



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Inside the black box

Technology and economics

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Preface

The central purpose of this book may be simply stated. Economists have long treated technological phenomena as events transpiring inside a black box. They have of course recognized that these events have significant economic consequences, and they have in fact devoted considerable effort and ingenuity to tracing, and even measuring, some of these consequences. Nevertheless, the economics profession has adhered rather strictly to a self-imposed ordinance not to inquire too seriously into what transpires inside that box.

The purpose of this book is to break open and to examine the contents of the black box into which technological change has been consigned by economists. I believe that by so doing a number of important economic problems can be powerfully illuminated. This is because the specific characteristics of certain technologies have ramifications for economic phenomena that cannot be understood without a close examination of these characteristics. Thus, I attempt to show in the following pages how specific features of individual technologies have shaped a number of developments of great concern to economists: the rate of productivity improvement, the nature of the learning process underlying technological change itself, the speed of technology transfer, and the effectiveness of government policies that are intended to influence technologies in particular ways.

The separate chapters of this book reflect a primary concern with some of the distinctive aspects of industrial technologies in the twentieth century: the increasing reliance upon science, but also the considerable subtlety and complexity of the dialectic between science and technology; the rapid growth in the development costs associated with new technologies, and the closely associated phenomena of lengthy lead times and the high degree of technological uncertainty associated with precisely predicting the eventual performance characteristics of newly emerging technologies; the changing structure of interindustry relationships, such as that between the makers of capital goods and their eventual users; and the changing characteristics of a technology over the course of its own life cycle. Each of the chapters in Part II represents an attempt to identify some significant characteristics of specific advanced industrial technologies – or of the process by which such technologies have emerged and have been introduced into the economy. The chapters in Parts III and IV continue this examination against the backdrop of a concern with issues of public policy and with the implications of technology transfer in the international context.

The book opens with a broad survey, in Part I, of the historical literature on technical change. It attempts to provide a guide to a wide range of writings, including those by some social historians and social theorists as well as economic historians and economists, that illuminate technological change as a historical phenomenon. It should not be necessary to belabor two points: (1) that past history is an indispensable source of information to anyone interested in characterizing technologies, and (2) that both the determinants and the consequences of technological innovation raise issues that go far beyond the generally recognized domain of the economist and the economic historian. The first chapter discusses aspects of the conceptualization of technological change and then goes on to consider what the literature has had to say on (1) the rate of technological change, (2) the forces influencing its direction, (3) the speed with which new technologies have diffused, and (4) the impact of technological change on the growth in productivity.

A separate chapter is devoted to Marx. Marx's intellectual impact has been so pervasive as to rank him as a major social force *in* history as well as an armchair interpreter *of* history. And yet, curiously enough, I argue that Marx's analysis of technological change opened doors to the study of the technological realm through which hardly anyone has subsequently passed.

Part II is, in important respects, the core of the book. Each of its chapters advances an argument about some significant characteristics of industrial technologies, characteristics that are typically suppressed in discussions of technological change conducted at high levels of aggregation or lacking in historical specificity. Chapter 3 explores a variety of less visible forms in which technological improvements enter the economy. Each of these forms, it is argued, is important in determining the connections between technological innovations and the growth of productivity flowing from innovation. Chapter 4 explicitly considers some significant characteristics of different energy forms. It became a common practice in the 1970s, following the Arab oil embargo, to treat energy as some undifferentiated mass expressible in Btus which it was in society's interests to minimize. This chapter examines some of the complexities of the long-term interactions between technological change and energy resources. It emphasizes, in particular, the frequently imperfect substitutability among energy sources in industrial contexts and the consequent suboptimality of criteria for energy utilization that fail to take specific characteristics of different energy forms into account.

Chapter 5, "On Technological Expectations," addresses an issue that is simultaneously relevant to a wide range of industries – indeed, to all industries that are experiencing, or are expected to experience, substantial rates of technical improvement. I argue that rational decision making with respect to the adoption of an innovation requires careful consideration of prospective rates of technological innovation. Such a consideration will often lead to counterintuitive decisions, including slow adoption rates that, from other perspectives, may appear to be irrational. Expectations about the future behavior of technological systems and their components are shown to be a major and neglected factor in the diffusion of new technologies.

The last two chapters of Part II are primarily concerned with issues of greatest relevance to high-technology industries – industries in which new product development involves large development costs, long lead times, and considerable technological uncertainty (especially concerning product performance characteristics) and that rely in significant ways upon knowledge that is close to the frontiers of present-day scientific research. Chapter 6, "Learning by Using," identifies an important source of learning that grows out of actual experience in using products characterized by a high degree of system complexity. In contrast to learning by doing, which deals with skill improvements that grow out of the productive process, learning by using involves an experience that begins where learning by doing ends. The importance of learning by using is explored in some detail with respect to aircraft, but reasons are advanced suggesting that it may be a much more pervasive phenomenon in high-technology industries.

The final chapter in Part II, "How Exogenous Is Science?" looks explicitly at the nature of science–technology interactions in high-technology industries. It examines some of the specific ways in which these industries have been drawing upon the expanding pool of scientific knowledge and techniques. The chapter also considers, however, a range of much broader questions concerning the institutionalization of science and the manner in which the agenda of science is formulated in advanced industrial societies. Thus, a major theme of the chapter is that, far from being exogenous forces to the economic arena, the content and direction of the scientific enterprise are heavily shaped by technological considerations that are, in turn, deeply embedded in the structure of industrial societies.

The three chapters constituting Part III share a common concern with the role of market forces in shaping both the rate and the direction of innovative activities. They attempt to look into the composition of forces constituting the demand and the supply for new products and processes, especially in high-technology industries. This analysis, in turn, has direct implications for government concern with accelerating the rate of innovative activity. Thus, policy considerations emerge as an important element of these chapters.

Chapter 8 examines the history of technical change in the commercial aircraft industry over the fifty-year period 1925–75. This industry has been, and remains, a remarkable success story in terms of both productivity growth and continued American success in international markets. For a variety of reasons, including the strategic military importance of aircraft and a concern with passenger safety, the federal government's role has been particularly prominent with respect to aircraft. This chapter evaluates the impact of government policies and considers the possible relevance of these policies to other industries. Chapter 9 examines the ongoing technological revolution embodied in very-large-scale integration. It points out that there are a variety of mediating factors that stand between an expanding technological capability and commercial success. The growth in circuit-element density, with the resulting dramatic improvement in the capability of a single chip, offers a great potential for the application of electronic techniques in many fields. The success of such applications will turn upon developments internal to the industry, but also upon the creation of mechanisms that will translate this new technological capability into tangible economic advantages. Chapter 10 focuses not upon an individual industry but upon a number of recent empirical studies of technical change. These studies, which share an emphasis upon the dominant role of market demand in the innovation process, have been widely cited as providing an adequate basis for a successful government innovation policy. It is argued that these studies are, analytically and conceptually, seriously incomplete. The chapter attempts to provide a more comprehensive framework for both analysis and policy formulation.

Finally, the two chapters of Part IV place the discussion of technological change in an international context, with the first chapter oriented toward its long history and the second toward the present and the future. Chapter 11 pays primary attention to the transfer of industrial technology from Britain to the rest of the world. This transfer encompasses a large part of the story of worldwide industrialization, because nineteenth-century industrialization was, in considerable measure, the story of the overseas transfer of the technologies already developed by the first industrial society. Particular attention is devoted to the conditions that shaped the success of these transfers, but a central concern is their eventual impact upon the technology-exporting country. The last chapter speculates about the prospects for the future from an American perspective, a perspective that is often dominated by apprehension over the loss of American technological leadership, especially in high-technology industries. By drawing upon some of the distinctive characteristics of high-technology industries, an attempt is made to identify possible elements of a future scenario. I am confident that the world economy of the 1990s will be powerfully shaped by the international distribution of technological capabilities; but it will also be shaped by economic and social forces that strongly influence the comparative effectiveness with which the available technologies are exploited. I also suspect that the world of the 1990s will be a good deal more complex – and more interesting – than the one currently depicted by the harbingers of The Japanese Challenge, just as the scenario presented in Jean-Jacques Servan-Schreiber's *The American Challenge,* published in 1968, bore little resemblance to the subsequent decade of the 1970s.

This book is, in many respects, a continuation of the intellectual enterprise that was embodied in my earlier book, *Perspectives on Technology.* Whereas in the introduction to that book I stated that my interest in coming to grips with technological change had had the effect of transforming an economist into an economic historian, I am now inclined to say that much of the content of the present book can be read as the musings of an economic historian who has stumbled – not entirely by accident! – into the twentieth century. For the benefit of economic historians who still think of themselves as young, and who take it for granted that to study history is to study some remote past, I must point out that the twentieth century is, by now, mostly history.

Contents

PART I

Views of technical progress

1 The historiography of technical progress

To encompass the entire historiography of technical progress in one essay is impossible, even if the essay were allowed to grow far longer than the present one. For, in a fundamental sense, the history of technical progress is inseparable from the history of civilization itself, dealing as it does with human efforts to raise productivity under an extremely diverse range of environmental conditions. Even if we were to define technology in a relatively narrow "hardware" sense – which we will not – and to exclude organizational, institutional, and managerial factors, the range of materials that one might wish to mention would still be disconcertingly large. What follows, therefore, is necessarily highly selective.

This essay will first consider the nature and character of technical progress. Successive sections will then explore the most relevant literature on the rate of technical progress, the direction of technical progress, the diffusion of new technologies, and finally, the impact of technical progress upon productivity growth.

Definition and characterization of technical progress

A central problem in examining technical progress, and one that makes it difficult even to define or characterize readily, is that it takes many different forms. For technical progress is not one thing; it is many things. Perhaps the most useful common denominator underlying its multitude of forms is that it constitutes certain kinds of knowledge that make it possible to produce (1) a greater volume of output or (2) a qualitatively superior output from a given amount of resources.

The second category is most important and should not be regarded as a minor afterthought. The great bulk of the writing by economists on

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the subject of technical change – both theoretical and empirical – treats the phenomenon as if it were solely cost-reducing in nature, that is, as if one could exhaust everything of significance about technical change in terms of the increases in output per unit of input that flow from it. Technical progress is typically treated as the introduction of new processes that reduce the cost of producing an essentially unchanged product. Perhaps the main reasons for the popularity of this approach are these: It is a useful simplification that makes it possible to analyze a wide range of problems with a relatively simple analytical apparatus, and it allows a quantitative approach to innumerable interesting economic questions. At the same time, however, to ignore product innovation and qualitative improvements in products is to ignore what may very well have been the most important long-term contribution of technical progress to human welfare. Western industrial societies today enjoy a higher level of material welfare not merely because they consume larger per capita amounts of the goods available, say, at the end of the Napoleonic wars. Rather, they have available entirely new forms of rapid transportation, instant communication, powerful energy sources, life-saving and pain-reducing medications, and a bewildering array of entirely new goods that were undreamed of 150 or 200 years ago. To exclude product innovation from technical progress, especially when we are considering long historical periods, is to play Hamlet without the prince.

Of course, not all economists have ignored product innovation. Not surprisingly, the subject has been treated most carefully and imaginatively by economists who have also been serious students of economic history. To begin with, Simon Kuznets has pointed out that whether an innovation concerns a product or a process depends very much upon whose perspective one is adopting (Kuznets, 1972). Process innovations typically involve new machinery or equipment in which they are embodied; this machinery or equipment constitutes a product innovation from the point of view of the firm that produces it. Thus, the Bessemer converter was a process innovation to iron and steel manufacturers but a product innovation to the suppliers of equipment to the iron and steel industry. Furthermore, Kuznets had richly documented as long ago as 1930 (Kuznets, 1930) the central role of product innovation in long-term economic growth.[1] Kuznets argued that high aggregative growth rates in industrial economies have reflected continuous shifts in product and industry mix. All rapidly growing industries eventually experience a

[1] An earlier summary of the book had appeared in the *Journal of Economic and Business History,* August 1929, pp. 534–60, and is reprinted in Kuznets (1953), chap. 9, "Retardation and Industrial Growth." See also Kuznets (1971), chap. 7.

slowdown in growth as the cost-reducing impact of technical innovation diminishes. Furthermore, because of the typically low long-term income and price elasticity of demand for old consumer goods, further cost-reducing innovations in these industries will have a relatively small aggregative impact. Therefore, continued rapid growth requires the development of new products and new industries.

Of course, Kuznets has not been entirely alone in his emphasis upon the importance of new products. Joseph Schumpeter had emphasized throughout his life the central role of technical progress in understanding the dynamics of capitalist growth. His great work, *Business Cycles* (1939), focused powerfully upon the historical role of technological innovation in accounting for the high degree of instability in capitalist economies. His later book, *Capitalism, Socialism, and Democracy* (1942), is a virtual paean to the beneficent impact of what he called the "perennial gales of creative destruction." These "gales" were closely tied to product innovation that swept away old industries producing old products. Thus, economic progress, for Schumpeter, did not consist of price cutting among harness makers. The competitive behavior that really mattered in the long run came from the innovative acts of automobile manufacturers, which abolished harness making as an economic activity. Thus, for Schumpeter, product innovation had fundamental implications for understanding the nature of capitalism as a historical force as well as the nature of the competitive process. For economists had erroneously assumed that the problem "is how capitalism administers existing structures, whereas the relevant problem is how it creates and destroys them" (Schumpeter, 1942, p. 84).

Schumpeter has also profoundly influenced the approach of economists and economic historians to the study of technical progress by his stress upon its discontinuous nature. To begin with, he defined innovation very broadly as a shift in a production function that might have a variety of causes. These causes encompass much more than technical progress in a narrow sense – that is, product or process innovation. In addition, they may include the opening up of a new market, the acquisition of a new source of raw materials, or a structural reorganization of an industry (Schumpeter, 1934, p. 66). Of even greater importance for our present discussion is Schumpeter's great emphasis upon technical progress as constituting major breaks, giant discontinuities with or disruptions of the past. It was an emphasis that fitted particularly well both with his analysis of the sociology of capitalist society[2] and with his search for the strategic factor in business cycles. (The clustering of

[2] Schumpeter states that "successful innovation . . . is a special case of the social phenomenon of leadership" (1928, pp. 33–4).

innovations was at the heart of Schumpeter's business cycle theory.) As he stated: "The historic and irreversible change in the way of doing things we call 'innovation' and we define: innovations are changes in production functions which cannot be decomposed into infinitesimal steps. Add as many mail-coaches as you please, you will never get a railroad by so doing" (Schumpeter, 1935, p. 7).

Schumpeter's emphasis upon the centrality of creative destruction as an integral part of the capitalist growth process has been sharply criticized by Strassmann (1959a). Strassmann points out that in the period 1850 to 1914 at least, the old and new technologies coexisted peacefully, often for several decades. Indeed, he shows that for some of the most important innovations in power production, ferrous metallurgy, and other industries, output under the old technology continued to grow in absolute terms long after the introduction of the new technology. (See also Strassmann, 1959b.)

In sharp contrast to Schumpeter's emphasis upon the discontinuous nature of technical progress – a view that left a strong imprint on an entire generation of professional economists – is another school of thought that has been more impressed with continuity in technological change. Many aspects of this perspective may be traced back to Marx, who was, after all, a contemporary of Darwin, and who pointed acutely to the evolutionary elements in machine design. Marx also emphasized the larger social forces at work in technical progress and minimized the role of individuals. As he pointed out: "A critical history of technology would show how little any of the inventions of the eighteenth century are the work of a single individual" (Marx, 1867, p. 406). Marx's views on the nature of technical progress are examined in some detail in Rosenberg (1976).

The foremost and most carefully articulated expression, in the twentieth century, of the view of technical progress that emphasizes continuity appears in the work of A. P. Usher (1954; the first edition appeared in 1929). Usher called attention not only to the elements of continuity but also to the cumulative significance, in the inventive process, of large numbers of changes, each one of small magnitude. Moreover, and also in contrast to Schumpeter, who was primarily concerned with the consequences of inventions and not their origins, Usher was very much concerned with analyzing the nature of the inventive process and the forces that influenced events at the technical level. Usher's concern with the emergence of novelty in history led him to pay careful attention to the factors that conditioned or set the stage for a particular inventive breakthrough.

There has been an interesting attempt to merge and reconcile some of the useful elements in the works of Schumpeter and Usher. In undertaking this reconcilation, Vernon Ruttan also attempted to clarify the three related but distinct concepts of invention, innovation, and technological change (Ruttan, 1959). In doing so, he suggests how Usher's theory may be used to complement Schumpeter's where the latter's theory is weak and perhaps defective.

The view of technical progress as consisting of a steady accretion 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* (1935a; see also his companion volume, 1935b). Although Gilfillan was primarily concerned with the social rather than the economic aspects of the process, his book provides a valuable close-up view of the gradual and piecemeal nature of technical progress, drawing heavily upon small refinements based upon 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 upon steel components as steel became cheaper, and the adoption of petroleum lubricants. In his discussion of the technological component of steamboat history in America, Louis Hunter in his book *Steamboats on the Western Rivers* (1949) also stresses the innumerable minor improvements and adaptations of an anonymous multitude of craftsmen, foremen, and mechanics.

Albert Fishlow's incisive study of productivity and technical progress in the American railroad system between 1870 and 1910 included an attempt to quantify the role of the separate factors at work in raising productivity and reducing costs (Fishlow, 1966). Productivity growth during this period was extremely high, and there were some important inventions, such as air brakes, automatic couplers and signaling devices, and the substitution of steel for iron rails. Nevertheless, Fishlow finds that the largest contribution to cost reduction by far was due to a succession of improvements in the design of locomotives and freight cars, even though the process included no readily distinguishable or memorable inventions. 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. [Fishlow, 1966, p. 635]