Factors Affecting the Diffusion of Technology

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I

The rate at which new techniques are adopted and incorporated into the productive process is, without doubt, one of the central questions of economic growth. New techniques exert their economic impact as a function of the rate at which they displace older techniques and the extent to which the new techniques are superior to the old ones. Although we are a still a very long way from being able to assess the exact role of technological change—as distinct from all other factors—in generating the rise in resource productivity which is at the heart of the growth process, it is, I think, clear that the contribution of technological change itself will have to be established through the study of diffusion. Only in this way can we develop a closer understanding of the rate at which new techniques, once invented, have been translated into events of economic significance.

Although these remarks are, I believe, sufficiently uncontroversial, it is a striking historiographical fact that the serious study of the diffusion of new techniques is an activity no more than fifteen years old.[1] Even today, if we focus upon the most critical events of the industrial revolution, such as the introduction of new techniques of power generation and the climactic events in metallurgy, our ignorance of the rate at which new techniques were adopted, and the factors accounting for these rates is, if not total, certainly no cause for professional self-congratulation. Much of the history of the past

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[1] For an admirable earlier study, see Marc Bloch's "Avenement et conquetes du moulin a eau," *Annales d'histoire economique et sociale*, 7 (1935), 538–563. Bloch provides a masterly analysis, turning primarily on changing legal and economic conditions as they affected the availability of servile labor, of the lag of an entire millennium between the invention of the watermill and its widespread adoption.

two centuries or so has been written by scholars with impressive credentials for technological history and its minutiae, but with a more limited appreciation of the economic consequences of technological events. Thus, H. W. Dickinson, in his classic account of the history of the steam engine states, with respect to the consequences of the improvements which Watt had affected, that by the end of the eighteenth century, "The textile industry had been transformed from handicraft into a machine industry."[2] Although Dickinson wrote with a commanding authority on purely technological matters, it is necessary to record that he was almost a half century off the mark with respect to his economic history. By the end of the eighteenth century a suitable technology simply did not exist for the application of power to fully mechanized spinning or weaving operations.[3]

If we turn to the recent works of economic historians for further assistance on an issue as central to industrialization as the diffusion of steam power in the nineteenth century, we are offered some illumination but not nearly as much, surely, as we are entitled to expect.[4] Habakkuk states that "steam did not begin to play an im-

[2] H. W. Dickinson, *A Short History of the Steam Engine* (Cambridge: Cambridge University Press, 1938), p. 89.

[3] Even in cotton textiles, the most fully mechanized of the textile branches, full mechanization was achieved only in the second quarter of the nineteenth century. The protracted agony of the hand-loom weavers was being acted out in the 1830s and 1840s as the improved power loom was widely adopted, and it was only in the latter decade that the number of power-loom weavers exceeded the number of hand-loom weavers—although the proportion of *output* accounted for by the hand-loom weavers was, of course, far smaller than the proportion which they constituted of the weaving labor force. Even so, there were an estimated 40,000 cotton hand-looms still at work in 1850. In woolen textiles, which was slower to mechanize, hand-loom weavers persisted in and around Leeds, the most highly mechanized woolen center, during the 1850s. J. H. Clapham, *An Economic History of Modern Britain*, (Cambridge: Cambridge University Press, 1962), I Ch. XIV; Phyllis Deane and W. A. Cole, *British Economic Growth 1688–1959* (Cambridge: Cambridge University Press, 1962), pp. 191–192. See also Maurice Dobb, *Studies in the Development of Capitalism* (London: Routledge and Kegan Paul, 1946), pp. 263–265.

[4] For evidence on the limited impact of Watt's steam engine on the broad range of British industries by 1800, a full quarter century after first practical success had been achieved, see John Lord, *Capital and Steam Power* (London: P. S. King and Son, 1923), Ch. 8. However, since Boulton and Watt's engine was widely pirated and Newcomen engines remained in use, Lord's figures should not be taken as representing the total amount of

portant role in powering the British economy until the 1830s and 1840s, and was not massively applied until the 1870s and 80s. Even as late as 1870 less than a million horsepower was generated by steam in the factories and workshops of Great Britain."[5] Although Habakkuk does not indicate the source, these assertions are clearly based on Mulhall's estimates which included a figure of 900,000 horsepower for the fixed steam-power of Great Britain in 1870.[6] Mulhall was, of course, a great statistical pioneer, but his estimates were necessarily crude and, in some cases, no more than informed guesses. It is, nevertheless, symptomatic of the limited research conducted on the subject of technological diffusion so far that our knowledge of the diffusion of steam power has not been advanced, in the twentieth century, substantially beyond Mulhall's venerable *Dictionary of Statistics*. This late nineteenth-century work is still the last word on the subject. Our knowledge of the sequence of events at the purely technical level remains far greater than our knowledge of the *translation* of technical events into events of economic significance.

The present paper attempts to take some steps toward closing the gap between the technical and the economic realms of discourse. In doing so, I am hopeful that we will eventually end up with a better understanding of the nature of the linkages between these two realms. Such an improved understanding should enable us to get a better handhold on the timing of the diffusion process and thereby make it possible to formulate and to test more precise hypotheses concerning the spread of new technologies. This paper does not attempt to examine the whole range of factors influencing diffusion. Rather, it concentrates on certain supply side considerations. Needless to say, alterations in relative factor and commodity prices also affect the rate of diffusion of new technologies—but that is obviously

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steam power in use in Great Britain. See A. E. Musson and E. Robinson, "The Early Growth of Steam Power," *Economic History Review*, 2nd series, 9 (April 1959), 418–439, and J. R. Harris, "The Employment of Steam Power in the 18th Century," *History*, 52 (1967), 133–148.

[5] H. J. Habakkuk, *American and British Technology in the 19th Century* (Cambridge: Cambridge University Press, 1962), pp. 184–185. See also A. E. Musson and Eric Robinson, *Science and Technology in the Industrial Revolution* (Manchester: University of Manchester Press, 1969), p. 72, and David Landes, *The Unbound Prometheus* (Cambridge: Cambridge University Press, 1969), p. 221.

[6] M. G. Mulhall, *The Dictionary of Statistics* (London: G. Routledge and Sons, Ltd., 1892), p. 545.

so. We argue here, not so obviously, that, factor and commodity prices aside, the rate at which new technologies replace old ones will depend upon the speed with which it is possible to overcome an array of supply side problems. These problems have not been uniformly resistant to efforts to overcome them, but have proven to be of varying degrees of intractability. This is the basic justification for the focus of this paper.

II

The Continuity of Inventive Activity

That the diffusion of inventions is an essentially economic phenomenon, the timing of which can be largely explained by expected profits, is by now well established. The extended labors of Griliches and Mansfield have clearly demonstrated the power and scope of purely economic explanations in the diffusion of individual inventions. However, if one examines the history of the diffusion of many inventions, one cannot help being struck by two characteristics of the diffusion process: its apparent overall slowness on the one hand and the wide variations in the rates of acceptance of different inventions, on the other.[7] It is argued in this paper that a better understanding of the timing of diffusion is possible by probing more deeply at the technological level itself, where it may be possible to identify factors accounting for both the general slowness as well as wide variations in the rate of diffusion.

How slow is slow? When we speak of diffusion as being relatively slow, we are obviously implying some sort of dating procedure as well as expressing a comparative or absolute judgment. It should be noted at the outset that whether inventions are measured as diffusing rapidly or slowly depends in large part upon the selection of dates. If one dates the steam engine from the achievements of Newcomen around the first decade of the eighteenth century rather than from the work of Watt in the last third of the eighteenth century, as is commonly the case, one gets a much slower rate of diffusion. But on the basis of criteria commonly employed, the case for dating the steam engine from Newcomen is a perfectly compelling one. His atmospheric steam engine was not only technically workable, it was commercially feasible as well. To be sure, it experienced great heat loss in its operation and was a voracious consumer of

[7] See, for example, E. Mansfield, "Technical Change and the Rate of Imitation," *Econometrica*, 29 (October 1961), 741–766.

fuel, but it nevertheless survived the market test and was widely used in the eighteenth century, primarily for pumping water out of mines. One very cautious study has identified 60 Newcomen engines for the period 1712–1733 and no less than 300 for the years 1734–1781.[8] Moreover, even in 1800, by which time Watt's patents had all expired, Newcomen engines not only continued to be used but, due apparently to their low construction and maintenance costs and long life expectancy, still continued to be *built*. One might almost be tempted to say of James Watt that he was "just an improver," although such a statement would be comparable to saying of Napoleon that he was just a soldier or of Bach that he was just a court musician. That is to say, Watt's improvements on the steam engine transformed it from an instrument of limited applicability at locations peculiarly favored by access to cheap fuel, to a generalized power source of much wider significance. Nevertheless, even if we date the steam engine from Watt's accomplishments of the 1760s and 1770s, it still took a full century of improvement and design change before this new power source surpassed water power in manufacturing and displaced the sail on ocean-going vessels.

The essential point to be grasped here is that inventive activity is, itself, best described as a gradual process of accretion, a cumulation of minor improvements, modifications, and economies, a sequence of events where, in general, continuities are much more important than discontinuities. Even where it is possible to identify major inventions which seem to represent entirely new concepts and therefore genuine discontinuities, sharp and dramatic departures from the past, there are usually pervasive technological as well as economic forces at work which tend to slow down and to flatten out the impact of such inventions in terms of their contribution to raising resource productivity. Thus, even the big technological breakthroughs which are associated with such names as Darby, Watt, Cort, and Bessemer, usually have much more gently declining slopes of cost reduction flowing from their technical contributions than the historical literature would lead us to expect.

The fact is that the period which is looked at as encompassing the diffusion of an invention is usually much more than that: It is a period when critical inventive activity (what Usher called "secondary inventions") and essential design improvements and modifications are still going on. Although we might be tempted to dismiss

[8] J. R. Harris, "Employment of Steam Power," p. 147.

this later work as much less important than the initial technological breakthrough, there is no good *economic* reason for this attitude, for it is precisely this later work which first establishes commercial feasibility and therefore shapes the possibilities for diffusion. We need to approach this whole area of research with a clearer appreciation of the continuum of inventive activity, running from initial conceptualization (the "Eureka! I have it!" stage) to establishment of technical feasibility (invention) to commercial feasibility (innovation) to subsequent diffusion. By concentrating our attention upon the sharp discontinuities associated with major inventions, we are misrepresenting the manner in which the gradual growth in the stock of useful knowledge is transformed into improvements in resource productivity.

Although we find it a convenient verbal shorthand to speak of the "displacement" of one technique by another, the historical process is often one of a series of smaller and highly tentative steps. Thus, there were several intermediate stages in the displacement of sail by steam: Steamships were at first fully rigged and long continued to carry at least auxiliary sails, particularly as an insurance against breakdowns (which were not infrequent) on long ocean voyages, whereas sailing ships, in their twilight days, were often furnished with auxiliary engines.

The inadequate conception of invention as an intermittent and discontinuous phenomenon has been shared by the historian and the economist. The historian finds that it immensely simplifies the writing of chronological history if particular events—in this case inventions—can be precisely pinpointed in time, just like the Great Fire of London, the accession of the House of Hanover to the British throne, the Treaty of Paris or the abolition of the Corn Laws. The economist, for his part, finds it enormously convenient for analytical purposes to distinguish between movements along existing isoquants in response to alterations in factor prices, and shifts in the isoquants themselves due to the intermittent phenomenon of technological change. Both disciplines, therefore, have in the past found it convenient to focus upon technological change as a discontinuous phenomenon which can be precisely located in historical time. But by breaking into the continuum of inventive activity in this way, we are, subtly but inevitably, distorting our approach to the diffusion process. Once an invention has been "made," after all, the natural expectation is that all that remains in the sequence is for it to be adopted. Any delay becomes a "lag."

However, in viewing the problem in this way, we are very much underestimating the technological and economic importance of the subsequent "improvements." We are engaging in a sort of conceptual foreshortening which distorts our view of later events. For we are led to treat the period after the conventional dating of an invention as one where a fairly well-established technique is awaiting adoption whereas, in fact, highly significant technological and economic adaptations are typically waiting to be made. It is this same foreshortening of perspective which greatly increases our general impression of the slowness of diffusion.

Thus, Enos has studied the length of the lag between invention and innovation for 35 important innovations and has subjected his results to statistical analysis. In his sample the arithmetic mean for the interval between invention and innovation is 13.6 years.[9] Enos defines the date of an invention as "the earliest conception of the product in substantially its commercial form" and dates an innovation from "the first commercial application or sale."[10] It is difficult, however, in view of his definition of invention, to know just what significance to attach to the size of these lags. In some cases the date selected for invention corresponds fairly closely to a time when the technical problems were reasonably well solved. In other cases his choice of dates seems to be based more closely upon "earliest conception," when many important technical problems still remained to be solved. For example, Enos places the invention of the cotton-picker in 1889 and its innovation in 1942—a lag of 53 years. It was in 1889 that Angus Campbell first made use, on an experimental basis, of a spindle-type picker, but the machine was far from constituting a satisfactory picker. As Jewkes and his co-authors had pointed out, "the machine left cotton on the ground and caused damage to the bolls and blooms."[11] It will be readily conceded that these are serious deficiencies in a device for picking cotton (even though one can conceive of possible price relationships where the adoption of such a machine would have been economically rational). Numerous important technical problems therefore remained to be

[9]John L. Enos, "Invention and Innovation in the Petroleum Refining Industry," in *The Rate and Direction of Inventive Activity* (Princeton: University Press, 1962), p. 309. Most of Enos's information is drawn from J. Jewkes, D. Sawers, and R. Stillerman, *The Sources of Invention* (London: St. Martin's Press, 1958).

[10]*Ibid.*, p. 308.

[11]Jewkes et al., *Sources*, p. 283

solved after 1889. Similar complaints can be raised over many of the other dates employed in the Enos study—such as the 79-year interval for the fluorescent lamp (invention dated 1859), the 56-year interval for the gyro-compass (invention dated 1852), or the 22-year interval for television (invention dated 1919).[12] In these and in many other cases, much critical and indispensable inventive activity remained to be performed. The length of the interval, in other words, was at least partly—and in many cases primarily—due to the time required for carrying out *further* inventive activity. It is therefore extremely difficult to know what significance ought to be attached to Enos's numerical findings concerning these "lags."

III

Improvements in Inventions after Their First Introduction

It follows from the conception of invention adopted in this paper that most inventions are relatively crude and inefficient at the date when they are first recognized as constituting a new invention. They are, of necessity, badly adapted to many of the ultimate uses to which they will eventually be put; therefore, they may offer only very small advantages, or perhaps none at all, over previously-existing techniques. Diffusion under these circumstances will necessarily be slow because the clear superiority of the new technique over the old has not yet been established or, perhaps, because the new technique or process alters the quality of the final product in unfortunate or unpredictable ways. Thus, as John Nef has shown, the emergence of a coal-using technology in England was seriously impeded in the seventeenth century by the fact that the use of the mineral fuel damaged the final product—as in the case of glass-making and the drying of malt for the brewing industry.[13] Indeed, it was out of this attempt to maintain high quality of final product while using coal as a fuel that major advances were made in furnace design and the technique of coking was eventually developed.[14] More important, the very slow diffusion of the coke-smelting of iron after Abraham Darby's first success in 1709 was due in part to the

[12] Enos, *Inventive Activity*, p. 307.

[13] John Nef, "The Progress of Technology and the Growth of Large-Scale Industry in Great Britain, 1540–1640," *Economic History Review*, 5 (1934), 15–18.

[14] Beer made of malt that had been dried by raw coal was, apparently, practically undrinkable.

fact that "coke pig-iron produced a bar inferior in tensility and ductility to that made from charcoal pig: it was 'cold-short' and unsuitable for the production of wares of quality."[15] Consequently the use of coke pig-iron was confined to the much smaller, cast iron branch of the iron industry. The adoption of a new technique, then, is often limited by imperfections in the product which, in turn, are only gradually overcome or bypassed. Such problems connected with quality control were long a source of persistent difficulties in the use of iron and steel. The inability to achieve a rigid and precise control of the quality and therefore of the performance characteristics of the metal was a major handicap in the application of ferrous materials to a range of industrial uses. Such control came only with the introduction of the Bessemer and open-hearth methods, since these made it possible to control the carbon content within very narrow limits.[16]

[15] T. S. Ashton, *Iron and Steel in the Industrial Revolution* (Manchester: University of Manchester Press, 1924), p. 35. Furthermore, as Ashton points out: "It seems very probable that the production of sound coke-iron was not a sudden creation but the result of many trials in which failure and success alternated. The inventory taken at Coalbrookdale in 1718 shows that there was an accumulation of 'sculls,' or defective iron, which were sold at a low price to a neighboring forgemaster. Such sculls may have been produced frequently in the early days of the process, and though it is beyond question that marketable iron was produced every year, it might have been difficult for Darby himself to say exactly when the problem had reached a final solution" (p. 33).

[16] The frequent inferiority and, therefore, slow diffusion of new inventions in their early stages of development is strikingly apparent in military history. The English long-bow swept the field at Agincourt in 1415, long after the first introduction of gunpowder and cannon into Europe. Although Europeans sought to develop an effective field artillery in the fifteenth century, they did not succeed in overcoming the technical problems involved until the first half of the seventeenth century. Until that time such weapons were of very limited effectiveness, aside from their use in sieges. Their limited mobility and slow rate of fire enabled them to be easily overcome by massed charges. See C. Cipolla, *Guns, Sails and Empires* (New York: Random House, 1965), Ch. 1 and Epilogue.

The Texas Rangers, in spite of all the guns and powder in their armories, could not establish a decisive superiority over the fierce Comanches under the special circumstances of mounted combat until the availability of the six shooter. For an absorbing account, see W. P. Webb, *The Great Plains* (Boston: Ginn and Co., 1931), pp. 167–179. Before the availability of multi-shot weapons, Webb concludes that the Indians were at a distinct advantage. "In the first place, the Texans carried at most three shots; the Comanche carried twoscore or more arrows. It took the Texan a minute to

If it is true that inventions in their early forms are often highly imperfect and constitute only slight improvements over earlier techniques, it also follows that the pace at which subsequent improvements are made will be a major determinant of the rate of diffusion.[17] Indeed it may very well be the case that such improvements will reduce total costs by an amount greater than the reduction in costs of the initial invention over the older techniques which it eventually replaced. Mak and Walton argue that, on the Louisville-New Orleans route, "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."[18] Not all of the improvement in productivity, of course, was attributable to technological change. In addition to the increase in cargo carrying capacity per measured ton and the extension of the navigation season, which *were* primarily

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reload his weapon; the Indian could in that time ride three hundred yards and discharge twenty arrows. The Texan had to dismount in order to use his rifle effectively at all, and it was his most reliable weapon; the Indian remained mounted throughout the combat. Apparently the one advantage possessed by the white man was a weapon of longer range and more deadly accuracy than the Indian's bow, but the agility of the Indian and the rapidity of his movements did much to offset this advantage" (p. 169).

[17] This is not to suggest that a continuous rate of improvement in a technology implies some continuous rate of its diffusion. When a technology is still at a very primitive stage in its development, even substantial reductions in cost may have little effect upon diffusion. On the other hand as a new technology reaches the cost levels of competing methods, relatively small additional cost reductions may bring it below critical threshold levels and thus lead to rapidly accelerating rates of diffusion. For a rigorous application of a threshold function in the study of diffusion, see Paul David, "The Mechanization of Reaping in the Ante-Bellum Midwest," in *Industrialization in Two Systems*, ed., H. Rosovsky (New York: John Wiley and Sons, 1966), pp. 3–28. David's threshold function, it should be noted, relates to farm size, and he demonstrates how the rising relative cost of harvest labor lowered that farm size, leading finally to the rapid introduction of the reaper in the Midwest during the 1850s.

[18] James Mak and Gary Walton, "Steamboats and the Great Productivity Surge in River Transportation," *Journal of Economic History*, 32 (September 1972), p. 625. They add: "We qualify this conclusion to the extent that the productivity gains from steam power, which are reflected in the fall in rates, 1815–20, may have been understated somewhat because of slow entry or limited competition in this early period. Nevertheless, there were 17 vessels in operation on Western rivers in 1817, and 69 were in operation by 1820. It seems reasonable to assume that the initial impact of the steam engine had occurred by 1820" (footnote 15, p. 625).

the result of technological changes, there were significant reductions in cargo collection times and passage times, which were not. Nevertheless, it is clear that the overall increase in total factor productivity associated with this major transportation innovation came in the years *following* its initial introduction.[19]

A similar conclusion is reached by Enos in his study of technical progress in the petroleum refining industry in the twentieth century. Enos examined 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 flowing from the subsequent improvements in the new process. Enos finds that the average annual cost reductions generated by the beta phase of each of these innovations considerably exceeds the average annual cost reductions generated by the alpha phase (4.5% as compared to 1.5%). On this basis he asserts: "The evidence from the petroleum refining industry indicates that improving a process contributes even more to technological progress than does its initial development."[20]

One final, general point needs to be made in concluding this section. It seems to be extraordinarily difficult to visualize and to anticipate the uses to which an invention will be put. Railroads were originally thought of as essentially feeders to canals and other forms of water transportation. In the early days of radio at the turn of the century, it was regarded primarily as a supplement to wire com-

[19] A cumulation of minor design changes on the steamboat had the effect of substantially increasing the length of the navigation season for each steamboat size class. By steadily reducing the 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. Thus, Mak and Walton state that, 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." (Mak and Walton, "Steamboats," p. 634.) See also Louis Hunter, *Steamboats on the Western Rivers* (Cambridge: Harvard University Press, 1949), Ch. 2 and pp. 219–225.

[20] John L. Enos, "A Measure of the Rate of Technological Progress in the Petroleum Refining Industry," *Journal of Industrial Economics*, 6 (June 1958), 180. See also the same author's "Invention and Innovation in the Petroleum Refining Industry," in *The Rate and Direction of Inventive Activity* (Princeton: Princeton University Press, 1962), pp. 299–321.

munication services, to be used only where wire was not practicable —as in certain isolated locations or for ships at sea.[21] Finally, even so versatile an inventor as Thomas Edison is said to have thought that the phonograph would be useful principally to record the wishes of old men on their death beds.

It is easy to sneer at such failures of vision and poverty of imagination—especially since, in history, we always have the immense advantage of knowing how the story ended. Nevertheless, past experience suggests that the prediction of how a given invention will fit into the social system, the uses to which it will be put, and the alterations it will generate, are all extraordinarily difficult intellectual exercises.[22] Such difficulties, in turn, must have played an important role in slowing down the pace of diffusion.

Even when an invention genuinely contains important elements of novelty, there is a strong tendency to conceptualize it in terms of the traditional or familiar. Thus the transition to a new technique is often slowed by the extreme difficulty of breaking away from the old forms and embracing the different logic of a new technique or principle.[23]

[21] This limited conception of the potential of the radio in turn slowed the pace at which it was developed because, as a result, "most of the original research on the development of wireless communication was initially oriented toward the relatively simple task of transmitting impulses for telegraphic communications." Frank Lynn, *An Investigation of the Rate of Development and Diffusion of Technology in Our Modern Industrial Society*, in *The Employment Impact of Technological Change*, 6 vols. (Washington, D.C.: U.S.G.P.O., 1966), II, p. 68.

[22] In a closely related context, Simon Kuznets has pointed to the almost congenital pessimism of professional judgments on the possibilities for technological change over the years. "Experts are usually specialists skilled in, and hence bound to, traditional views; and they are, because of their knowledge of one field, likely to be cautious and unduly conservative. Hertz, a great physicist, denied the practical importance of shortwaves, and others at the end of the nineteenth century reached the conclusion that little more could be done on the structure of matter. Malthus, Ricardo, and Marx, great economists, made incorrect prognoses of technological change at the very time that the scientific bases for these changes were evolving. On the other hand, imaginative tyros like Jules Verne and H. G. Wells seemed to sense the potentialities of technological change. It is well to take cognizance of this consistently conservative bias of experts in evaluating the hypothesis of an unlimited effective increase in the stock of knowledge and in the corresponding potential of economic growth" (Simon Kuznets, *Economic Growth and Structure* [New York: W. W. Norton and Co., 1965], p. 89).

[23] Marx saw this point clearly: "To what an extent the old forms of the instruments of production influenced their new forms at first starting, is

IV

The Development of Technical Skills Among Users

Closely associated with this gradual improvement in the innovation itself is the development of the human skills upon which the use of the new technique depends in order to be effectively exploited. There is, in other words, a learning period the length of which will depend upon many factors, including the complexity of the new techniques, the extent to which they are novel or rely on skills already available or transferable from other industries, etc.[24] There

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shown by, amongst other things, the most superficial comparison of the present powerloom with the old one, of the modern blowing apparatus of a blast-furnace with the first inefficient mechanical reproduction of the ordinary bellows, and perhaps more strikingly than in any other way, by the attempts before the invention of the present locomotive, to construct a locomotive that actually had two feet, which after the fashion of a horse, it raised alternately from the ground. It is only after considerable development of the science of mechanics, and accumulated practical experience, that the form of a machine becomes settled entirely in accordance with mechanical principles, and emancipated from the traditional form of the tool that gave rise to it" (Karl Marx, *Capital* [New York: Modern Library Edition, n.d.], p. 418). Similarly on water, abortive attempts were made to imitate nature. One such attempt—Lord Stanhope's ill-fated paddle steamer—has been preserved in the sad lines of the poet, T. Baker (fl. 1837–1857):

> Lord Stanhope hit upon a novel plan
> Of bringing forth this vast Leviathan
> (This notion first Genevois' genius struck);
> His frame was made to emulate the duck;
>
> Webb'd feet had he, in Ocean's brine to play;
> With whale-like might he whirl'd aloft the spray;
> But made with all this splash but little speed;
> Alas! the duck was doom'd not to succeed!

The Steam-Engine, Canto IV

As reprinted in D. B. Wyndham Lewis and Charles Lee, *The Stuffed Owl: An Anthology of Bad Verse* (London: J. M. Dent and Sons 1952), pp. 193–194.

[24] In this sense, the *sequence* of events in history becomes very important in explaining the experiences of individual industries. The problems encountered and solved in industry A often turn out to provide valuable externalities in the form of knowledge, techniques and labor skills which become available to industries B, C, and D. Thus, Usher has argued that the industrial revolution in England owed much to the technical skills which had been developed by generations of craftsmen in the production of

is abundant evidence from a variety of sources showing sustained reductions in real labor costs per unit of output in situations where labor was employed in a plant using unchanged facilities. Indeed, the phenomenon is sufficiently well established that it has come to be known as the "Horndal Effect," after the Swedish steelworks where output per manhour was observed to increase at about 2% per year for fifteen years in spite of the fact that the plant and production techniques remained unchanged. The phenomenon has been further documented in several industries, most notably air-frame production, machine tools, shipbuilding, and textiles.[25]

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clocks and watches. Machines which had been developed in this trade "stand out as the most conspicuous examples of instruments of precision. The lessons learned by the craftsmen of these trades formed the basis for the development of the engineering sciences in the late eighteenth century and the early nineteenth century. These timekeepers presented a substantial array of notable devices for the control of motion. These devices involved all the primary problems of geared mechanisms. The marine chronometer required delicate adjustments to the expansion and contraction of metals during small changes of temperature. The pendulum clocks presented important problems in the theory of dynamics. The development of the pendulum clock rested upon a complete mathematical treatment of the forces operating in a pendulum. The escapements of both clocks and watches called for considerable refinements in the design of gear teeth, and the problems received full mathematical treatment in the course of the eighteenth century. Much of the work done for Arkwright on the spinning machine was entrusted to a clockmaker. George Stephenson learned much of his mechanics by repairing and studying clocks. The rapid development of the engineering sciences after Watt's inventions was largely due to the extensive mathematical treatment of the problems of dynamics involved in the construction of these small instruments of precision" (W. Bowden, M. Karpovich and A. P. Usher, *An Economic History of Europe Since 1750* [New York: American Book Co., 1937], p. 308). See also A. E. Musson and E. Robinson, "The Origins of Engineering in Lancashire," *Journal of Economic History*, 20 (June 1960), especially 219–222. Musson and Robinson conclude "that clock-, if not watch-, makers, and above all clock-tool makers, were in very great demand for textile-machine making and contributed materially to the early growth of engineering" (p. 222).

[25] A. Alchian, "Reliability of Progress Curves in Airframe Production," *Econometrica*, 31 (October 1963), 679–692; Werner Hirsch, "Firm Progress Ratios," *Econometrica*, 24 (April 1956), 136–143; Leonard Rapping, "Learning and World War II Production Functions," *Review of Economics and Statistics*, 47 (1965), 81–86; Paul David, "Learning by Doing and Tariff Protection: A Reconsideration of the Case of the Ante-Bellum U.S. Cotton Textile Industry," *Journal of Economic History*, 30, (September 1970), 521–601; Kenneth Arrow, "The Economic Implications of Learning by Doing," *Review of Economic Studies*, 29 (June 1962), 155–173. According

While the existence of learning curves within the framework of an *established* technology is well recognized, the role of learning experiences in accounting for the gradual improvements of *new* technologies and their slow diffusion has not received much attention. Since it takes time to acquire such skills, it will also take time to establish the superior efficiency of a new technique over existing ones. The point is nicely illustrated with respect to the adoption of Henry Cort's puddling process:

> One of the most important problems associated with puddling in its early years was that of training a labor force that could produce high quality bar iron with the process. The ironmasters who initially adopted puddling had to train workers in the use of a process that was not only new, but was also somewhat of a "mystery" to everyone, including Cort. An efficient puddler was a workman who could not only do the strenuous labor of moving masses of iron in and out of the puddling furnaces, but could also develop a "feel" for the process itself. He had to learn to determine from the color of the flames in the puddling furnace and the texture of the molten metal when the pig iron was fully decarburized or had "come to nature," i.e., when the carbon and other impurities had been sufficiently removed. Puddling was a backbreaking job that also required a great deal of judgment and experience was probably the best teacher. The development of a highly skilled labor force was crucial to the success of the puddling process and the lack of such a labor force was probably the greatest single impediment to its rapid adoption.[26]

The adoption of the steam engine afforded innumerable ex-

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to Hirsch, the U.S. Air Force "for quite some time had recognized that the direct labor input per airframe declined substantially as cumulative airframe output went up. The Stanford Research Institute, and the RAND Corporation initiated extensive studies in the late forties, and the early conclusions were that, in so far as World War II airframe data were concerned, doubling cumulative airframe output was accompanied by an average reduction in direct labor requirements of about 20%. This meant that the average labor requirement after doubling quantities of output was about 80% of what it had been before. Soon the aircraft industry began talking about the 'eighty per cent curve'" (Hirsch, p. 136). It is possible, of course, that cost reductions which have been attributed to learning by doing have actually been due to other factors which have not been correctly identified, especially in cases where learning by doing has been defined as a residual. See John Chipman, "Induced Technical Change and Patterns of International Trade," in *The Technology Factor in International Trade*, ed. Raymond Vernon (New York: National Bureau of Economic Research, 1970), pp. 95–98.

[26]Charles K. Hyde, "Technological Change in the British Iron Industry, 1700–1860," unpublished doctoral dissertation, University of Wisconsin, pp. 112–113. See also Landes, p. 92.

amples of the importance as well as the slow accumulation of know-how, which is essential to the successful operation of a new technology. The length of life and the frequency of breakdowns of steam engines required that overloading be scrupulously avoided, but this in turn involved the accumulation of experience concerning optimum loads. Again, the life expectancy of engine boilers required careful attention to such matters as pressure levels and appropriate feed-water arrangements—indeed, when these matters were *not* attended to, the life of a boiler was likely to be abruptly, and sometimes disastrously, terminated.[27]

The manner in which these new technical skills are acquired is relevant to the speed of the diffusion process in another way. Many of the technical skills are acquired through direct, on-the-job participation in the work process. Since these include a large component of uncodified skills (or know-how), such skills were not readily transferable through formal education or the printed word, but required the movement of qualified personnel. Where and to the extent that this was so, it placed a serious constraint upon the speed of geographic diffusion.[28]

V

The Development of Skills in Machine-making

The next portion of my argument deals with the development of the skills involved not in *using* the new techniques but in developing the skills and facilities in machine-making itself. This involves the broadest questions of industrial organization and specialization and lies at the very heart of the industrialization process. Successful invention and successful *diffusion* of inventions in industrializing economies has required, above all, a growth in the capacity to devise, to adapt, and of course, to produce at low cost, machinery which has been made suitable to highly specialized end uses. Before a new invention can join the family of technical options genuinely available to the economy, elaborate arrangements must sometimes be made.

[27] Loss of life was especially fearful aboard steamboats on western rivers, and this loss of life led to an early assertion of the investigatory and regulatory activites of the federal government. See John G. Burke, "Bursting Boilers and Federal Power," *Technology and Culture*, 7 (Winter 1966).

[28] Nathan Rosenberg, "Economic Development and the Transfer of Technology: Some Historical Perspectives," *Technology and Culture*, 11 (October 1970), 550–575.

The mere conceptualization of a solution may be, and often has been, very far removed in calendar time from the availability of a method which is technologically workable, much less commercially feasible.

It is an often-told tale in the history of inventions that they have to sit on the shelves long after their initial conceptualization because of the absence of the appropriate mechanical skills, facilities, and design and engineering capacity required to translate them into a working reality. This is why the emergence of a capital goods industry, with a sophisticated knowledge of metallurgy and the capacity to perform reliable precision work in metals, was so critical to industrialization in its eighteenth- and nineteenth-century form. The desperate and unsuccessful improvisations which otherwise had to be resorted to is perfectly captured in the picture of James Watt stuffing soaked rags in the gaps between his pistons and cylinders in an effort to prevent loss of steam, until Wilkinson's boring mill finally provided him with reasonably accurate cylinders. The commercial practicability of Watt's steam engine with its separate condensing chamber really dates from 1776, the year in which Wilkinson's boring mill, invented in 1774, became available for the preparation of his cylinders.[29]

It might be said of Watt that he was singularly lucky in having a cannon-maker such as Wilkinson nearby, but the essential point, surely, is that his conceptualizations were not so far in advance of the technical capacities of the metal-workers of his day as to render his ideas unfeasible.[30] Such was the lot of da Vinci whose notebooks are crowded with machinery sketches far in advance of the technical

[29] K. R. Gilbert, "Machine Tools," in Charles Singer et al., *A History of Technology* (London: Oxford University Press, 1958), IV, p. 421. See also S. Smiles, *Industrial Biography* (London: John Murray 1908), pp. 178–182. As Landes points out about the separate condenser, Watt "saved the energy that had previously been dissipated in reheating the cylinder at each stroke. This was the decisive breakthrough to an 'age of steam' not only because of the immediate economy of fuel (consumption per output was about a fourth that of the Newcomen machine) but even more because this improvement opened the way to continuing advances in efficiency that eventually brought the steam-engine within reach of all branches of the economy and made of it a universal prime mover" (Landes, *Unbound Prometheus*, p. 102).

[30] At a much earlier date, the cannon makers had borrowed important techniques, especially that of casting in bronze, from the makers of church bells. Such are the vagaries—and ironies—of the industrial learning process. Cipolla, pp. 23, 25.

skills of early sixteenth-century Florence or Europe. Breech-loading cannon had been made as early as the sixteenth century but could not be fired in reasonable safety (to the user at least!) until precision in metal-working made it possible to produce an airtight breech and properly-fitting case. Christopher Polham, a Swede, devised many techniques for the application of machinery to the quantity production of metal and metal products, but could not successfully implement his conceptions with the power sources and clumsy wooden machinery of the first half of the eighteenth century. Charles Babbage had already conceived of the main features of the modern computer over a hundred years ago and had incorporated these features into his "analytical engine," a project for which he actually received a large subsidy from the British Government. Babbage's failure to complete his ingenious scheme was due to the inability of contemporary British metal-working to deliver the components which were indispensable to the machine's success.[31]

People like da Vinci and Babbage were, to use the popular phrase, "far ahead of their time." But, to give the phrase some operational content, it is the state of development of the capital goods industries, more than any other single factor, which determines whether and to what extent an invention is ahead of its time. Each important invention goes through a gestation period of varying length, while the capital goods industries adapt themselves to the special needs and requirements of the new technique. Therefore the pace of technical advance in the user industry may depend critically upon events in the capital goods sector. This process of problem-solving and accommodation is central to a better understanding of the timing of technical change and the rate of diffusion of new inventions.[32] For it is the speed with which performance characteristics are improved, techniques modified to meet the needs of specialized users, and the price of the invention gradually reduced, which determine its acceptability among an increasingly widening circle of potential users.

[31] S. H. Hollingdale and G. C. Tootill, *Electronic Computers* (London: Pelican, 1965), p. 46 and Ch. 2 and 3. Babbage, it is interesting to note, had borrowed the system of punched cards from the Jacquard loom—where they had been used to control the introduction of threads in weaving brocade. See Charles Babbage, *Passages from the Life of a Philosopher* (London: Longman, Green, Longman, Roberts, and Green, 1864), pp. 116–118.

[32] Nathan Rosenberg, "Technological Change in the Machine Tool Industry, 1840–1910," *Journal of Economic History*, 23 (December 1963).

VI

Complementarities

A further element significantly affecting the timing of the diffusion process, and one where the capital goods sector also plays an important role, lies in the complementarity in productive activity between different techniques. That is to say, a given invention, however promising, often cannot fulfill anything like its potential unless *other* inventions are made relaxing or bypassing constraints which would otherwise hamper its diffusion and expansion. It is for this reason that a single technological breakthrough hardly ever constitutes a complete innovation. Before the productivity-increasing benefits of any single breakthrough can be realized, many other accommodations need to be made. The expansion of a productive activity runs into a series of new constraints or bottlenecks. As one bottleneck is overcome, others eventually assert themselves and need to be expanded. Although these bottlenecks can often be overcome by committing more resources to a particular activity, frequently inventive activity is called for. In both cases, however, time-consuming procedures are involved which hold back the further expansion and diffusion of the new technique.

The history of American railroads in the second half of the nineteenth and the early twentieth centuries provides compelling evidence that the growth in productivity was the product of many subsequent inventions, none of which was available in the early years of railroad building—say 1840. The growth in productivity was, to begin with, very great. It has been calculated that the incremental expenses required for meeting the railroad demands of 1910 traffic loads with the technology available back in 1870 would have amounted to about $1.3 billion. The cumulation of small innovations and relatively modest individual design changes brought about, between 1870 and 1910 alone, a more than tripling of freight car capacities with only a small increase in dead weight, and a more than doubling of locomotive force with the introduction of more powerful engines. The greater loads and greater speeds made possible by the improved rolling stock could not have been achieved, however, without several other significant inventions: the control of train movements through use of the telegraph, block signalling, air brakes, automatic couplers, and the substitution of steel rails for iron. Not all these inventions were equally significant in reducing costs, nor were they, as a result, adopted with equal speed. Air brakes and automatic couplers (first employed in 1869 and 1873 respectively) were coolly received and were eventually adopted only after the passage of national legislation.[33] Steel rails, however, in spite of their considerably higher price, were rapidly adopted. Steel rails were first used by the Pennsylvania Railroad in the early 1860s, and by 1890 they accounted for 80% of all track mileage.[34] The critical importance of steel rails to the growth in railroad productivity was that they were far more durable, lasting more than ten times as long as iron rails, and that they were capable of bearing far heavier loads than iron rails without breaking. Indeed, the old iron rails were simply incapable of supporting the 1910 locomotives, and would have crushed under their average weight of 70 tons.[35]

The argument made here with respect to complementarities in railroad operation could, if space permitted, be expanded to encompass other classes of invention not so far mentioned, such as bridgebuilding. Bridgebuilding in both America and Great Britain underwent drastic changes in structure, design, and materials as the railroad network expanded and confronted engineers with problems and requirements respecting such matters as strength, rigidity, and fire resistance for which there was absolutely no precedent in the pre-railroad age. The need to provide bridges suitable to the requirements of the railroads led, in Great Britain, to a systematic study of iron as a building material. The outcome of this study was a major advance in knowledge concerning the structural properties of iron —resistance of beams and plates, strength of girders, compression and tensile strengths, etc.[36] The knowledge thus acquired soon had a wide range of applications wherever iron was used as a building

[33] A. Fishlow, "Productivity and Technological Change in the Railroad Sector, 1840–1910," in Studies in Income and Wealth, no. 30, *Output, Employment and Productivity in the United States after 1800* (New York: National Bureau of Economic Research 1966), pp. 635, 641.

[34] As Fishlow points out, the main advantage of the air brake and automatic coupler was increased speed. "Greater speed in itself is not an unmixed blessing, however. Unless engine capacity is not being fully utilized, higher speeds can be attained only by the sacrifice of load. What the air brake and automatic coupler really did, therefore, was to allow a greater element of choice in train operation, permitting higher speed when it was more desirable than larger loads." *Ibid.*, p. 636.

[35] *Ibid.*, pp. 635, 639–640.

[36] "Report of the Commissioners Appointed to Inquire into the Application of Iron to Railway Structures," *Parliamentary Papers*, 1849, Vol. 29; William Fairbairn, *Useful Information for Engineers*, London, 1860, vol. II, pp. 223–228.

material—in shipbuilding, multistoried buildings, cranes, steam engines, etc.

The present discussion is merely illustrative of a much larger class of complementarities which exert significant effects upon the pattern of diffusion. The argument could readily be duplicated almost endlessly from different sectors of industry and agriculture.[37]

VII

Improvements in "Old" Technologies

The discussion so far has examined a variety of factors which have the effect of slowing down the diffusion of new techniques. We have considered several classes of reasons why the full productivity-increasing effects of a new technique may take a great deal of time to assert themselves. There is, however, an additional powerful explanation for such slowness which has received surprisingly little attention. That is, the "old" technology continues to be improved after the introduction of the "new," thus postponing even further the time when the old technology is clearly outmoded. Yet, curiously, it is a very general practice among historians to fix their attention upon the story of the new method as soon as its technical feasibility has been established and to terminate all interest in the old. The result, again, is to sharpen the belief in abrupt and dramatic discontinuities in the historical record.

A closer look at this record discloses not only the persistence of

[37]The contemporary experience with the introduction of new, high-yielding rice and wheat varieties in Southeast Asia forcefully exemplifies the argument advanced here. It is currently being discovered that the adoption of the high-yielding rice varieties generates a whole new series of requirements with respect to fertilizer use, water management, harvesting, processing (drying, storing, milling, grading), and disease and insect control. Although many of these problems can be dealt with by conventional means, others cannot, e.g., double-cropping calls for low-cost harvesting, threshing, and other machinery of a kind not existing ten years ago. Much attention is currently being devoted to the development of such machinery at the International Rice Research Institute at Los Banos, The Philippines, where the new rice varieties were first developed.

The really distinctive feature of the new rice varieties is that they have been genetically designed so that they are highly fertilizer-responsive. Indeed, without large doses of fertilizer the new varieties are no more productive than the old ones. A continued diffusion of the new varieties would seem to call for cost-reducing innovations in the provision of fertilizer and the entire range of complementary inputs. Better still would be the development of new seed varieties not *requiring* these complementary inputs.

old technologies in places where location or resource availability provided special advantages, but often major improvements in these technologies long after they were supposed to have expired. Thus, the slowness with which the stationary steam engine, as noted earlier, established itself as a new power source in the first half of the nineteenth century, was due in part to important improvements which continued to be made in design and construction of water wheels. Many of these improvements centered around the introduction of iron as a building material, and men like William Fairbairn could achieve international reputations well into the nineteenth century as builders of water wheels.[38] In fact, early steam engines were commonly used to supplement the action of a water mill by pumping the water from the lower mill pond back to the upper pond—thus enabling it to run over the water wheel many times. Needless to say, this was a cumbersome and inefficient arrangement. Nevertheless, until the development of the rotative steam engine which converted the oscillation of the beam into rotary motion, it was an essential expedient since the steam engine prior to that was really no more than a water pump.[39]

An additional fillip was given to the utilization of water after 1840 as a result of the introduction of the water turbine, which further reduced the cost of water power.[40] In America, where early industry had been heavily concentrated in New England, a region with highly favorable water power locations, water power was probably the main power source for manufacturing until well into the second half of the nineteenth century. Even as late as 1869, steam power accounted for barely over one half of primary-power capacity in U.S. manufacturing—51.8% as compared to 48.2% for water.[41] In

[38] William Pole, *The Life of Sir William Fairbairn, Bart* (London: Longmans, Green and Co., 1877), and William Fairbairn, *Treatise on Mills and Millwork* (London: Longman; Part I, 1861 and Part II, 1863).

[39] R. L. Hills, *Power in the Industrial Revolution* (Manchester: Manchester University Press 1970), Ch. 8. Hills also points out that the waterwheel was long preferred to the steam engine in spinning because "it was essential to have as regular speed as possible. Until some method of automatically controlling the revolutions had been found, the waterwheel with its greater steadiness was preferable" (*Ibid.*, p. 175).

[40] Victor Clark, *History of Manufactures in U.S.* (New York: McGraw-Hill, 1929), II, pp. 407–408. Although of French origin, much of the practical development of the turbine was performed in America.

[41] Allen H. Fenichel, "Growth and Diffusion of Power in Manufacturing, 1839–1910," in Studies in Income and Wealth no. 30, *Output, Employment and Productivity in the United States after 1800* (New York: National

general it may be said that steam power tended to be adopted earliest in locations where water power sources were scarce and where fuel was either abundant or easily transportable.

Even so "primitive" a power source as the windmill, which might have been regarded as a certain early casualty to the steam engine, experienced a considerable growth in at least one English county. According to Finch, the number of windmills in Kent employed in the grinding of corn grew from 95 to 239 between 1769 and the 1840s.[42] By the 1860s steam had decisively established its superiority over wind in cornmills, and windmills continued to be operated only so long as they provided quasi-rents to their owners. Jevons, writing in the middle of the 1860s, pointed out: "Wind-cornmills still go on working until they are burnt down, or go out of repair; they are then never rebuilt, but their work is transferred to steam-mills."[43]

In iron and steel, where the location of particular resource inputs and their chemical properties played an extremely important role (especially because of the intimate connection between the presence of such chemicals as sulfur and phosphorus and a poor quality final product), the introduction into the United States of the modern, mineral-based British technology was long delayed. Furthermore, the old and the new technology coexisted for long periods of time after the new technology was finally introduced. As late as 1840 almost 100% of all pig iron in the U.S. was still being produced with charcoal. Although the proportion subsequently declined rapidly as anthracite and, later, bituminous coal were introduced,[44] the tonnage of pig iron produced by charcoal continued to rise through the 1880s and reached its alltime annual peak in 1890.[45] The most interesting point here for present purposes is that during the 1840s and 1850s, when the new mineral fuel tech-

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Bureau of Economic Research, 1966), pp. 443–478, Appendix B. In absolute terms waterpower capacity continued to grow through the first decade of the twentieth century (Table A-1).

[42] William Coles-Finch, *Watermills and Windmills* (London: C. W. Daniel, 1933), pp. 136–137.

[43] W. S. Jevons, *The Coal Question* (London: Macmillan and Co., 1865), p. 136.

[44] "The proportion of pig iron made with charcoal declined from close to 100 per cent in 1840 to about 45 per cent in the middle 1850s ... and to about 25 per cent at the close of the Civil War" (Peter Temin, *Iron and Steel in 19th Century America* [Cambridge: MIT Press, 1964], p. 82).

[45] *Ibid.*, Table C-2.

nology was being introduced, it was primarily the reduction in the demand for charcoal iron which accounted for the relative decline in the charcoal sector as compared to the mineral fuel sector. Indeed, Fogel and Engerman actually conclude that, between 1842 and 1858, the growth in total factor productivity in the "backward" charcoal sector probably exceeded the growth in total factor productivity in the "modern" anthracite sector.[46]

My point so far has been that one of the reasons new technologies seem to displace old ones slowly is that the old technologies continue to improve. But the point needs to be seen within a larger framework, for there is often an intimate connection between innovations, on the one hand, and improvements in older technologies on the other. That is to say, innovations often appear to *induce* vigorous and imaginative responses on the part of industries for which they are providing close substitutes. What is being suggested here is a possible lack of symmetry in the manner in which business firms respond to alterations in their profit prospects. The imminent threat to a firm's profit margins which are presented by the rise of a new competing technology seems often in history to have served as a more effective agent in generating improvements in efficiency than the more diffuse pressures of intra-industry competition. Indeed, such asymmetries may be an important key to a better understanding of the workings of the competitive process, even though they find no place at present in formal economic theory.

Thus it has often been asserted that, by the 1850s, the iron hull cargo steamship had displaced the sailing ship and that Britain built its worldwide trading empire on the new vessel. In fact, while the complex problems of designing an efficient steamship, with its iron hull, engines, screw propellers, and very high fuel requirements, were being worked out, the wooden sailing ship also underwent a series of drastic changes. Builders of sailing ships responded to the competition of iron and steam by a number of imaginative changes in hull design, including the use of iron itself in a "composite" hull —wood placed on an iron skeleton. They adopted a range of labor-saving machinery to reduce crew requirements. According to Graham:

[46] Robert Fogel and Stanley Engerman, "A Model for the Explanation of Industrial Expansion During the 19th Century: With an Application to the American Iron Industry," as reprinted in *The Reinterpretation of American Economic History*, Robert Fogel and Stanley Engerman, (New York: Harper and Row, 1971), pp. 159–162.

> Although the steam ship had successfully wedged its way into the overseas trade, mainly by carrying passengers and subsidized mails, the evolving sailing ship of the 1860's and 1870's—faster than its predecessors, with double the space for cargo in proportion to tonnage, and manned and navigated by about one-third the number of men—retained on broad oceans a predominance almost as marked as that of the screw steamer in the coastal and neighbouring waters of Europe. Even when the opening of the Suez Canal in 1869 reduced the longest gap between coaling stations from some 5,000 to 2,000 miles, although the China trade was eventually lost, most of the traffic to the Bay of Bengal, the East Indies, South America or Australia, was still conducted by the sailing ship which continued to be the more economical carrier for the greatly expanding trade in bulky commodities, such as iron and coal, the jute and rice of India and Burma, the wool of Australia, the nitrate fertilizer of Chile and the wheat of California.[47]

Even the rapid growth of the steamship fleet in the 1870s offered some consolation to the sailing ship: "it was coal more than any other article that brought a new lease of life to the commercial sailing ship in the latter days of her ascendancy. As the cheapest coal carrier, as well as the cheapest warehouse in the world, the sailing ship became the chief replenisher of overseas coaling bases and depots."[48] Furthermore, some of the design changes which improved the performance of the sailing ship were also made possible by steam, in this case by the steam tugboat which, "taking them in and out of harbor, relieved the windjammers of need for handiness, enabling greater length and fine lines, and enabling guaranteed sailings out of a harbor."[49]

[47] C. S. Graham, "The Ascendancy of the Sailing Ship, 1850–1885," *Economic History Review*, 2nd series, 9 (August 1956), 81. For a careful examination of the economic impact of technological changes in the steamship, see Charles K. Harley, "The Shift from Sailing Ships to Steamships, 1850–1890: a Study in Technological Change and its Diffusion," in *Essays on a Mature Economy: Britain after 1840*, ed. Donald N. McCloskey (London: Methuen, 1971), pp. 215–231.

[48] *Ibid.*, p. 84

[49] S. C. Gilfillan, *Inventing the Ship* (Chicago: Follett Publishing Co., 1935), p. 157. It is not unusual for the "new" technology to extend the life of the "old" by providing it with some form of externality. Thus, the arrival of the steamboat on western rivers brought about significant reductions in labor costs in flatboat operation by providing flatboatmen with a speedy form of upriver transportation—a trip which had previously been both very slow and costly. See E. Haites and J. Mak, "Ohio and Mississippi River Transportation, 1810–1860," *Explorations in Economic History*, 8 (Winter 1970–1971), fn. 36, and Mak and Walton, "Steamboats," p. 19.

By the 1880s the sailing ship finally lost its dominance even on long distance hauls to steamships, which were now equipped with high pressure compound engines and a range of superior components provided by the recent breakthroughs in steel-making technology—including the very important boiler plates and boiler tubes, so essential to high pressure and fuel economy.[50] The sailing ship of the 1880s was far superior to its predecessor of 1850 or so, and it seems plausible to attribute this improvement to the strong competition of steam.[51] Obviously one cannot assert this with authority, because we do not know what the sailing ship of the 1880s would have been like in the absence of such intertechnological competition. But it seems like a reasonable conjecture for which there is analogous evidence in the experience of other industries. Thus, technological competition recently appears to have been a powerful force among materials producers (where, for example, the increasing competition from aluminum seems to have led to the setting up of product-research and engineering laboratories in the steel industry), among suppliers of transportation services, and among the major kinds of fuel. Not only does this form of competition generate economically-beneficial consequences; it also plays a significant role in explaining the rate of diffusion of some new techniques.

[50] See Douglass North, "Ocean Freight Rates and Economic Development, 1750–1913," *Journal of Economic History*, 18, (December 1958); Douglass North, *Growth and Welfare in the American Past* (Englewood-Cliffs, N.J.: Prentice-Hall, 1966), Ch. 9; and Gary Walton, "Productivity Change in Ocean Shipping After 1870: A Comment," *Journal of Economic History*, 30 (June 1970). North states: "Although the steamship substituted for the sailing ship in passenger travel as early as 1850, it did not substitute for the sailing ship in the carriage of bulk goods in ocean transportation until much later. Indeed, as late as 1880 most of the goods carried in ocean transportation were going by sail, and the changeover from sail to steam did not occur in most of the long-haul routes in the world until the very end of the nineteenth century . . ." (*Growth and Welfare*, p. 110).

[51] The sailing ship adapted to its more specialized role as a long-distance carrier of bulk cargoes by modifying its sails and rigging so as to reduce crew requirements. In part this was done by "abolishing the lightest sails, broadening the upper yards, and cutting in two the largest sails until furling could replace almost all reefing" (S. C. Gilfillan, p. 160). The American merchant fleet was slower than the British in substituting steam for sail. As late as 1913 almost 20% of the gross tonnage of American merchant vessels still consisted of sailing vessels. *Historical Statistics of the U.S., Colonial Times to 1957* (Washington, D.C.: U.S. Printing Office, 1960), p. 444.

VIII

Diffusion and its Institutional Context

This paper has discussed, at some length, several categories of technological considerations which have influenced the pace of diffusion. Needless to say, the treatment has been suggestive rather than exhaustive; in fact, the number of variables—social, legal, and institutional as well as economic and technological—which might retard the diffusion process is virtually limitless. Nevertheless, it is important that an effort be made to maintain conceptual clarity among these categories because our understanding of the process of long-term economic growth is influenced, in important ways, by this conceptual apparatus. Ever since Abramovitz and Solow opened up the problem of "The Residual," economists have been attempting to sort out the contributions of various factors to economic growth and, particularly, to measure the contribution of technological change as distinguished from all other possible factors. Whereas the entire residual was for some time uncritically attributed to technological change (although not by Abramovitz or Solow) a later, more discriminating approach has attempted to isolate other factors—changes in organization, improvements in the quality of the labor force, etc.—and to measure their separate contributions.[52] In this difficult but essential process of "cutting technological change down to size," however, there is a danger of going too far, by assigning an independent and separate role to factors which really exert their effects upon the growth of productivity by retarding or accelerating the rate of technological diffusion.

A recent example of the position I am criticizing is North's

[52] North threw out the following challenge several years ago: "I would hazard the speculation that if we ever did the research necessary to get some crude idea of the magnitudes involved, we would discover that improved economic organization was as important as technological change in the development of the Western world between 1500 and 1830. I mean by this, improvements in the factor and product markets, reduction in impediments to efficient resource allocation, and economies of scale. Moreover, the complementarity between physical and human capital in the development, application, and spread of technological change requires equal analytical attention before we can begin to make sense on this subject. Clearly, we need to overhaul our view of the whole process by which the Western world developed in the last five or six centuries" (Douglass North, "The State of Economic History," *American Economic Review, Papers and Proceedings*, 55 [May 1965], 87–88.

otherwise admirable study of "Sources of Productivity Change in Ocean Shipping, 1600–1850."[53] North states that his objective is to "identify as precisely as possible those sources of productivity usually lumped into the general category of technological change." And, he adds: "The conclusion which emerges from the study is that a decline in piracy and an improvement in economic organization account for most of the productivity change observed."[54]

With a portion of North's argument there is no disagreement whatever. North makes an important contribution to our understanding of productivity growth during the period by demonstrating that organizational and marketing improvements were highly significant. He shows that, in the tobacco trade before the Revolutionary War, the increased number of round trips per year was due, not to increased speed resulting from technological change, but rather to the introduction of a system of factors and an increasing centralization of inventories. These organizational improvements, by making it easier and much quicker for ships to secure cargoes, substantially reduced the ratio of port time to sea time, and thereby sharply increased the quantity of freight which could be carried by a given stock of ships.[55]

The other portion of North's argument, involving an attempt to downgrade the contribution of technological change to the growth of productivity in ocean shipping, is more questionable. North finds that, before 1800, the most important source of the great reduction in crew size requirements was the decline in piracy and privateering. His "downgrading" of the role of technical change proceeds as follows:

> One can ask at this point . . . the extent to which technical changes in shipping and in ship construction account for the changes in manning requirements and, indeed, in observed ship speed. There is no doubt that the ship of the nineteenth century was in striking contrast to the ship of the early seventeenth century. Except for one crucial point it could be argued that smaller crews were made feasible precisely by technological improvements in sail and rigging. The obstacle to this argument is that by 1600 the Dutch had developed a ship, the flute, which cost less to construct than existing ships, had a tons-per-man ratio similar to that of nineteenth-century ships on the Atlantic route, was at least as fast as existing ships, and could be (and was) constructed of 500–600 tons burden. While the design was copied and

[53] *Journal of Political Economy*, 76 (September–October 1968), 953–970.
[54] *Ibid.*, p. 953.
[55] *Ibid.*, pp. 960–963.

> modified over the next two centuries, the essential economic characteristics were not basically altered. The enigma to be explained, therefore, is why the flute (or ships of similar design) took so long to spread to all the commodity routes in the world, once it had entered the Baltic route and the English coal trade in the first half of the seventeenth century. The answer lies in the very nature of the flute and its great advantages in that it was lightly built, frequently carried no armament, was easy to sail, and had simple rigging. These characteristics had all come about because the Dutch enjoyed a large-volume bulk trade in the Baltic, where piracy had already been eliminated. Only as privateering was driven from other seas and as improvements took place in market organization was it possible to put into general active service ships designed exclusively for the carrying trade.[56]

The trouble with this paragraph is that the diffusion process has been completely lost from view. A superior technology in the form of the Dutch flute existed by 1600, but security considerations long confined its adoption to a small portion of ocean trade. As piracy and privateering were suppressed in the course of the eighteenth century, the superior vessel was widely adopted on new routes with the expected rise in productivity. But, if all this is so, the elimination of piracy and privateering emerge as factors which influence shipping productivity only as intervening variables: i.e., the threat which they posed to the security of shipping was responsible for *the very slow diffusion of a superior technology*—"the flute (or ships of similar design.)" There seems to be general agreement that, in the *absence* of the security threat, the flute design would have been adopted much earlier.[57] North, however, in his legitimate concern with deflating the overblown spectre of technological change, gives the impression—doubtless unintended—that it was scarcely of any significance whatever in the period with which he is concerned. It goes unmentioned in his final sentence, which states: "The conclusion one draws is that the decline of piracy and privateering and the development of markets and international trade shared honors as primary

[56] *Ibid.*, p. 964.

[57] Thus Walton states, with respect to colonial shipping: "As the obstacles of piracy and similar hazards were eliminated, specialized cargo-carrying vessels possessing the input characteristics of the flyboat were adopted. In the process, the costs of shipping were substantially reduced, which had a favorable impact on the development of a trading Atlantic community" (Gary Walton, "Obstacles to Technical Diffusion in Ocean Shipping, 1675–1775," *Explorations in Economic History*, 8 (Winter 1970–1971), p. 136.

factors in the growth of shipping efficiency over this two-and-a-half century period."[58]

The interpretation which North has placed upon his historical account has been restated by Fogel and Engerman in their volume, *The Reinterpretation of American Economic History*, where North's article has been reprinted. Fogel and Engerman regularly refer to North's article as showing that factor productivity did not rise as a result of *new* inventions.

> In the case of ocean shipping, Douglass North ... found that a rapid and protracted increase in total factor productivity took place despite the absence of a single major *new* invention. According to North the rise of efficiency was due largely to the change in the proportion of large ships in the Atlantic fleet. This diffusion of large ships was set off, not by *new* technological knowledge, but by a change in institutional conditions.[59]

And, earlier: "Thus, *new* equipment plays virtually no role in Douglass North's explanation of the 50 per cent fall in the cost of ocean transportation that he finds for the 250-year period between 1600 and the middle of the nineteenth century."[60]

But if a superior ship designed specifically for improved cargo-carrying capacity had been developed by 1600, it is no verbal quibble to say that the improvements in ocean shipping productivity due to the eventual adoption of this design should correctly be regarded as belonging to the category of technological change. The portion of North's paper dealing with piracy is not an explanation of productivity growth which is *independent* of technological change, although it is frequently made to sound that way. Rather, it is a cogent and forceful explanation for the very slow *diffusion* of a major techno-

[58] North, "Sources of Productivity Change," p. 967.

[59] Robert Fogel and Stanley Engerman, *The Reinterpretation of American Economic History* (New York: Harper and Row, 1971), p. 206, emphasis added.

[60] *Ibid.*, p. 5, emphasis added. Also, p. 100: "North argues that most of these changes were due to improved organization rather than new equipment.... He holds that no *new* technological knowledge was required for the switch from fleets of predominantly small ships to fleets of predominantly large ones.... What then explains the dominance of the small over the large ship in the seventeenth and eighteenth centuries and then the rapid shift toward large ships between 1800 and 1860? North again finds the answer not in *new* technological knowledge, but in institutional change. He argues that the elimination of piracy made it feasible to build large, light vessels for the exclusive purpose of carrying cargoes." [Emphasis added.]

logical innovation. What seems to be at issue here—and this emerges with particular clarity in the writing of Fogel and Engerman—is that benefits attributable to technological change are being arbitrarily confined to recent or "new" developments. But there is no obvious reason why the productivity-increasing effects of technological change should be confined to changes of recent vintage. Surely the essential point, on which all would agree, is that the productivity of any technology is never independent of its institutional context and therefore needs to be studied within that context. North's paper should be interpreted as a striking demonstration of this point, for he shows how this institutional context can account for the very slow diffusion of a superior shipping technology.

IX

The several arguments of this paper all add up to a perspective and a program for research rather than a sharply defined set of conclusions. A variety of reasons have been advanced for believing that a new technique establishes its advantages over old ones only slowly, and it has been argued that the apparent slowness of the *diffusion* of technologies is linked to this process and needs to be studied in relation to it. In spite of the occasional appearance of inventions which seem to be spectacular for their *technological* novelty, the *economic* impact of such inventions is much more diffuse and gradual. Their introduction into the texture of the economy is more accurately—if less dramatically—viewed as occurring along a gradual downward slope of real costs rather than as a Schumpeterian gale of creative destruction. At the same time, it is perfectly apparent that the question posed earlier has not been answered: How slow is slow? (How fast is fast?). But it should be clear by now that I would not worry excessively about that failure so long as we can advance our understanding of the reasons for the *actual* historical pace of technological diffusion. Once that pace has been established, we can each go our separate ways in deciding what we choose to regard as fast or slow.