

COMPUTER AND DYNAMO

The Modern Productivity Paradox in a Not-Too Distant Mirror

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Abstract

Many observers of contemporary economic trends have been perplexed by the contemporary conjuncture of rapid technological innovation with disappointingly slow gains in measured productivity. The purpose of this essay is to show modern economists, and others who share their puzzlement in this matter, the direct relevance to their concerns of historical studies that trace the evolution of techno-economic regimes formed around "general purpose engines". For this purpose an explicit parallel is drawn between two such engines -- the computer and the dynamo. Although the analogy between information technology and electrical technology would have many limitations were it to be interpreted very literally, it nevertheless proves illuminating. Each of the principal empirical phenomena that go to make up modern perceptions of a "productivity paradox", had a striking historical precedent in the conditions that obtained a little less than a century ago in the industrialized West. In 1900 contemporaries might well have said that the electric dynamos were to be seen "everywhere but in the economic statistics". Exploring the reasons for that state of affairs, and the features of commonality between computer and dynamo -- particularly in the dynamics of their diffusion and their incremental improvement, and the problems of capturing their initial effects with conventional productivity measures -- provides some clues to help understand our current situation. The paper stresses the importance of keeping an appropriately long time-frame in mind when discussing the connections between the information revolution and productivity growth, as well as appreciating the contingent, path-dependent nature of the process of transition between one techno-economic regime and the next.

Keywords: productivity slowdown, diffusion of innovations, economics of technology, information technology, electric power industry.

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--"A man may love a paradox without losing his wit or his honesty." Walter Savage Landor, in The Dial, 1841.

My purpose in this essay is to show modern economists, and others who find themselves perplexed by the contemporary conjuncture of rapid technological innovation and disappointingly slow gains in measured productivity, the direct relevance to their interests of historical studies of the evolution of techno-economic regimes formed around "general purpose engines". To do this I have drawn an explicit parallel between two such "engines"--the computer and the dynamo.¹

Although the analogy between information technology and electrical technology has many limitations when literally interpreted, the features of commonality that can be seen in the dynamics of their pervasive diffusion, their incremental improvement, and their confluence with other complementary technologies, are quite instructive nonetheless. They may provide some needed guidance as to the appropriate time-frame for us to keep in mind when discussing future developments in information technologies and their likely long-run impacts on living standards and on economic and social organization in the industrialized nations. They also may provide a context in which some aspects of the current condition referred to as the "productivity paradox" are less surprising, and more readily understood.

¹ Parallels between the computer and other general purpose engines have been cited before, e.g., by Simon (1986). On the economics of "general purpose technologies," see Bresnahan and Trajtenberg (1989).

1. Paradox Lost, and Regained

The conveners of the O.E.C.D. International Seminar on Science, Technology and Economics Growth have directed our attention to a puzzling and possibly worrisome aspect of the recent macroeconomic experience of the industrialized nations (OECD--DSTI Programme, 1989: p.1). Economic growth has slowed since the mid-1970s to a degree that is not accounted for by the concurrent retarded growth rate of productive inputs, implying that the pace of total factor productivity advance also has slowed down. During the preceding twenty years the convention had become firmly established among economic analysts that total factor productivity increases (measured with various degrees of refinement) were attributable to the influence of "technical change", "the advance of knowledge", and suchlike--fruits of the commercial exploitation of science through investment in R&D, as well as improvements of efficiency derived from the accumulation of actual production experience. By that convention, then, the pace of realized technical progress must have abruptly diminished during the 1970s, despite the contemporaneous emergence of a surge of major technological innovations in the area of microelectronics and communication technology, in composite materials, and in biotechnology.

Thus, we are presented with a disturbing irony:

"Whereas the industrialized countries have built up a previously unequalled scientific and technological capacity, and technological change seems pervasive in everyday life, [those] countries appear to be finding it increasingly hard to translate this capacity into measurable productivity increases..."
(OECD:CSTP Programme, 1989)

It is to this unexpected juxtaposition that the label "the productivity paradox" lately has become affixed. The notion that there is something anomalous, and possibly even self-contradictory in the prevailing state of affairs also has acquired a specific formulation, along with wider currency, from the quip attributed to Professor Robert Solow: "We see the computers everywhere but in the economic statistics."

The latter, Solovian formulation of the productivity paradox admits of both a broad and a narrow interpretation. Which of these we find ourselves

addressing will depend upon whether the reference to computers is treated as essentially symbolic, or taken quite literally, to indicate a particular disappointment of productivity expectations regarding microelectronic-based computer and communications technologies; and also as we consider the productivity measures to refer to the national productivity aggregates or to specific sectors where more extensive investment embodying computer and communications technologies has occurred. More than one observer has remarked that in the U.S. the recent boom in office automation using electronic data processing equipment, and the related rise of the computer-intensity of service industries--especially banking, finance, and insurance, wholesale and retail trade--have not been accompanied by surging indices of output per manhour in those activities (see e.g., Roach (1987, 1988), Baily and Gordon (1988), Ayres (1989)).

Paradoxes, like other logical propositions, proceed from premises. Yet, in the case at hand, the empirical foundations for the broader of the two proposed renderings of the "productivity paradox" seem too shaky to justify treating the matter as more than superficially puzzling. In the first place, it is debateable that the pace of realized technical progress actually has slowed. The pioneer discoverers of the total factor productivity residual were originally cautious about identifying it exclusively with technological change, much less with the fruits of organized R&D. Abramovitz (1956) called it "a measure of our ignorance," and others, like Jorgenson and Griliches (1967), doubting the conceptualization of sustained efficiency growth as something akin to manna falling (costlessly) from the heavens, set out to show that the residual arose from errors in measuring the inputs. It says something about economics as a profession that the shrinkage, let alone the temporary disappearance of a quantity once thought to measure our ignorance has now come to be viewed as a dire condition to which national leaders should attend. In effect, economic growth experts presently are engaged in advising how most quickly to reestablish their former state of ignorance.

In the second place, the pace of realized technical change is not tightly tied to the current rate of innovation. Innovations are not immediately commercially adopted, and their effects upon the economy are not invariant, being conditioned on many things--including rapidly altering macroeconomic

circumstances and slowly changing institutional and cultural settings. Moses Abramovitz (1987,1989) has provided an incisive analysis of the way in which slippage between the advancing frontier of technology and actual practice creates potentialities for rapid productivity growth, potentialities that will by no means automatically be realized. Applying this to the immediate historical context of the post WW II era, in which it is essential to view the retardation of aggregate economic growth and widespread slowdown of productivity advances experienced among the industrialized nations of the West, Abramovitz (1989) tells us that some significant part of the slowdown was to be expected in large part because the realization of the potentialities for rapid advance inherently was a self-limiting process; it rested on an enlarged, but, nevertheless, an ultimately exhaustible pool of high-yielding investment opportunities. Insofar as the post WW II episode of accelerated economic growth derived momentum from the existence of a Depression-and War-formed backlog of un-utilized and partially exploited industrial technologies that were introduced in the 1920s and 1930s, and further elaborated during the 1940s, there is no obvious reason to suppose that this momentum was indefinitely sustainable even in the absence of adverse real and monetary disturbances in the international economy. Indeed, quite dramatic changes would have been required to recreate, from innovations first introduced toward the close of the 1960s, an equivalently large pool of applicable technologies.

Furthermore, it is quite conceivable that the slowdown of real income growth and productivity would have been even more pronounced than was experienced since 1973, were it not for the current wave of technological innovations. Whatever impetus to investment, market expansion, and cost-reduction the latter might have provided, the resulting stimulus to growth would remain difficult to discern amidst the combined effects of the exhaustion of the old backlog of technological opportunities, the maturation of the technological regime based on continuous process and mass production industries, and the adverse impact (post 1973) of the higher cost of energy upon the energy-intensive, heavy industrial sector.

Because the premises on which the broader interpretation of the so-called "productivity paradox" has been constructed are of such dubious validity, I find it more interesting and challenging to focus the following

discussion on the narrower problem of the computer revolution's seeming failure thus far to reflect itself in a surge of productivity growth in the sectors that have seen substantial investment in electronic data processing equipment.² Is the "computer-automated office" little more than a snare and delusion, as Roach's (1986, 1987, 1988) reports initially seemed to suggest? Perhaps the capital formation represented by those outlays which, in the mid-1980s, saw expenditures for computers accounting for approximately one-half of U.S. gross private domestic investment in equipment, were misallocated? Or does the fault lie with the conventional productivity measures, which are failing to fully capture the contributions to economic welfare that properly can be attributed to the newly installed computer technology? Should we even be expecting a surge in productivity from the computer-communications revolution at this time?

2. Technological Presbyopia--Symptoms and Remedy

In thinking about the microeconomics of information technology--or, of biotechnology, new materials, and other developing "generic" and systemic technologies--one often is prone to suffer from a kind of "telescopic vision": the possible future appears both closer at hand and more vivid than the necessary intervening, temporally more proximate events on the path leading to that destination. There is an understandable inclination to concentrate on the future, holding onto the prospect of dramatic improvements in the material circumstances of the mass of humanity without having to contemplate overt conflicts that could be provoked by the purposive redistribution of existing wealth. In the long-run it may be a functional

² This is not confined to the non-commodity producing sectors of the business economy, for, the revival of labor productivity growth in U.S. manufacturing during 1979-87 has only succeeded in restoring the 1948-73 trend rate of advance. And even so, as has been pointed out by Denison (1988) and Baily and Gordon (1988), much of this revival is directly attributable to the extremely rapid rate of measured output and productivity advance that the Commerce Department has managed to procure for the non-electrical machinery industry by dint of employing a hedonic price deflator for computer equipment.

response on the part of the modern industrial democracies to try to direct the energies of society away from redistributive struggles and toward the cooperative conquest of the "endless frontier" of science, and its commercial exploitation through technological research and development. But, in such efforts, we should retain a proper sense of how long that long-run may be: at a 2 per cent per annum rate of improvement in the average standard of living, it will take about 80 years to bring those initially in the lowest fifth of the income distribution up to the level enjoyed by the median income recipient at the beginning of the process.

The predisposition to be overly forward-looking has other serious drawbacks. Indeed, despite the tendency of our culture to regard far-sightedness as less of a disability than myopia, the condition could be deemed a pathology and termed "technological presbyopia." It causes the afflicted to focus their attention on the arrival and not on the journey. Sufferers lose a proper sense of the complexity and historical contingency of the processes involved in technological change and the entanglement of the latter with economic, social, political, and legal transformations. There is no automaticity in the implementation of a new technological paradigm, such as that which we presently discern is emerging from the confluence of advances in computer and communications technologies. As Freeman and Perez (1986) have so rightly emphasized, many intricate societal and institutional adjustments, transcending in complexity and uncertainty the redirection of private investment planning, are usually entailed in effecting the passage from one "technological regime" to another.³ On this view there are likely to be many difficulties and obstacles that normal market processes cannot readily overcome. Indeed, these may cause markets to reflect and amplify consequences of mal-alignments in institutions and politically determined patterns of resource allocation that remain better adapted the old Fordist, continuous production paradigm of industrial operations that characterized energy-intensive, standardized product manufacturing, than they are to a new

³ Simon (1986:p.5) recently has expressed the same perception in regard, specifically, to the impact of information technology innovations on the process of education: "It seems equally obvious to me that computers will not revolutionize education until there are massive changes in the organization and administrative structure of the educational system as well."

information-intensive regime of computer integrated manufacturing and distribution such as has been envisaged by many recent commentators.

Perhaps the simplest and most common symptom experienced by technological presbyopic observers, is one that stems from the warping of the sense of time: the recurring sensation of puzzlement that consequences of the perceived trajectory of technology whose realization is expected momentarily do not in fact seem to be manifesting themselves. The easiest and probably the most effective remedy I can recommend for this condition is to spend more time in backward-looking pursuits, seeking a deeper understanding of the actual historical experience involved in passages from one techno-economic regime to a successor. Accordingly, I shall eschew casual references to the steam revolution, the dynamo revolution, the computer revolution, and revolutions before, and beyond these, in favor of more closely examining the evolutionary dynamics of the particular regime that developed around the technology of universal electricity supply networks.

My historical comparison between the computer and the dynamo also aspires to identify and call attention to some systematic conditions that may be contributory to the particular conjuncture that many contemporary observers have found unsettling, or at least perplexing: the persisting slowdown of measured productivity growth in the economy at large, or in its major sectors, concurrent with the rapid movement towards a technological paradigm (computer integrated design, production and distribution) that is viewed to have enormous productivity-raising potentials. To be sure, at the heart of some of those conditions will be found some difficult problems of economic measurement, encountered particularly during the early phases in the evolution of general purpose technologies. But, I find ample grounds (e.g., in Baily and Gordon (1988), and Gordon and Baily (1989)) to believe that the paradoxical conjuncture is not a statistical artifact arising somehow from the variegated measurement conventions subscribed to by national income accountants in the world's industrial societies. Precisely because it seems to be in substantial part a reality rather than a popular or statistical delusion, there should be interest in any explanatory framework that proves helpful in close analysis of a generally comparable historical experience. The clues supplied thereby should help us to identify, in the case of modern

information technologies, a number of critical factors affecting the relationship between the aggregate (or sectoral) productivity growth rate and the dynamics of an emerging trajectory of intertwined efficiency improvements and increasing penetration of productive activities by the new general purpose technology.

3. A Not-Too-Distant Mirror⁴

The ease with which it is possible to justify holding up the "dynamo age" as a mirror to our own times is rather remarkable, and the very existence of this historical precedent may go far towards dispelling from the present circumstances some of the penumbra of mystery with which discussions of "the productivity paradox" have come to be surrounded. If modern analysts of this matter are confronted with an actual puzzle, at least there may be some comfort (and some clues) in the knowledge that it is not a wholly novel puzzle. For each of the principal empirical phenomena that go to make up this contemporary perception of a "productivity paradox," a striking precedent can be found in the state of affairs that existed in the industrialized West a little less than a century ago. Except that the symbolic image and reality of new technology is now the computer, whereas it was then the dynamo.

Just about 90 years ago (and not far from O.E.C.D.'s headquarters in the Chateau de Muette), a visitor to Paris might descend from the Palais du Trocadero to the river--through the hilly park dotted with the exotic pavilions of Indo-China, Cambodia, Senegal, Tunisia and Algeria, and proceed via the Pont d'Iena to the Seine's left bank. There, in the Champ de Mars, he (or she) would come upon the vast iron and glass halls containing the main exhibits of technology at the 1900 Paris Exposition (see Figure 1a; Mandell (1967: Ch.4), for description). The Paris 1900 Exposition was the first to exhibit at large number of bicycles and automobiles (the French automobile industry being very advanced at the time), and featured other technical innovations such as the first demonstration of X-rays, of "wireless telegraphy", and sound synchronized with movies. Nevertheless, commentators

⁴ With apologies to Barbara Tuchman.

of the day remarked that in comparison with previous international fairs it offered few startling scientific discoveries or technological breakthroughs.⁵

Instead, what the 1900 Exposition appeared to contemporaries to reveal more clearly than anything else in this respect was the fulfillment of promises held out by earlier inventions; the power of modern technology, particularly the electrical technology first introduced at the Paris 1881 Exposition, to effect striking transformations in the material conditions of life for urban dwellers. This was evident not only inside the Palais de Electricity (see Figure 1b) but outside as well. Although Europeans already knew of electric lighting for decades, never before Paris 1900 had it been used to illuminate a whole city--in such a way that outdoor festivals could continue into the night.

It was evident too in the vastly larger, and more efficient machines that were crammed into the largest of those exhibition halls--the Gallerie des Machines (see Figure 2). A modern historian of Paris 1900 has written of the impact made by the new, immense dynamos exhibited by Germany, as well as of the railway engines, blast furnaces, cranes, and tractors that were, likewise, larger, faster, cheaper, and incredibly more efficient than their predecessors (Mandell (1967:p. 68)):

"In a march of material progress that shocked some observers, new machines rendered outmoded and, as if by magic transformed into junk those that were the ultimates in efficiency just a few years earlier."

Among the contemporary visitors drawn to the 1900 Exposition, and one who was particularly obsessed with the contents of the Gallerie des Machines, there was the brooding American historian-philosopher, Henry Adams, then in his sixtieth year. This erudite descendent of two American presidents described himself as having haunted the exhibits of electrical machinery, relating, in a letter written some months later to his friend John Hay, how he would

"...sit by the hour over the great dynamos, watching them run noiselessly and smoothly as planets and asking them--with infinite courtesy--where the Hell they are going. They are marvelous. The

⁵ The German coin-slot restaurant, which would seem to have been the first "automat", presumably did not qualify in the latter category. See Mandell (1967): p.68.

Gods are not in it. Chiefly the Germans....It is a new century, and what we used to call electricity is its God."⁶

Subsequently, in his autobiography, The Education of Henry Adams (1906), he elaborated upon this theme, seeking to grasp the meaning of what he had seen, and to articulate what he felt were its disturbing portents for the future of humanity; in the essay now regarded as a classic, entitled "Dynamo and Virgin", he wrote, referring to himself in the third person (Adams (1906: p.380)):

"...to Adams the dynamo became a symbol of infinity. As he grew accustomed to the great gallery of machines, he began to feel the forty-foot dynamos as a moral force, much as the early Christians felt the Cross....Before the end, one began to pray to it; inherited instinct taught the natural expression of man before silent and infinite force. Among the thousand symbols of ultimate energy, the dynamo was not so human as some, but it was the most expressive."

Having marked 1900 as the dawning of the epoch of the dynamo as cultural and psychological force in human affairs, Adams brooded about the fate of the civilization now that its former energizing symbols--those of the Cross, and of the image of the Virgin Mary, whose force might still be felt at a few, confined places such as Lourdes and Chartres--had thus been suddenly supplanted by this new and utterly materialist sign of boundless power.⁷

Whatever one might say about such metaphysical speculations, it is hard to withhold from Adams credit for appreciating in 1900 that the world was just entering a new technological era, for seeing the dynamo's significance as a

⁶ See Adams (1951: p.220) for letter to John Hay, November 7, 1900.

⁷ In Adams' symbolic juxtaposition, the Virgin represented all that was distinctively human, but the dynamo pointed to the annihilation of all human values, first through the regimentation achieved by an antlike society, and then by the triumph of impersonal cosmic force over all life. In another classic essay, Adams is taken to task by White (1968)--not for harboring depressing thoughts about the fate of mankind, but for subscribing to orthodox Cartesian dualism, which perceives the subjective and spiritual as being distinct and opposed to the objective and material. Rejecting that separation of mind from matter, White (1968: p.63) finds at Chartres and the other cathedrals of the twelfth and thirteenth centuries "a sublime fusion of high spirituality and advanced technology", and he develops a compelling argument for the existence of close connections between Christian theological views of man's relationship to Nature and the burst of technological innovations that was forthcoming from the medieval West.

portent of things yet to come, rather than as epitomizing what had been accomplished by human ingenuity and enterprise. The technological regime that eventually would be built up around the core innovation of the electric dynamo had remained in an essentially inchoate, pre-paradigm phase from 1870 to about 1893--that is to say, from the introduction of Gramme's ring winding for direct current dynamos to the decision to implement an alternating current generation and distribution network for the Niagara project in the U.S. Only thereafter had its developmental trajectory become defined, as the technology for electricity generation and transmission passed quickly through a phase of "paradigm emergence" during the period 1893-1907.

Thus, a visitor who was dazzled by the display of electric lighting that brightened the Paris nights during the 1900 Exhibition, and overwhelmed by the enormous dynamos massed on the Champ de Mars, could be excused for going away impressed simply with the marvelous feats of engineering that already had been accomplished. Paris 1900 may have seemed to many contemporaries the fulfillment of what had been promised two decades before by the inventive breakthroughs achieved by Edison and others, in the generation of electricity and its application to lighting. But, in actuality, at the dawning of the twentieth century the new techno-economic regime was just taking shape clearly in America and Germany: the universal electricity supply utility, a system based upon the generation of alternating current in massive central power stations, for distribution via a transmission network extended across a wide geographic area to residential and business customers who would use it not only for lighting, but also for traction work in the form of electric street-cars and railways, and myriad industrial applications ranging from power to drive machinery to electrolysis. At the time, this still was both a relatively novel an engineering concept and a bold, innovative strategy for expanding the field of electrical utility enterprise. Engineers and entrepreneurs with vision looked forward to the profound transformations that electrification would bring to factories, stores and homes as the new technology formed complementary modules with, and stimulated the further development of recent communications technology innovations--such as the telephone, radio, the phonograph, and sound-synchronized movies.

It may provide a helpful perspective on our present technological situation to notice that a visitor to Paris 1900, surrounded as he or she would then have been by the evidence of the international scope of the already existing electrical manufacturing industry that filled many of the foreign exhibitor's halls in the Champ de Mars, was situated about as far distant in time from the introduction of the carbon filament incandescent lamp by Edison, and Swann (1879), and of the Edison central generating station in New York and London (1881), as today we stand from comparable "breakthrough" events in the computer revolution: the introduction of the 1,043 byte memory chip (1969) and the silicon microprocessor (1970) by Intel. (See Figure 3 for a more detailed time-line comparison.) In announcing 1900 as end of the epoch of the Virgin and the beginning of the reign of the dynamo, Henry Adams himself remarked that the dynamos were not a novelty, but rather were among the most familiar objects--which they were to someone who had been attending international expositions since 1881.

Had he been less the brooding philosopher, however, Adams presumably would not have dwelt so on symbolic meanings, and future portents. He would have been more concerned to identify and gauge what impact electricity technology already had made in the material sphere. Indeed, had Henry Adams had the interests and wit of an economist of Nobel Laureate stature--such as Robert Solow--he might well have been better remembered today, not for the juxtaposing the great images of the dynamo and the Virgin, but, instead, for anticipating Solow with the quip: "We see the dynamos everywhere but in the economic statistics."

Indeed, he would have had good grounds--as good as exist in the modern day case of the computer--for having uttered such a remark! Consider the following set of facts that economic historians have assembled about the fin du siecle economy. First, the rate of labor productivity growth in the aggregate economy and the industrial sector of Great Britain (the leader country among the world's industrializing nations) appeared to have slowed appreciably as the nineteenth century drew to its close (see Matthews et al. (1982:p. 31); Crafts (1988) for discussion). There continues to be substantial diversity of opinion among the experts as to the precise timing of the slowdown in Britain's growth of industrial production and real GDP, and

about the timing and extent of the concomitant deceleration of the trend rate of increase in labor productivity (see Crafts, Leybourne, and Mills (1989a, 1989b)). Nevertheless, it is generally agreed that during the so-called "Edwardian Boom" of 1900-13 the British pace of secular productivity advance (if it remained positive at all) had sunk to its lowest levels since the late eighteenth century.

Yet, and this is the second fact, coincident with these depressingly sluggish macroeconomic tendencies, Britain's formal scientific and technological establishment was undergoing a remarkably vigorous expansion. Pollard (1989: Ch.3) has recently pointed out that between 1890 and 1910 the cumulative total of English graduates in science and engineering was increased 10-fold, rising from 1447 to 14,330; chairs and fellowships in engineering as well as in science were founded in the older Scots and even in the ancient English universities in this period. (Cambridge gained three Nobel prizes in physics with the five-year interval, 1904-08.) In Pollard's view, the eleven civic universities and colleges, beside London, that came into existence in this same era represented counterparts to the rising German technical universities, while polytechniques in London, and technical and evening classes in the provinces multiplied with great rapidity. The development of academic capacity in science and engineering, evidently, did not suffice in these circumstances to avert a decline in the rate of productivity advance, any more than had been the case more recently in the U.S. and western Europe.

Third, a concurrent retardation of labor productivity growth--although not one that pushed the trend growth rate down so low as it was in Britain--can be seen to have been taking place in the U.S. (See Table 1.) Here, too, there is some disagreement over details among the statistical sources: Kendrick's (1961) estimates show a marked retardation in the total factor productivity (TFP) growth rate during the period 1890-1912, whereas the more recent Abramovitz-David (given in Table 1) suggest a pause in the secular acceleration of TFP growth during the 1890-1905 trend period. Both sources concur, however, that there was a slowdown in the pace of average labor productivity increases after 1890, or thereabouts.

In the U.S., to add a fourth parallel with events of the post WW II boom and the post-1973 slowdown, a very high pace of advance had been maintained

over the preceding extended period (1869-1892). Some part of the latter postbellum surge (the reference now is to the 1861-65 Civil War in America) of U.S. economic growth and productivity may also, like its contemporary counterpart, have owed some of its impetus to a "catch-up" process such as Abramovitz (1987, 1989) describes.

Still other macroeconomic aspects of the present find corresponding reflections in the not-too-distant mirror to which I am pointing. In the fifth place, one may note that among the suspected causes underlying the U.S. labor productivity slowdown which set in for at least two decades after 1890, attention recently has been focused upon the absorption of the first heavy waves of the "new", Southern European immigration that brought more than 18 million people to the U.S. in the period 1890-1921. This form of demographic pressure has a parallel with the adjustments set in motion late in the 1960s by the entrance of the post-WW II "baby boom" cohorts into the American labor market.

A further, sixth parallel emerges from re-estimates of earlier manufacturing labor productivity and total factor productivity in the U.S. (See Table 2 and Figure 4a.) These have revealed a marked slowing of growth during 1888-1907. Seventh, this retardation in industrial productivity growth was echoed in the virtually constancy of wage rates in manufacturing relative to the wholesale prices of industrial products. (See Figure 4b, top chart) Inasmuch as the prices of industrial products dominated the movements of the wholesale price index used by Douglas (1927) to deflate wage rates in manufacturing, the index of real unit labor costs that is graphed in the top panel of Figure 4b could be taken to reflect the time-pattern of changes in the marginal productivity of labor--at least for cost-minimizing firms operating in competitive markets.⁸ Hence, such quantitative indications as have been provided by Rees (1961) to the effect that material standard of living of manufacturing wage-earners was actually improving during 1890-1914

⁸ One may note (from comparison of the middle and upper panels of Figure 4b) that the average wage rate in services declined vis-a-vis that in manufacturing, because the price deflator used by Douglas (1927) was the same for the two sectors. But, by the same token, the interpretation of the real wage series for service sector workers as a real unit labor cost index is less justifiable than is the case for manufacturing.

(see Figure 4b, bottom chart), hinge on the divergence in that period between the movements of wholesale prices and those of a carefully reconstructed (NBER) consumer price index. It turns out to be the sluggish movement of items such as rent, and shrinking real margins in retailing, that cause the NBER real wage series to show an upward trend for manufacturing workers over the 1890-1914 period.

One might very well continue on in the same vein, and comment on the rise of finance capitalism around 1900, when attention turned increasingly towards ways to make money by arranging mergers among existing enterprises and selling their stock to the public, rather than through commercial exploitation of technological improvements or marketing innovations (See Nelson (1959:pp. 5, 29).) Equally reminiscent of the present, there was an impending change among the rich nationals of the world in the locus of industrial and economic "leadership"--as the U.S. index of per capita real gross domestic production forged ahead of that of the corresponding index for Britain. But, surely, my point already is made. The outward facts conform to the condition that could be described, in the immortal words of the New York Yankees' great baseball catcher, Yogi Berra, as a classic case of "deja vu all over again." The surface resemblance is at least sufficiently arresting to suggest that it may be rewarding for economists and others to look back more closely at the historical experience of the "dynamo revolution" when thinking about the future of information technology and its applications.

4. The Dynamo Revolution (Briefly) Reconsidered

The detailed story of the progress of electrification (see, e.g., Byatt (1979), Hughes (1983), Minami (1987)) offers ample evidence illustrating and elaborating upon the points that Freeman and Perez (1986) have stressed in suggesting that productivity could remain sluggish because the emergence of information technology as the basis for a new techno-economic regime is likely to be an uncertain, quite protracted, and historically contingent process.

The basic breakthroughs which raised the energy efficiency in electricity generating to levels where commercial application became feasible occurred during 1856-1880 (see Figure 3 and 5). Between 1880 and 1893 direct

current had been displaced as the standard for electricity network construction, the new polyphase alternating current had emerged after 1887 as the basis for a universal supply system--abetted by the role of rotary converter in offering a "gateway" through which d.c. traction and lighting systems could be assimilated and served as parts of larger generation and transmission networks (see David (1987) and David and Bunn (1988)). Widespread deployment of the new technology, however, still had not occurred some twenty years later. Available measures of the extent of diffusion reveal the still quite limited degree (proportionate measures are under 5 per cent) to which electrification had penetrated manufacturing establishments and residential dwellings in urban and rural America at the beginning of this century. These provide a perspective quite different from the impressions conveyed to visitors at the Paris 1900 Exhibition (see statistics in Table 3). The case of the dynamo therefore suggests then that when considering technological paradigm shifts that have the potential to create the core of a new technological regime, a time scale as long as 40-50 years may be at least what is required for the full impact on the growth of productivity to register itself in the conventional indicators.

A simple, heuristic model (see Appendix, esp. Table A1) exhibits the relationships between the extent of diffusion of a labor-saving technology and the growth rate of average labor productivity. Contrary to unschooled intuition, there is a tendency for the productivity growth rate to reach its maximum only after the inflection point of a classic, logistic diffusion path has been passed. In Figure 9, the curve labelled "phi-1" shows the effects on aggregate industry labor productivity growth of the diffusion of a new technology that is characterized by a fixed, temporally invariant advantage in terms of labor productivity. This tendency is reinforced where the new technology itself undergoes improvements of its relative efficiency with respect to labor use--improvements that depend directly and indirectly upon the extent of its adoption. (See the curve labelled "phi-2" in Figure 9.)

Such was the case historically with the early twentieth century electricity supply systems that exhibited (a) technical scale economies, (b) economies of functional specialization (the training of a workforce), (c) network scale economies achieved through load balancing, and (d) a range of "learning" effects whose impacts upon operating and construction economies were enhanced by the expansion of more standardized central station and

transmission network designs. Similar endogenous efficiency gains, tied to the extent of diffusion, were eventually realized by the electrical manufacturing industry in the U.S., which took an active role in fostering standardization of system parameters (such as a.c. cycle frequencies) and equipment specifications--ostensibly for the purpose of achieving economies of scale in manufacturing.⁹

Figure 10 shows how a conventional calculation of the TFP residual for the industry would look, if the "improvements" of the new technology augments "capital" as well as "labor" at the same rates: this is the assumption of Hicks neutrality of improvements on the basic innovation, for which the TFP rate is given by $[A^*|HiN]$. The alternative assumption of Harrod neutrality in the endogenous improvements, confining the latter to affect only the productivity of labor employed on the new technology, naturally yields a somewhat lower aggregate TFP residual (given in Table A1 as $[A^*|HaN]$). But, like its Hicksian counterpart, this rate rises to attain its maximum only when approximately 70 percent of aggregate output is being produced using the new technology.

There is, however, a dark side to be seen in this conceptualization of secular diffusion as a positive feedback process: the same nexus that binds the process of technology adoption together with that of technology elaboration and incremental efficiency improvements, can leave each hostage to delays or impediments in the other. Thus, if producers of capital equipment embodying new technologies avail themselves of patent protection to extract higher profit margins, installations of such equipment will be curtailed. One likely consequence is that there will be fewer firms than otherwise, among the population of potential users of the new technology, who would be acquiring experience in installing that particular type of equipment, or in a position to add to the pool of managers and workers trained to operate it.¹⁰ Many

⁹ See David and Bunn (1988)). Standardization, as a route to cost reduction, was also promoted actively by leading entrepreneurs in the electrical utilities industry, such as Samuel Insull (see MacMahon (1984: pp. 88-89)).

¹⁰ MacMahon (1984: pp. 104-05) points out that early in the present century the electrical power companies in the U.S. had very few electrical engineers, or operating personnel with a thorough technical grasp of power station technology, and thus were obliged to rely entirely upon the engineering expertise of the constructors and vendors of electrical apparatus and systems.

other considerations that, similarly, would impinge adversely upon microeconomic decisions to invest in durable structures and equipment required to implement the new technological paradigm--such as the (anticipated) risks of technical or economic obsolescence, uncertainties about which particular variant designs would emerge as industry-wide standards, institutional or legal problems encountered in arranging financing of novel capital assets, and other, still more extraneous influences that slowed the pace of adoption--could result in positive feedbacks that reduced the rate of endogenous improvement in the technology, thereby blunting one the forces driving the diffusion process itself. (These points receive further discussion and formal treatment in David (1986), and David and Olsen (1986).)

As important as it will be for us to try to trace how the diffusion of electric power, and its eventual thorough permeation and transformation of manufacturing activities, came to be translated into a great surge in measured industrial productivity growth rates, it remains just as important to first grasp some of the special the reasons why substantial industrial productivity increases were not recorded at earlier stages of the factory electrification process in the U.S. Part of the delay in the exploitation of the potential industrial productivity gains offered by the dynamo, of course, was due simply to the durability of old manufacturing plants embodying technology adapted to the regime of mechanical power derived from water and steam. Thus, it tended to be those branches of industry that were undergoing most rapid expansion in the early twentieth century--tobacco, fabricated metals, transportation equipment, and electrical machinery itself--that afforded greater opportunities for the construction of new, electrified plants along the lines recommended by progressive industrial engineers (see DuBoff (1979: p. 142; compare Table 5, col.4, above, for the high degree of electrification achieved by the latter three industries as of 1919).¹¹

¹¹ To further emphasize this basic point that high rates of net capital formation are likely to generate positive "vintage effects" on productivity by lowering the mean age of the capital stock, without requiring any alteration in industries' replacement policies, it may be observed that this form of what Alexander Gerschenkron (following Thorstein Veblen) referred to as "the advantages of backwardness" favored more rapid electrification of manufacturing in Japan vis-a-vis the U.S. In Japan the share of primary power capacity in manufacturing

The persistence of durable industrial facilities embodying older power generation and transmission equipment had further consequences that are worth noticing. During the early phase of the factory electrification movement in the U.S. when the "group drive" system of power transmission remained in vogue--a phase shown by Figure 6 to have extended from the mid-1890s to the eve of the 1920s--the retrofitting of existing plants typically entailed adding primary electric motors to the existing stock of equipment. According to Duboff (1979: p. 144):

"At this early stage, the innovating plants usually kept their systems of belts and shafting and installed electric motors to drive separate shafting sections hooked onto machine counter and jack shafts. Each motor, mounted a short distance away, would drive related groups of machines. This 'group drive' at first proved cheaper than installing a complete system of electric motors on each machine ('unit drive'), since the steam engine and shafting could be retained. Both initial investment and costs of abandonment could be avoided."

While factory owners rationally could ignore the sunk costs of the existing power transmission apparatus, and simply calculate whether the benefits in the form of reduced power requirements and improved machine speed control justified the marginal capital expenditures required to install the group drive system, productivity accountants have to reckon that the original belt and shaft equipment, and the primary engines that powered them, remained in place as available capacity.

The effect, of course, would be to contribute to raising the apparent (and actual) capital-output ratio in manufacturing during the first two decades of the twentieth century, thereby raising labor productivity without doing anything appreciable for total factor productivity. This sort of doubling-up, or overlay of one technical system upon a pre-existing stratum, is not at all unusual during historical transitions from one technological paradigm to a new one. When steam engines first began to be installed at cotton-spinning mills in England during the closing decades of the eighteenth

establishments represented by electric motors rose from 0.9 percent in 1904, to 51.1 percent in 1919; whereas, for the U.S. the corresponding figures for those dates were 3.3 percent and 31.6 percent. Moreover, at the level of the individual branches of manufacturing in each case, save for the printing and publishing industry, the date at which electric horsepower capacity exceeded the power capacity represented by steam engines came earlier in the twentieth century in Japan than was the case in the U.S. See Minami (1987: pp. 139-140 and Tables 6-8, 6-9).

century, they often were employed not directly as the source of mechanical drive, but, as "returning engines" which lifted water back up to the top of a water-wheel that would turn the factory drive shafts and gears with the requisite degree of regularity (see, e.g., von Tunzelmann (1978: pp. 142-43, 171-72)). Indeed, the same phenomenon has been remarked upon recently in the case of the computer's application in numerous data processing and recording functions, where old paper-based procedures are being retained alongside the new, microelectronic-based methods--sometimes to the detriment of each system's performance.¹²

Another cause of the reason for delay of substantial measured productivity growth until the industrial electrification boom of the 1920s lies in the nature of the new products, and the process applications that tend to be found for an emergent general purpose technology during the initial phases of its development. In this regard, again, one may find some counterparts of problems frequently mentioned today in connection with the suspected impact of the computer: (1) unmeasured quality changes associated with the introduction of novel commodities, and (2) the early bias of the new technology toward enhanced production of goods and services had previously gone uncaptured by the conventional production or consumption statistics. Exemplifying this in the case of the dynamo, are the initial applications made prior to 1914 in the fields of lighting equipment, and urban transportation. Qualitative characteristics such as brightness, ease of maintenance, and fire safety were important features of incandescent lighting. Analogously, one can point to the convenience of faster trip speeds and shorter passenger waiting times afforded by electric trams--saving the urban workingman from 30 to 45

¹² Baily and Gordon (1988:pp.401-02) cite, as an instance, a situation that is said to exist in some retail banking operations, where the difficulties caused by trying to tailor available standard computer software packages to fit their idiosyncratic operating procedures have led many banks to retain the pre-existing paper-based recording system while introducing the new methods in parallel. In this case, unlike the illustrations from the steam and dynamo revolution, the dual system has been observed to possess some distinctly dysfunctional modes. For example, when a bank account is closed by making computer entries and by having paperwork processed at the head office, it is quite possible that by the time the paperwork is completed the computer will have charged a new service charge to the account, and then refuse to close it because the balance is shown as being negative.

minutes per day, on average, not to mention the value of greater comfort whilst in transit (see Wright (1895: p. 350), Byatt (1979: pp.29-45)).¹³

There is an additional measurement problem to notice, one that may be more apposite to the case of information technologies than it was to the experience of the electricity supply and equipment manufacturing industries. The greater is the perceived capacity of an emerging generic technology to be widely applied, and to undergo sequential improvements in a variety of specific contexts, the greater is the inducement for intangible investments to be undertaken in exploratory uses prior to undertaking durable major commitments of resources to the implementation of the technology in one or another variant form. Figure 11 addresses this effect: "reculier pour mieux sauter." Indeed, it may be a fully rational private investment strategy to expend resources on a succession of learning trials, each requiring dropping back to a lower curve, without commitment of still further resources to full-scale implementation and a prolonged progress up one learning function. The objective is to develop a capability to evaluate and quickly implement an eventual dominant form of the technology. Thus, the prospects of radical enhancements of endogenous improvement opportunities in the future may engender a slower rate of realized efficiency advances in near term, and corresponding unmeasured intangible investments in keeping abreast of the evolving generic technology. In the case of factory electrification, the prospects for more far-reaching transformations of manufacturing processes, and promises that there would be successive advances in techniques for within-plant distribution of power via electrical wires (from line shaft drive, to group drive, to unit drive), may have encouraged experimentation with

¹³ In his concluding chapter on "The Ethical Influence of Machinery on Labor" Carroll D. Wright (1895: p.350) wrote: "Rapid transit, through the application of electricity to street cars, has in many cases added from one half to three quarters of an hour of the day to the workingman's available time. This is the influence of invention, and a moral influence, for it betters his condition, helps him to a higher plane, facilitates social intercourse, and in every way gives him better opportunities for enjoying all that belongs to his environment." It is not clear that all this social benefit would be captured by a calculation, such as that produced for the case of British electric trams by Byatt (1979: pp.39-40), in which passenger minutes saved per trip was assigned a shadow-value equal to one-third of the workingman's average rate of pay when employed. Even so, Byatt's calculations show that omission of this indirect benefit of the electrification of trams results in a 50 percent underestimate of the true social gains that were derived.

piecemeal installations of secondary electric motors in some shops and machine-rooms within existing establishments.

Beyond the conditions obtaining among the potential demanders of electrical equipment and electric power that militated against immediate rapid diffusion, there were forces operating with similar effect from the side of supply--that is to say, among the producers and vendors who formed the electrical manufacturing industry, and the public utility companies. Among the supply-side circumstances that had tended to slow the application of electricity across a wide range of industrial activities we should particularly notice the exercise of market power by members of the tight oligopoly that had been formed among the electrical manufacturers--indeed, in many lines of the business, a virtual duopoly, following the merger of Edison General Electric and Thompson-Houston into the General Electric Company in 1892, and the patent pooling agreement concluded between General Electric and Westinghouse in 1896 (see Passer (1972: Ch. 20). It is likely that the market structure among the equipment vendors worked to delay the decline of the relative prices of electrical apparatus up to 1900 (see Figure 12). Further, given the dependence of the utilities upon the electrical equipment manufacturers for cost-saving advances in technology, it contributed to slowing the fall in the real costs of electricity to consumers, thereby delaying the process of electrification in the U.S. until late in the first decade of this century (see Table 4 and Figure 13).

It was not until 1907-17 that electric power costs to industrial users underwent a dramatic fall (see Figure 14). The latter period immediately followed the spread of "consolidated" electric utilities organized on the pattern pioneered by Samuel Insull, president of the Chicago-based Consolidated Edison Company, and the related establishment of regional regulation of the electricity utility industry (see Hughes (1983:Ch. 7), MacDonald (1962), MacMahon (1984:pp.102-16)). Only thereafter did the extent of the electrification of direct mechanical drive in manufacturing establishments approach the halfway mark, setting the stage for the turbulent developments of the 1920s, when the promise of productivity-enhancing factory electrification at last began to be widely realized.

5. Factory Electrification, the Unit Drive, and the Industrial TFP Surge

The initial phase of factory electrification, up to about 1907, had seen the installation of generators for lighting, and the replacement of steam engines with one or more electric motors functioning as prime movers. These developments left the intra-plant power transmission system based on line shafts and belt drives essentially unchanged, which greatly eased the introduction of electricity in some form into existing manufacturing facilities. But, by the same token, the new technology's impact was closely circumscribed because partial electrification left the fundamental problems of mechanical power distribution unaddressed, namely, the large friction losses in the system and the necessity of turning all the shafting in the plant regardless of the number of machines in operation (see Devine (1983)).

During the 1890s most engineers in the U.S. advised against running any but the largest machines with individual electric motors, mainly because the power capacity required to drive a group of machines (from a short line shaft, a practice called "group drive") was much less than the sum of the capacities required to drive each machine separately. By the middle of the following decade, however, the consensus of informed opinion had shifted to the view that individual (or "unit") drive eventually would become the dominant method for driving nearly all large tools, and there were enthusiasts who projected visions of a time ("soon") when the individual drive would be adopted for even very small machines (Devine (1983:p.362)). The advantages of the unit drive for factory design were manifold, extending well beyond the savings in inputs of fuel deriving from dispensing with the need to keep all the line shafts turning, and the greater energy efficiency achieved by reducing friction losses in transmission. This was remarked upon by an engineer for an American electrical equipment manufacturer, writing as early on in the diffusion process as 1901:¹⁴

"There were many factories which introduced electric power because we engaged to save from 20 to 60 percent of their coal bill; but such savings as these are not what has caused the tremendous activity in electric power equipment that is today spreading all over this country [sic]...those who first introduced electric power on this basis found that they were making other savings than

¹⁴ F. B. Crocker (of the Crocker-Wheeler Electric Company), "The Electric Distribution of Power in Workshops," Journal of the Franklin Institute, 151 (January, 1901):p.8, as quoted in Devine (1983:p.364).

those that had been promised, which might be called indirect savings."

In the short run, the additional, "indirect" gains came from: (1) reduced labor requirements for oiling and maintaining the old belt-drive apparatus; (2) better utilization of labor and materials through rationalization of work-flow and reduced requirements for materials handling, which was made possible due to the greater flexibility of factory lay-outs when the latter were freed from the constraints formerly imposed by the requirement of orthogonal placement of drive-shafts and machinery; (3) improved machine control leading to increased in output quantity and quality, which was achieved by eliminating the problem of belt slippage (which caused the speed of some machines to vary with load), and by taking advantage of the ease with which desired alterations in machine speed could be made by using direct current motors.¹⁵

Over the longer-run, in which re-design of the entire factory structure itself would become a relevant consideration, indirect economies were derived from the elimination of the need for bracing to support the heavy shafting and belt-housings for the power transmission apparatus (typically mounted overhead). This afforded (4) savings in fixed capital through lighter factory construction, and (5) further capital-savings deriving from the possibility of building single-story plants, whereas the aim of reducing the power-losses in turning very long line shafts had formerly dictated multi-story structures. Single-story, linear layouts of factories, in turn, permitted (6) closer attention to optimizing materials handling, and flexible reconfiguration of

¹⁵ According to Devine (1983:p. 366), up to 1900 virtually all industrial electric drive was powered by d.c. motors, which typically were shuntwound machines offering speed variations over a range of 3 or 4 to 1 simply by rheostatic control. Use of a gearbox afforded a still wider range. The alternating current polyphase motors introduced subsequently (after Tesla's invention of the induction motor in 1887) had several advantages in factory power applications--principally, in being smaller, lighter, and sparkless. But, their speed (being governed by the frequency of the current, rather than the voltage) could not be varied without seriously degrading their performance. Devine (1983:p.367) advances the interesting conjecture that the early twentieth century trend in manufacturing engineering towards the use of special purpose machine-tools, which reduced the need for a large range of speed control, may have been induced by the emergence of universal electricity supply networks standardized on alternating current, and the consequent impetus toward installation of unit drive systems with a.c. motors. See David (1987), and David and Bunn (1988), for other implications of the difference between the operating characteristics of d.c. and a.c. motors.

machine placement and handling equipment to accommodate subsequent changes in product and process designs within the new structures. As a related consideration, (7) the modularity of the unit drive power system, along with the flexibility of wiring, curtailed losses of production during retrofitting of plants, since the entire power system did not have to be shut down in order to carry out maintenance and replacement of some of the machinery.

There were still other advantages that were more qualitative in character, or at least likely to affect costs and conventional productivity measures only indirectly. These included: (8) lighter, cleaner factories, made possible by the introduction of skylights where formerly overhead transmission apparatus had been installed, and through the elimination of the myriad strands of rotating belting that previously swirled dust and grease through the air; (9) greatly reduced risks of fire, particular catastrophic fires spread from floor to floor via the flues formed by the openings left in ceilings to accommodate the passage of belting; (10) reduced risks of worker injuries from moving belting, or lower costs of achieving shop-floor safety by installation of screens and housings around the mechanical power transmissions apparatus.

As Devine (1983) has shown, all this was understood in principle and anticipated in the writings and speeches of far-sighted (possibly presbyopic) electrical and mechanical engineers in the U.S. before the end of the nineteenth century. Yet, the implementation required working out the details in the context of new industrial plant, and it was not until the 1920s that these potential advantages of the unit drive system came to be fully exploited in typical manufacturing facilities. Whereas the overall extent of electrification of total mechanical drive (horsepower capacity) in U.S. factories rose by approximately 25 percentage points in each of the decades 1909-19 and 1919-29, the penetration of secondary electric motors in manufacturing establishments--reflecting adoption of the unit drive system--was particularly concentrated in the latter decade (see Table 3, cols. 1, 2). Between 1919 and 1929 the fraction of total direct drive horsepower capacity in manufacturing that was represented by secondary electric motors surged upwards from 0.326 to 0.564, accounting for more than three-fifths of the increase that was recorded over the two decades following 1909.

That there was a close connection between the foregoing technical developments related to factory electrification and the marked surge in the

aggregate TFP growth rate in U.S. manufacturing during the period 1919-29 (see Table 2) has been suggested by a number of writers (see e.g., Schurr and Netschert (1960), DuBoff (1966, 1967, 1979), Devine (1983), Woolf(1984)). Previous studies have either not attempted, or not succeeded in providing more empirical substantiation for the argument, by pinning down the quantitative relationship between factory electrification and productivity gains in a cross-section study of industries.¹⁶ One reason why this relationship may have appeared elusive to earlier investigators may be the reliance that has been placed upon (Kendrick's (1961)) productivity measures for manufacturing industries that have been estimated on a value added basis (real value added per unit of labor and capital input), rather than on industry level measures that made allowance for the effects of changes in the relationship between the quantities of (gross) output and purchased, intermediate inputs. The lack of correlation between the alternative estimates of the acceleration of industrial productivity growth during the 1920s, corresponding to those differing conceptual bases, may be seen by comparing the first two columns of Table 5.

Nevertheless, a significantly positive association did exist during the 1920s between the proportionate increase in secondary electric motor capacity and the rise in that decade in Woolf's (1984) estimates of the industry's total factor productivity growth rate adjusted for energy inputs, as is virtually self-evident from inspection of columns 2 and 3 in Table 5. For the 15 industries involved, a simple linear (OLS) regression of the latter variable on the former, confirms the statistical significance of the relationship, and accounts for approximately 25 percent of the cross-section variance.¹⁷

It would be too extreme and simplistic a view, however, to attribute everything that happened to the growth rate of manufacturing productivity in

¹⁶ The one attempt explicitly reported, by DuBoff (1979: Ch.7, sought to link electrification to the growth of the average productivity of capital, and was inconclusive in its findings.

¹⁷ The regression results are as follows:

$$\text{ACCEL} = 0.226 + 1.211 \text{ CHSEMHP}, \quad R^2(\text{adj.}) = .251; \quad F(1, 13) = 5.68,$$

$$(0.973) \quad (0.508)$$

where standard errors of the coefficients are shown in parentheses, and the variables ACCEL and CHSEMHP correspond to those defined in columns 2 and 3 of Table 5, respectively. At the 95 percent confidence level the critical value of $F(1,3)$ is 4.67.

the 1920s to this one set of technical changes, far-reaching as they were. Certainly, the simple cross-section regression relationship that has been identified as holding within the manufacturing sector only could explain half, at most, of the approximate 5 percentage point acceleration in the average annual rate of aggregate industrial productivity growth for the 1920s.¹⁸

¹⁸ This assertion is based on a comparison of the change in the annual average rate of industrial productivity growth rate (ACCEL) that is predicted by the cross-section regression equation in the previous footnote --when the ratio between installed secondary electric motor horsepower capacity at the end of a decade and that at the decade's beginning (i.e., CHSEMHP) is 1.81. The latter is the ratio found for the aggregate of U.S. manufacturing establishments in 1929, relative to 1919, according to DuBoff (1979: Table 13, p. 58). The predicted acceleration works out to be 2.42 percentage points. From Table 2, column 4 (above) it is seen that between 1909-19 and 1919-29 the TFP growth rate accelerated by 5.12 percentage points. The fraction 2.42/5.12 is rather less than one-half.

The denominator in this, however, derives from a net output (real value added) index divided by an index of (geometrically weighted) labor and capital inputs; it makes no allowance for intermediate inputs purchased outside the manufacturing sector, whereas such allowance is made (at least for purchased energy) in the data underlying the regression variable ACCEL, as is noted in Table 5. Maintaining the standard assumptions it is possible analytically to relate the rate of total input productivity growth, denoted here by a_T , to the net output-based factor productivity (TFP) growth rate, denoted here by a_F , as follows: $a_T = (1-w_M)[a_F + (g - n)] + w_M(g - m)$, where, w_M is the share of purchased inputs, g , n , and m , are the rates of growth of real gross output, real net output, and the volume of purchased intermediate inputs, respectively. When the proportions between net output, intermediate inputs and gross output are fixed, it is obvious that total input productivity for an open sector must be growing less rapidly than TFP. Those simplifying assumptions do not hold in the present case, and, moreover, what we are interested in is whether the decade-to-decade change in a_T is overstated or understated by the estimated acceleration of a_F . Rather surprisingly, the best estimates I have been able to make of total input productivity growth (that allow for changes in the use of purchased intermediate inputs) in the manufacturing sector turn out to yield approximately the same (5.3 percentage point per annum) acceleration for the 1920s compared with the preceding decade.

The reason is that, according to estimates made by Kendrick (1961: Table D-6, p. 426) for U. S. manufacturing, the magnitude $(g-n)$ was negative in the decade 1909-1919 and positive during 1919-29, showing an acceleration of 3.92 percent points. The slowing growth in purchases of electric power by manufacturing appears to have contributed a subsidiary amount to the same effect. Although corresponding estimates for the magnitude $(g-m)$ are not available, it may be noted that if-- apart from energy input purchases--inputs purchased outside manufacturing grew in strict proportion to gross output of the sector, there would have been a slight acceleration, amounting to 0.33 percentage points in the magnitude $(g-m)$, during the decade 1919-29. (This is based on comparison of the gross output index from Kendrick (1961: p. 426), and figures for purchased power consumption in manufacturing derived from DuBoff (1979: Table 20, p. 80), allowing purchased power a weight of .067 in all purchased intermediate inputs. The latter is consistent with the value posited for $w_M = .45$, given the share of labor in value added as 0.75 from Kendrick (1961: Table D-14, p.543) and the estimate derived from DuBoff

Hence, there must have been other proximate sources for the apparent temporal correlation observed at the level of the aggregate manufacturing sector, between the rising stock of secondary electric motors associated with the diffusion of the unit drive system and the surge in industrial productivity.

We should therefore pause long enough to notice the contributions that were being made during this era by the capital-saving effects of the technological and organizational innovations that underlay the growth of continuous process manufacturing and the spread of continuous shift-work, most notably in the petroleum products, paper, and chemical industries (see Lorant (1966: Chs.3, 4, 5). The 1920s brought major technological breakthroughs to the first two among this trio of industries, in the form of thermal cracking processes for batch and continuous flow refining operations, and the automatically electric sectional machine drive (resulting in enormously higher speeds of Fourindier machines), respectively. The rise of new, organic chemical products, such as plastic-housed radio sets, quick-drying synthetic lacquers for auto paints, coal tar dyes for textiles, and the increasing popularity of rayon, and synthetics of all kinds, fostered the creation of an entire branch of the chemical industry that had not existed in the U.S. prior to WW I. These new products called for the installation of new chemical plants, facilities that gave fullest scope for the implementation of the latest principles of continuous processing, in which the importance of automatic control was quickly recognized. As early as 1922, the American Chemical Society held a portentous symposium on automatic process control; and by 1929 a trade journal devoted to chemical and metallurgical engineering was able to report that:

"just as CONTINUOUS PROCESSING is everywhere replacing batch handling as soon as it can be applied profitably, automatic control is taking the place of manual operation as rapidly as it proves itself."¹⁹

(1979: Tables E-20, E-21) that purchased electric power costs were .025 of the manufacturing wage bill in 1929.) The adjusted estimate for ACCEL that emerges from all this is: $(5.12 + 3.92)(.55) + (0.33)(.45) = 5.3$.

¹⁹ Quoted from "The Unit Processes and Automatic Control", Chemical and Metallurgical Engineering, 36 (April, 1929), p. 252, by Lorant (1966: p. 187). The Automatic Process Control Symposium at the 64th Meeting of the American Chemical Society, held in Pittsburgh, Pennsylvania, September 4-8, 1922, was reported by the Journal of Industrial and Engineering Chemistry, 14 (November, 1922).

But even these developments, which did not involve the replacement of shafts by wires, were not untouched by the dynamo revolution. Quite additional to the fact that automatic process control engineering made use of electrical instrumentation and electro-mechanical relays, electrification was a key complementary element in the foregoing innovations if only because pulp- and paper-making, chemical production, and petroleum refining, like the primary metals, and the stone, clay and glass industries--where there were similar movements towards electrical instrumentation for process control, and greater intensity in the utilization of fixed facilities--also were branches of manufacture that made particularly heavy use of electricity for process heat (see Jerome (1934: pp. 62-63, 252-253; DuBoff (1979:pp. 179-181).

More generic productivity-enhancing consequences of the expansionary macroeconomic environment of the 1920s must also have played a part in the productivity surge, as existing industrial facilities, and fixed elements of the supervisory and clerical workforce, came to be more fully utilized. The much more scrupulous attention being given to the efficiency with which the work-process was organized, signalled by the post-WW I fusion of Taylorism with Fordism, drew some of its impetus from the emergence of rising expectations regarding the level of real unit labor costs, which also tended to favor further capital-labor substitutions through greater mechanization. Those expectations, which (as Figure 4a shows) were realized in the course of the boom of the 1920s, should be linked not only to the rise of "business unionism" in the trade union movement, but, more deeply, to the changes of national policy that had put a permanent end to the epoch of free immigration.

6. Conclusion and the Limits of Historical Analogy

My conclusions are summarized simply enough. Our present situation is not unprecedented, if we take the suitably long view. There are indeed some remarkable resemblances between the recent phenomena of "the productivity paradox" attending the onset of the computer revolution, and an historically distant constellation of economic and technological developments observable around 1900. At that time the leading industrial countries were experiencing the early phases of their transition from an industrial regime based on steam to the one that was being built up around electricity; but, in the United States, as well as in Great Britain, the decades surrounding the turn of the

century were marked by greatly retarded rates of industrial productivity advance.

Initial applications of electricity to lighting and traction power for urban transportation systems involved substantial qualitative improvements of the outputs involved, and, undoubtedly, contributed significantly more to the growth of economic welfare than is revealed by the conventional measures of real product and productivity available for the era 1890-1914. By the end of that period, however, in the U.S. and Germany there had already emerged the technological paradigm of universal electrical supply systems designed to cut costs by means of load-balancing over geographically extensive territories while achieving ordinary economies of scale in generation at large central stations. Following WW I the eventual reduction of the cost of this form of power to industrial users promoted widespread electrification of American manufacturing facilities and, in particular, the adoption of the unit drive. As engineers had foreseen in the late 1890s, the changes that were eventually implemented a quarter of a century later permitted a thorough rationalization of factory construction designs and internal layouts of production lines and materials handling techniques, thereby raising the measured efficiency of labor and capital inputs in many established branches of manufacturing.

Thus, the full transformation of industrial processes by the new power technology was a drawn out and by no means certain affair. It did not reach full fruition until more than half of factory mechanical drive capacity had been electrified--a stage that was attained only some forty years after the first central electric power stations began operating in New York and London. When it finally came, however, the delayed payoff was very palpable in the U.S.: the acceleration of manufacturing labor productivity and total factor productivity growth after 1919 was quite marked, correlated with the more intensive use of secondary electric motors, and was the main proximate source of the quickening pace of total factor productivity growth observable in the economy as a whole.

There is a generic message in the foregoing account of the contingencies and delays in the interactive dynamic of diffusion and elaboration, whereby a complex, interrelated technological system was created around a new, general purpose engine. Familiarity with the story of the dynamo revolution may thus serve as a useful antidote, to counteract the worst excesses of technological presbyopia concerning the computer revolution. The latter condition has a

dual manifestation. There is, on the one hand, the buoyant conviction that we are embarked on a pre-determined course of diffusion, leading swiftly and inexorably toward the successful transformation of the entire range of productive activities in a way that will render them palpably more efficient; and, on the other hand, there is the depressing suspicion that something has gone terrible awry, fostered by the disappointment of premature expectations about the information revolution's impact upon the conventional productivity indicators and our material standard of living. But, closer study of some economic history of technology should help us to avoid both the pitfall of undue sanguinity and the pitfall of unrealistic impatience as we proceed on our journey into the information age.

Some caution is nevertheless warranted, lest one fall prey to the errors of overly literal analogizing. Computers are not dynamos. The nature of man-machine interactions and the technical problems of designing efficient interfaces for humans and computers are enormously more subtle and complex than those that arose in the implementation of electric lighting and power technology. Moreover, information as an economic commodity is not like electric current. It has special attributes that make direct measurement of its production and allocation very difficult and reliance upon conventional market processes very problematic.

For one thing, information lacks the property of super-additivity: the quantitative analyst cannot meaningfully suppose that what one sector or industry uses will not be available for use by others. Another thing about information is that, in comparison with the cost of generating it, the direct marginal cost of its transmission are negligible. Consequently, in some cases its ability to generate a stream of economic rents must be preserved by the maintenance of secrecy--a contrived limitation on its distribution. To operate efficiently information networks may have to compromise the security of the information itself, and therefore jeopardize the value of their products. Such problems are not encountered in arranging the distribution of electricity, or natural gas, much less ordinary commodities produced by agriculture or industry.

Information is different, too, in that it can give rise to "overload", a special form of congestion effect arising from inhibitions on the exercise of the option of free disposal, which is usually presumed to characterize standard economic commodities. Negligible costs of distribution are one cause

of "overload"; information transmitters are encouraged to be indiscriminant in broadcasting their output. At the user end, free disposal may be an unjustified assumption in the economic analysis of information systems, because we come from cultures that value previously scarce information and have been taught the desirability of screening everything. (What else is the content of the injunction not to judge a book by its cover?) Screening is costly, however, so that while this form of consumption raises the risk averse information recipient's personal welfare, too much of this commodity can interfere with the measurable production of goods and services. Few other goods suddenly turn into "bads" in this way; we typically think of valuables as being distinct from junk, but now are having to learn to cope with "junk mail", "junk phone calls", and even "junk FAX".

It may be thought that the information structures of firms--the nature of the data they collect and generate, the way they distribute it, and how it is processed for interpretation--are closely analogous to the physical arrangement and materials flow patterns of production and transportation systems. In one sense they are; they do represent sunk fixed costs, and the variable cost of using them does not rise as they age. Unlike those conventional structures and equipment stocks, however, information structures per se do not automatically undergo significant physical depreciation--even though the magnetic storage medium used with electronic and microelectronic devices may deteriorate; and such structures may, of course, become economically obsolete, in the sense of no longer being worth maintaining. But, one cannot count on the mere passage of time to eventually provide an opportunity to radically redesign the information structure, and operating mode of an enterprise--in the way that one can count upon the deterioration of structures and equipment to provide an occasion to replace them with capital assets embodying, or facilitating a more efficient organization of production. Consequently, there is likely to be a very strong inertial component in the evolution of information-intensive production organizations.

Yet even these cautionary qualifications seem to serve only to further reinforce one of the main thrusts of the dynamo analogy. They suggest the existence of special difficulties in the commercialization of novel information technologies that have to be overcome before the mass of information users can benefit in their roles as producers.

Table 1

Manhour Productivity and Total Factor Productivity Growth Rates:
U.S. (Private) Domestic Economy, 1800-1967 (in percent per annum)

Periods	<u>Abramovitz-David Estimates for:</u>				<u>Kendrick-Commerce Estimates</u>		
	<u>Domestic Economy</u>		<u>Private Domestic Economy</u>		<u>Private Domestic Economy</u>		
	Output per Manhour	Crude Total Factor Productivity	Output per Manhour	Crude Total Factor Productivity	Periods	Output per Manhour	Total Factor Productivity
1800-1855'	0.63	0.35	0.65	0.35			
1855-1871'	0.18	-0.23	0.18	-0.22			
1871-1890'	1.75	0.88	1.78	0.89	"1869-1890"	2.48	1.94
1890-1905'	1.32	0.83	1.34	0.84	"1890-1905"	1.44	1.27
					"1890-1912"	1.82	1.01
					"1912-1928"	2.34	1.72
1905-1927'	2.35	1.61	2.46	1.74	'1905-1927'	2.09	1.52
1927-1967'	2.47	1.86	2.76	2.09	'1927-1967'	2.73	1.93

Notes: Periods are as follows: '1800-1855'=-1800-1853/57; '-1871'=-1869/73; '-1890'=-1888/92; '-1905'=-1903/07; '-1927'=-1925/29; '-1967'=-1965/69. Alternative periods are "1869-1890"=1869-1889/91' "-1912"=-1911/13; "-1928"=-1927/29.

Sources: See Abramovitz-David (1973) and David (1977) for description of underlying estimates. "Crude" TFP estimates use manhours labor inputs, unweighted capital stocks, gross factor shares. See Abramovitz-David(1973) and Kendrick (1961), Tables A-XVIII, A-XI, A-XXII, for Kendrick-Commerce estimates shown here for '1927-1967', and "1869" to "1928", respectively.

Table 2

Average Labor Productivity and Total Factor Productivity Growth Rates:
U.S. Manufacturing Sector, 1869-1948, in percent per annum

Periods	Estimates based on Kendrick's Measures for Output & Inputs				Estimates based on Alternative Measures for Output Labor Inputs		
	($\dot{V}-\dot{H}$)	($\dot{V}-\dot{L}$)	(\dot{A}_a)	(\dot{A}_g)	($\dot{V}-\dot{H}$)	($\dot{V}-\dot{L}$)	(\dot{A}_g)
1869-1889	1.67	1.60	1.41	0.77	3.97	3.96	2.99
1869-1879	0.95	0.96	0.87	0.31	3.23	3.24	2.61
1879-1889	2.40	2.24	1.96	1.23	4.71	4.69	3.37
1889-1909	1.37	1.44	0.09	0.68	1.39	1.31	0.70
1889-1899	1.43	1.43	1.12	0.86	1.14	1.15	0.65
1899-1909	1.31	1.46	0.72	0.50	1.64	1.47	0.74
1909-1929	3.34	3.18	2.77	2.70			
1909-1919	1.15	0.82	0.29	0.17			
1919-1929	5.59	5.59	5.31	5.29			
1929-1948	1.76	1.61	1.76				
1929-1937	1.97	1.82	1.95	1.96			
1937-1948	1.56	1.39	1.56	1.56			

Key: Asterisked variables denote growth rates for gross product originating per man hour ($\dot{V}-\dot{L}^*$); growth rates for total factor productivity from arithmetic weighting of inputs (\dot{A}_a), and from geometric weighting of inputs (\dot{A}_g).

Sources: Kendrick-based estimates calculated from labor productivity and capital productivity data in Kendrick (1961), Table D-I, cols. 5,7,11. Table D-14 for decadal factor share weights, 1919-1948. For 1869-1919, the 1919-29 weights were used throughout.

: Alternative estimates calculated from Gallman (1966), p. 43 constant (1879) dollar value added for (V); manhours (H) from sectoral data underlying aggregate manhours in David (1977); (L) from adjustment of H by ratio of weighted labor inputs to manhours given by Kendrick (1960), Table D-I, cols. 6 and 4, respectively. The capital input estimates from Kendrick (1960), D-I, col. 8, and the alternative labor input estimates were geometrically weighted, using the invariant (1919-29 Kendrick (1960), Table D-14) weights .232 and .768, respectively.

Table 3

The Diffusion of Electric Power Applications in the U.S., 1889-1954

Measures of Proportional Extent of:

Year	<u>Factory Electrification</u>		<u>Household Electrification</u>			
	Electrification of Mechanical Drive in Manufacturing Establishments	Penetration of Secondary Electric Motors in Manufacturing Establishments	Electric Lightings of <u>Dwelling Units:</u> Urban Families	All Families	Electrical Appliance Penetration of <u>Dwelling Units:</u> Vacuum Cleaners	Mechanical Refrigerators
	(1)	(2)	(3)	(4)	(5)	(6)
1889	.003	.003	0	0
1899	.048	.030	.08	.03	0	0
1904	.115	.085				
1909	.247	.173	.33	.15	0	0
1914	.376	.252				
1919	.531	.326	.47	.35	.09	.005
1924	.671	.450			.16	.02
1929	.784	.564	.85	.68	.30	.08
1939	.861	.689	.96	.7944
1954	.865	.571	.97	.86	.54	.85

Notes and Sources: (1) Primary and secondary Electric Motor HPs as Proportion of Total Mechanical Drive (HPs) in Manufacturing. Calculated from Duboff (1979), Tables 13, E-6.

2) Secondary Electric Motor HPs as Proportion of Non-Electric Direct Drive HPs plus Secondary Electric Motor HPs. Calculated from Duboff (1979), Tables 13, E-6.

3),(4) Proportion of U.S. Dwelling Units wired for Electric Lighting, from Lebergott (1976), Table 15, p. 278.

5),(6) Proportion of U.S. Dwelling Units with Vacuum Cleaners, Mechanical Refrigerators, from Lebergott (1976), Table 17, p. 287. 1924 estimates geometrically interpolated; 1954 geometrically interpolated between observations for 1950 and 1960.

Table 4

Indexes of Real Cost of Electricity Supply in U.S., 1883-1950

Year	Inverse of Total Factor Productivity for Electric Utilities (Kendrick) Index 1900=100	Tons of Coal per Kwh Index 1900=100	Central Station Costs per Kwh relative to CPI Index 1900=100	All Residential Electricity Charge per Kwh relative to CPI Index 1900=100
1883	200.0	...	153.8	126.6
1890	160.0	...	130.8	116.4
1900	100.0	100.0	100.0	100.0
1910	80.0	60.0	80.0	49.4
1920	60.0	26.0	32.3	21.5
1930	32.0	22.0	23.1	19.0
1940	26.0	12.0	...	13.9
1950	24.0	7.0	...	6.3

Sources: Column (1): 1883-1929 from Orrok (1930: pp. 330-31); 1930-1950 from U.S. Hist. Statistics...to 1970, p. 826, in Lebergott (1984), p. 353.

Column (2): from Kendrick (1960), Table H-VI.

Column (3): 1883-1929 Central Station Costs (Orrok (1930)) from Lebergott (1984), p. 353, deflated by U.S. consumer price index from David and Solar (1977), Table 1.

Column (4): Average charge per Kwh for all residential consumers from U.S. Bureau of Census (1977), U.S. Historical Statistics...to 1976, Vol. I, p. 827, deflated by U.S. consumer price index from David and Solar (1977), Table 1. The relative price of residential electricity shown for 1900 and 1910 are based on the available observations for 1902 and 1912, respectively.

Table 5

The Growth of Secondary Electric Motor (Horsepower) Capacity and the Acceleration of Total Input Productivity in U.S. Manufacturing, 1919-1929

Industry	Percentage points of Change in Total Factor Productivity <u>Growth Rate from 1909-19 to 1919-29</u>		Ratio of Secondary Electric Motor HP Capacity in 1929 to that Capacity in 1919	Proportion of Primary HP Capacity Electrified in 1919
	Kendrick (1961) Estimates (unadjusted for energy inputs) (1)	Woolf (1984) Estimates (adjusted for energy inputs) (2)		
			(3)	(4)
Paper products	0.7	4.40	3.34	0.34
Leather products	2.4	4.30	1.02	0.74
Stone, clay, glass	5.0	4.10	2.42	0.54
Lumber products	3.7	3.42	2.83	0.19
Textiles	2.0	3.90	1.48	0.58
Chemicals	8.1	3.80	1.78	0.65
Petroleum & Coal products	9.6	3.20	2.91	0.57
Machinery, electrical	3.2	2.27	1.03	0.96
Iron and steel	6.0	1.60	1.99	0.37
Food products	5.7	1.60	1.45	0.47
Machinery, non-electrical	2.2	1.56	1.29	0.76
Nonferrous metals	2.3	0.60	1.14	0.85
Rubber	0.3	0.50	1.49	0.79
Printing and publishing	0.7	0.30	1.16	0.93
Transportation equipment	1.4	-0.60	1.45	0.86

Sources: (1),(2): From Woolf (1984), Table 2. Estimates in col. (2) for Electrical and Non-electrical machinery were obtained by combining Kendrick's figures using (value added) weights of .333 and .667, respectively, and finding Woolf's estimate for machinery to be 0.71 of the combined figure. The latter multiplier was used to scale down the col. (1) estimates. (3),(4): From Duboff (1979) Tables E-12c,d; Table 26, respectively.

Table A1

Simulated Time Paths for Growth Rates of Aggregate Average Labor Productivity (π^*) and Aggregate Total Factor Productivity (\dot{A})

Date	Diffusion: Model 1		Diffusion and Learning: Model 2			
	Extent of Diffusion	$\alpha = .381$	$\lambda = .110$ $\theta = 0$	$\alpha = .332$	$\pi_N/\pi_0 = 1.20$ at $D = .01$	$\bar{\omega}_N = 0.5$
t (years)	D(t) (output share)	$\pi_1^*(t)$ (percent)	$\pi_2^*(t)$ (percent)	$\omega_L(t)$	$[\dot{A}(t) HaN]$ (percent)	$[\dot{A}(t) HiN]$ (percent)
-42	.01	0.07	0.04	.995	-.01	-.01
-27	.05	0.33	0.28	.975	.01	.02
-20	.10	0.65	0.60	.950	.07	.09
-16	.15	0.96	0.93	.925	.16	.19
-13	.20	1.24	1.25	.900	.25	.29
-10	.25	1.51	1.56	.875	.33	.37
- 8	.30	1.75	1.85	.850	.41	.46
- 4	.40	2.17	2.37	.800	.52	.57
0	.50	2.46	2.77	.750	.70	.76
4	.60	2.60	3.00	.700	.78	.83
8	.70	2.52	3.00	.650	.80	.85
10	.75	2.38	2.89	.625	.77	.81
13	.80	2.16	2.66	.600	.72	.76
16	.85	1.83	2.30	.575	.63	.66
20	.90	1.38	1.78	.550	.48	.50
27	.95	0.78	1.04	.525	.28	.29
42	.99	0.17	0.24	.505	.07	.07

Sources: See Appendix A text for derivation of formulae:

$$D(t) = (1 + e^{-\lambda t})^{-1}$$

$$\pi_i^* = ([\beta(t)(1-\theta) + \theta] / [1 - \beta(t)D(t)]) (D(t)[1 - D(t)]\lambda) 100, \text{ where:}$$

$$\beta(t) = 1 - \alpha[D(t)]^{-\theta} \text{ and } \alpha = (\pi_0/\pi_N)(.01)^\theta, \text{ for } i=1, \theta=0, i=2, 0 < \theta < 1.$$

$$\omega_L(t) = 1 - D(t)[1 - \bar{\omega}_N]$$

$$[\dot{A}(t)|HaN] = [\pi_2^*(t)]\omega_L(t) - [1 - \omega_L(t)]\lambda[1 - D(t)]$$

$$[\dot{A}(t)|HiN] = [\dot{A}(t)|HaN] + \lambda\theta(1 - \bar{\omega}_N)[D(t)][1 - D(t)]$$

Technical Appendix A

Innovation Diffusion and Productivity Growth Rates: A Heuristic Model

A.0 Introduction

This appendix describes a simple model designed to show the direct and indirect effects of the diffusion of a "radical" or "fundamental" process-innovation upon the measured growth of input productivity. It is assumed that the innovation results in lower labor input requirements per unit of output, compared with a pre-existing technology, so that labor productivity in the industry, sector or economy into which it is introduced will be determined as the weighted average of the labor productivity levels characteristic of the new and old technologies, the weights being given by the extent of diffusion. By "direct effect" is meant the impact upon the aggregate level of productivity of a redistribution of production from the old to the new-style process, the latter being more efficient in its use of inputs. By "indirect effects" are meant the whole range of (positive feedback) consequences that more widespread use of the new technology has upon its relative level of productivity -- vis a vis the old technology-- in all applications.

For simplicity the main relationships posited here are of a reduced form nature; they do not exhibit the conditions governing decisions by producers to adopt the new technology, nor the decisions by suppliers of the new process-equipment to make available enhancements, nor the ways in which users acquire greater proficiency in application of the new technology. Consequently, the model showing

how the rate of diffusion (and the extent of diffusion at a specific point in time) will be related to the aggregate productivity growth rate does not exhibit the complex interdependence that may be supposed to exist between the rate of diffusion and the rate of endogenous improvement occurring in the new technology (see, e.g., David and Olsen (1986)).

A.1 The General Model of the Labor Productivity Growth Rate

The following notation refers to an industry, sector or economy producing a homogeneous output, V:

$\pi_j(t)$ is output per unit of labor input using the j-tu technique at time t, where $j = 0$ represents the "old" technique and $j = N$, the "new" technique; $\pi_N(t) \geq \pi_0(t)$ for all t;

$D(t)$ is the proportion of aggregate output produced using technique N, at time t;

$\pi(t)$ is aggregate labor productivity at time t;

$\pi^*(t) \equiv \partial \ln \pi(t) / \partial t$ is the (proportional) rate of change of the variable $\pi(t)$;

$$\pi(t) = [(1-D(t)) / \pi_0(t) + D(t) / \pi_N(t)]^{-1} . \quad (A1)$$

Assumption (1): $\pi_0(t) = \pi_0$ for all t.

This holds that the old technology undergoes no improvement or deterioration in its (fixed) unit labor input requirements. For simplicity we shall suppose the old technique uses only labor, so that π_0 cannot be affected by factor substitution.

Assumption (2): $\pi_N(t) = \pi_N(D(t))$, $\frac{\partial^1 \pi_N}{\partial D} > 0$, $\frac{\partial^2 \pi_N}{\partial D^2} < 0$.

This assumption posits an "improvement function" for π_N , s.t. labor productivity on the new technique will be increased as the process becomes more widely diffused, although such incremental enhancements predicated upon greater adoption are subject to diminishing marginal returns.

The general expression for the growth rate of labor productivity $\pi^*(t)$ in terms of $D(t)$ is found by first rewriting (A1) as

$$\pi(t) = \left[\frac{\pi_0}{1 - [\beta(t)]D(t)} \right], \quad (A2)$$

$$\text{defining } \beta(t) \equiv \left[1 - \frac{\pi_0}{\pi_N(t)} \right].$$

Then, differentiating (A2) with respect to t and multiplying through by $[\pi(t)]^{-1}$, we obtain:

$$\pi^* = \frac{d\pi}{dt} \frac{1}{\pi} \left[\frac{\beta(t)}{1 - [\beta(t)]D(t)} \right] \frac{dD(t)}{dt} + \left[\frac{[1 - \beta(t)] \epsilon(t)}{1 - [\beta(t)]D(t)} \right] \frac{dD(t)}{dt}$$

$$\text{defining } \epsilon(t) \equiv \frac{\partial \pi_N(t)}{\partial D(t)} \cdot \frac{D(t)}{\pi_N(t)}. \quad (A3)$$

In equation (A3) the first term on the R.H.S. gives the direct effect of diffusion, which is the total effect in the simplest case where neither the new nor the old technologies undergo any change in their respective unit labor input requirements, i.e., where $\epsilon(t) = 0$, and $\pi_N(t) = \pi_N(0)$ for all t . The second term on the R.H.S., obviously, gives the indirect effect of a change in the extent of diffusion on π^*

via the induced incremental improvement of the new technique's productivity in all uses.

A.2 The Lagged Impact of Diffusion in the Simple Model of Direct Effects

Imposing the restrictions $\epsilon(t) = 0$ and $\pi_N(t) = \pi_N(0)$, so that $\beta(t) = \beta > 0$ for all t , we obtain from (A3) the expression for the labor productivity growth rate where only the direct effect of diffusion is operating:

$$\pi_1^*(t) = \left[\frac{\beta}{1-\beta D(t)} \right] \frac{dD(t)}{dt}, \quad \beta > 0. \quad (A4)$$

From this it is evident that π_1^* is not simply proportional to the change in the extent of diffusion (dD), and so does not reach a maximum when $\frac{dD(t)}{dt}$ reaches its maximum. This is readily shown by

differentiating $\pi_1^*(t)$ with respect to time, whence we obtain

$$\frac{d\pi_1^*(t)}{dt} = \left[\frac{\beta}{1-\beta D(t)} \right] \left[\frac{d^2 D}{dt^2} \right] + (\pi_1^*)^2. \quad (A5)$$

When, at $\max \frac{dD}{dt}$, $\frac{d^2 D}{dt^2} = 0$, $\frac{d\pi_1^*(t)}{dt} \rightarrow (\pi_1^*)^2$. For the typical case \max

(dD) occurs in the interval between $D=0$ and $D=1$, so $[\pi_1^* | \max(dD)] > 0$, which implies $\pi_1^*(t)$ cannot be at a maximum. Since the term in brackets () on the R.H.S. of equation (A4) is increasing monotonically in $D(t)$, the $\max \{\pi_1^*(t)\}$ -point will occur at a time after $\max (dD)$ occurs.

A.3 Specifications of the Model

For computational convenience we can make the following specification assumptions:

Assumption 3: The diffusion path is logistic, with asymptotic saturation at $d(\infty) = 1$. This implies the following expressions for the level, and the absolute and proportional changes in $D(t)$:

$$D(t) = (1 + e^{-\lambda t})^{-1}, \quad \lambda > 0; \quad (A6)$$

$$\frac{dD(t)}{dt} = \lambda[1-D(t)]D(t); \quad (A7a)$$

$$\dot{D}(t) = \lambda[1-D(t)]. \quad (A7b)$$

Assumption 4: The endogenous "improvement function" for the new technology is characterized by a constant (less-than unitary) elasticity of response to the increased extent of diffusion:

$$\pi_N(t) = [\pi_N(o)] \left[\frac{(D(t))^\theta}{(\kappa)} \right], \quad 0 < \theta < 1. \quad (A8)$$

where κ is an arbitrary normalization constant.

It may be remarked that equation (A8) gives the "improvement function" the classic learning curve or "progress function" form suggested by Hirsch (1952) and Arrow (1962), if we interpret the extent of diffusion as an index of experience gained with the new technology. Such an interpretation would be straightforward when the innovation came embodied in infinitely durable machines of a fixed capacity, so that the proportion of output represented by the capacity of the new machine stock would vary directly with the cumulated output of the

industry supplying such equipment, and also with the cumulated volume of gross investment represented by those machines. However, the interpretation of the reduced form improvement function is meant to be more general and more comprehensive than the usual learning-by-doing and learning-by using formulations, as the text points out.

The foregoing specifications, in conjunction with equation (A3), lead to the following simulation equations for the direct and indirect effects combined:

$$\begin{aligned} \pi_2^*(t) &= \left[\frac{\beta(t)(1-\theta) + \theta}{1 - [\beta(t)]D(t)} \right] \left[D(t) [1-D(t)]^\lambda, \right] \\ \beta(t) &= 1 - \alpha [D(t)]^{-\theta}, \end{aligned} \quad (A9)$$

where $\alpha = \frac{\pi_o}{\pi_N(o)}$ ($\kappa = \frac{\pi_o}{\pi_N(o)} (.10)^\theta$), by convention.

In the special case in which there are no indirect effects, i.e., $\epsilon(t) = \theta = 0$, the simulation equations reduce to:

$$\pi_1^*(t) = \left[\frac{[1 - \pi_o/\pi_N(o)]^\lambda}{1 - [1 - (\pi_o/\pi_N(o))]D(t)} \right] \left[D(t) [1-D(t)]^\lambda \right]. \quad (A10)$$

A.4 Total Factor Productivity Growth Rates

Given the expressions for the labor productivity growth rate in the foregoing sections, we can derive corresponding expressions for the proportional growth rate of total factor productivity, \dot{A}^* . To do so it is necessary to specify the time rates of change of output per unit of capital input, denoted ($\dot{\nu}^*$), and the share of labor in the aggregate output of the sector in question, $\omega_L(t)$. The latter is taken as the

estimate for the elasticity of output with respect to labor input for the conventional Solow-type residual computation:

$$\dot{A}^* = [\omega_L(t) \dot{\pi}^*(t) + [1-\omega_L(t)] \dot{\nu}^*(t)] \quad . \quad (A11)$$

A.4.1 Labor's Share

Assumption 5: The share of labor (elasticity of output w.r.t. labor input) characteristic of the new technology is a constant, ω_N .

Since, as suggested by the remarks on Assumption 1, the share of labor in the old technology-sector of the economy is taken to be unity, we can write $\omega_L(t) = 1-D(t)[1-\omega_N]$.

(A12)

A.4.2 The Growth Rate of Capital Productivity

The aggregate capital productivity growth rate obviously depends upon the rate of change in the extent of diffusion, and the level and changes occurring in the productivity of capital used in the new technology segment of the industry (or sector). Denoting the latter by $\nu_N(t)$, the aggregate capital productivity is simply:

$$\nu(t) = (D(t)/\nu_N(t))^{-1} = \nu_N(t)/D(t) \quad (A13)$$

because no capital is used in the old technology sector (see Assumption 1, for discussion.)

From equation (A13), by differentiation, and multiplication of both sides of the resulting expression by $1/\nu(t)$, we obtain:

$$\dot{\nu}^*(t) = \dot{\nu}_N^*(t) - \dot{D}^*(t) \quad . \quad (A14)$$

There are two alternative special assumptions of interest in regard to $\dot{\nu}_N^*(t)$.

Assumption 6a: Improvements in the efficiency of the new technology due to endogenous, diffusion-dependent changes are Harrod-neutral, i.e., they affect $\pi_N(t)$, but, leave $\dot{\nu}_N^*(t) = 0$. Thus $\nu_N(t) = \nu_N(0)$, for all t . This assumption implies that:

$$[\dot{\nu}^*(t)|\text{HaN}] = -\dot{D}^*(t) \quad . \quad (\text{A15})$$

Alternatively, we may consider:

Assumption 6b: Improvements in the efficiency of the new technology due to endogenous, diffusion-dependent changes are Hicks-neutral, i.e., they result in $\dot{\nu}_N^*(t) = \dot{\pi}_N^*(t)$ for all t . Making use of eq. (A8), this assumption implies that

$$[\dot{\nu}^*(t)|\text{HiN}] = \theta[\dot{D}^*(t)] - \dot{D}^*(t) = -(1-\theta)\dot{D}^*(t) \quad . \quad (\text{A16})$$

A.4.3 Simulation Equations for the TFP Growth Rate

Combining the results given by equations (A11) and (A15) and (A16), alternatively, we find for the Harrod-neutrality and Hicks-neutrality cases, respectively:

$$[\dot{A}^*(t) | \text{HaN}] = [\dot{\pi}_2^*(t)]\omega_L(t) - [1-\omega_L(t)]\dot{D}^*(t) \quad (\text{A16})$$

and

$$[\dot{A}^*(t) | \text{HiN}] = [\dot{\pi}_2^*(t)]\omega_L(t) - [1-\omega_L(t)](1-\theta)\dot{D}^*(t) \quad . \quad (\text{A17})$$

Substituting for $\omega_L(t)$ from equation (A12), for $\dot{D}^*(t)$ from (A7b), these expressions may be rewritten in the form:

$$[\dot{A}^*(t) | \text{HaN}] = \dot{\pi}_2^*(t)[1-(1-\omega_N)D(t)] - \lambda(1-\omega_N)D(t)[1-D(t)] \quad (\text{A18})$$

and

$$[\dot{A}^*(t) | \text{HiN}] = [\dot{A}^*(t) | \text{HaN}] + \theta\lambda(1-\omega_N)D(t)[1-d(t)] \quad . \quad (\text{A19})$$

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Figures for *Computer and Dynamo*

Paul A. David
Stanford University

June, 1989

Revised: July, 1989



PALAIS DES FILS, TISSUS, VÊTEMENTS; DE LA MÉCANIQUE; DE L'ÉLECTRICITÉ; DE L'AGRICULTURE ET DES ALIMENTS

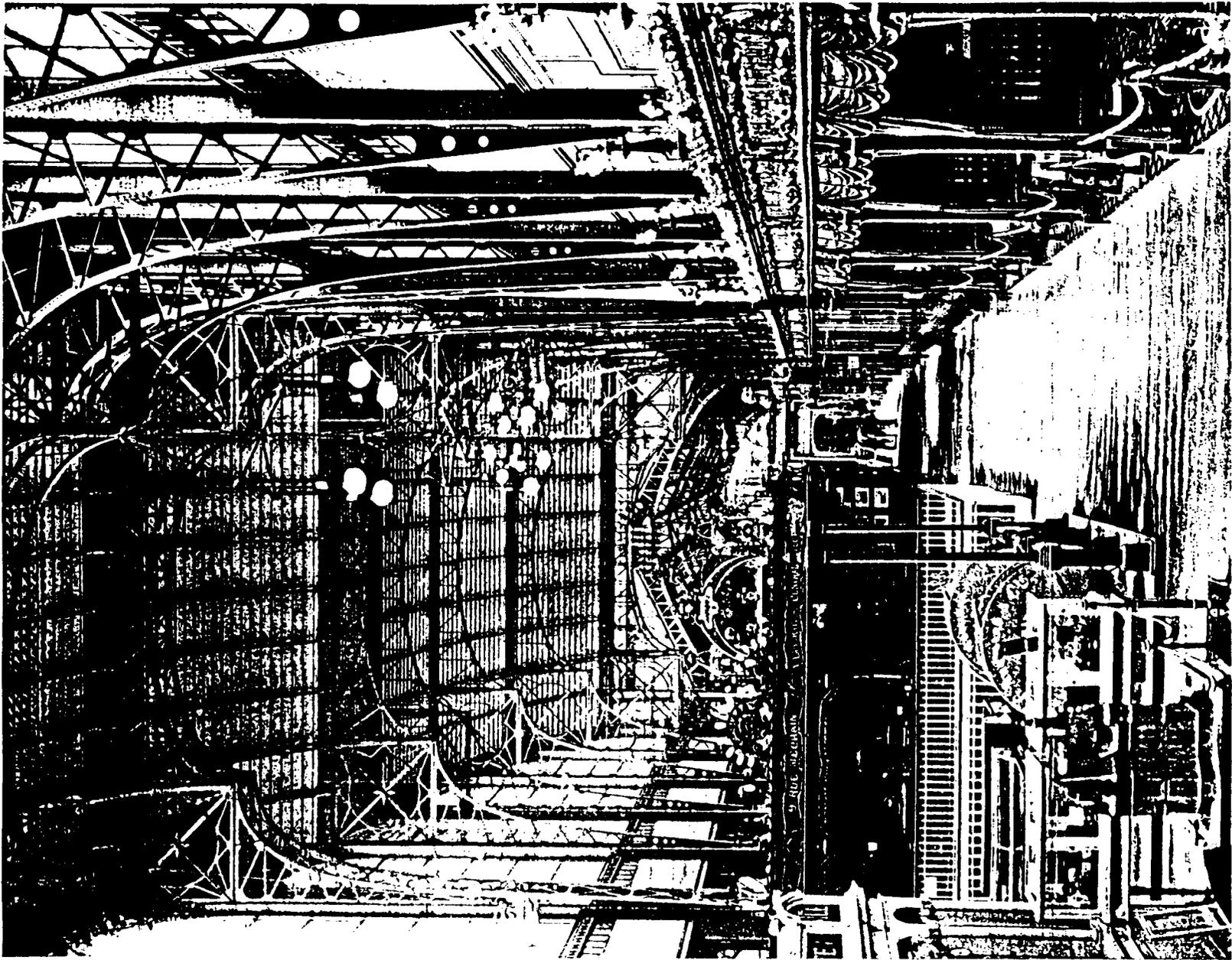
CHATEAU-D'EAU

PALAIS DE L'INDUSTRIE CHIMIQUE; DU GÉNIE CIVIL ET DES MOYENS DE TRANSPORT

(CHAMP DE MARS)

VUE PRISE DE LA PREMIÈRE PLATEFORME DE LA TOUR DE 300 MÈTRES

Figure 1a

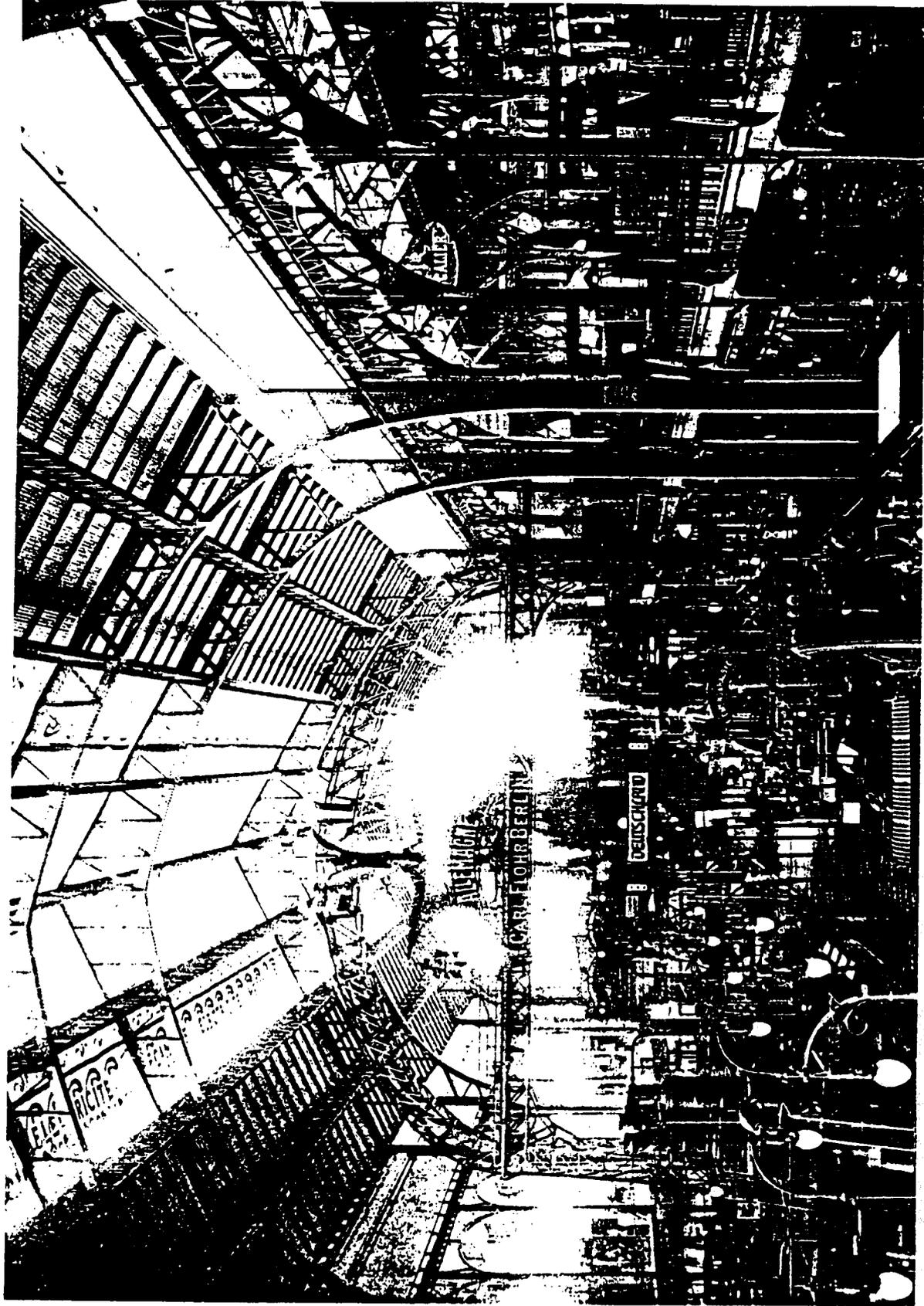


PALAIS DE L'ELECTRICITÉ

(CHAMP DE MARS - COTE DE L'AVENUE DE LA BOURDONNAIS)

SECTION FRANÇAISE - ÉTAGE)

Figure 1b



HALL DES MACHINES (CHAMP DE MARS)

SECTIONS ÉTRANGÈRES

Figure 2

FIGURE 3

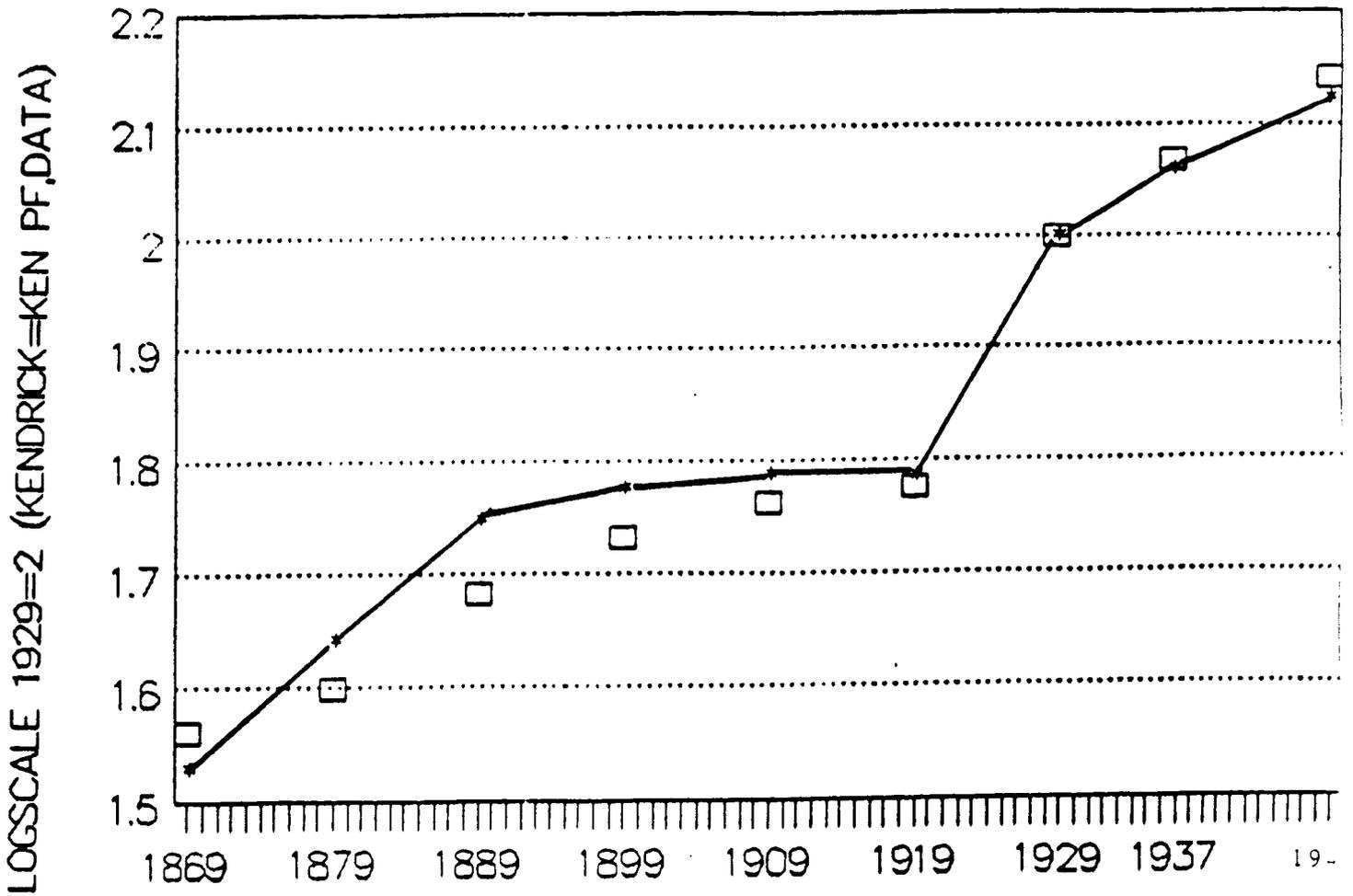
Corresponding Time Lines for Technological Events in the Dynamo and Computer "Revolutions"

1841 - Pixii d.c. magneto	1930 - Analogue computer - Bush-Hazen
	1937 - Concept of computability - Turing
	1938 - Electronic computer prototype - Atanasoff
	1939 - Electromechanical relay computer - Stibnitz
1856 - Holmes magneto	1944 - IBM Mark I - Automatic computer - Aiken
	1945 - Electronic Digital Computer - Eckert & Mauchly
1858 - Holmes magneto in Dungeness lighthouse	1948 - Transistor developed at Bell Labs
	1952 - UNIVAC I, Commercial Electronic Computer
	1954 - Transistorized Computer - Philco 2000
1870 - Gramme dynamo (ring winding)	1958 - Commercial solid state magnetic core, Monolithic integrated circuits - Noyce, Kilby
1872 - v.Hefner-Altaneck dynamo (drum winding)	
1873 - Gamme type Dynamo-motor	
1876 - Jablochkov Electric Candle	1965 - Integrated circuit computer--Control Data
1878 - Bush a.c. arc lighting	Hybrid circuit computer--IBM 360
1879 - Edison, Fox-Lane Swann Lamp	
1881 - Edison Central Stations	1971 - Memory chip--Intel
	1970 - Silicon microprocessor--Intel
1885 - van de Poelle electric tram	
1886 - Sprague electric traction system	
1887 - Tesla a.c. induction motor, Bradley rotary convertor, a.c. meter	1976 - 16K memory chip
	1977 - Minicomputers introduced--DEC(VAX)
	1979 - 8088 microcomputer introduced
1900 - Paris International Exhibition	1989 - OECD International Seminar

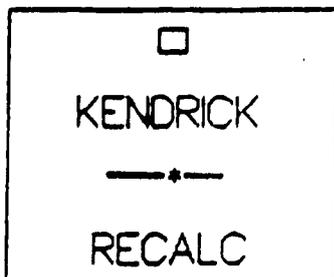
Sources: From chronologies in David (1987) and Ayres (1989).

FIGURE 4a

U.S. MANUFACTURING, TOTAL FACTOR PRODUCTIVITY
1869 - 1948



Source: See Table 2



ALL MANUFACTURING INDUSTRIES

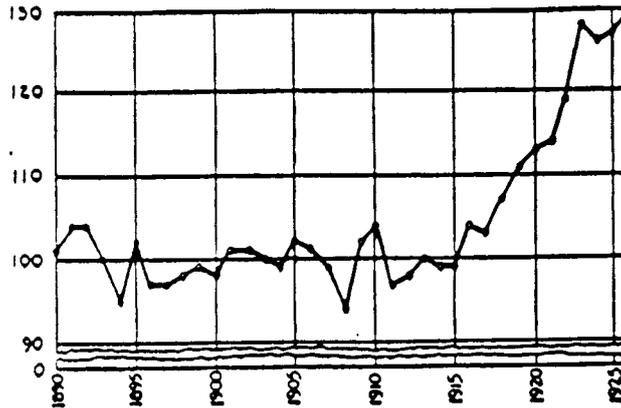


CHART 42. MOVEMENT OF REAL ANNUAL EARNINGS OF EMPLOYED WAGE-EARNERS IN ALL MANUFACTURING INDUSTRIES

Source: Douglas
SALARIED AND CLERICAL LABOR

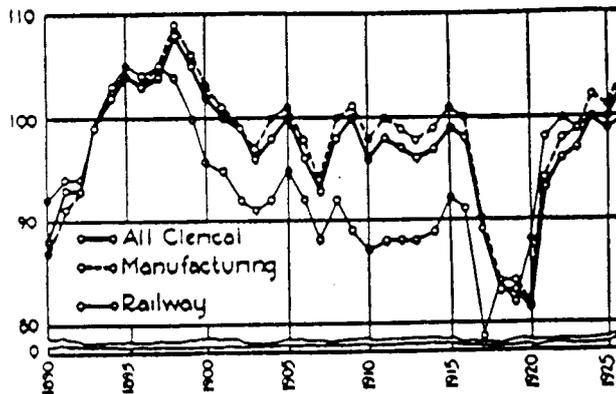
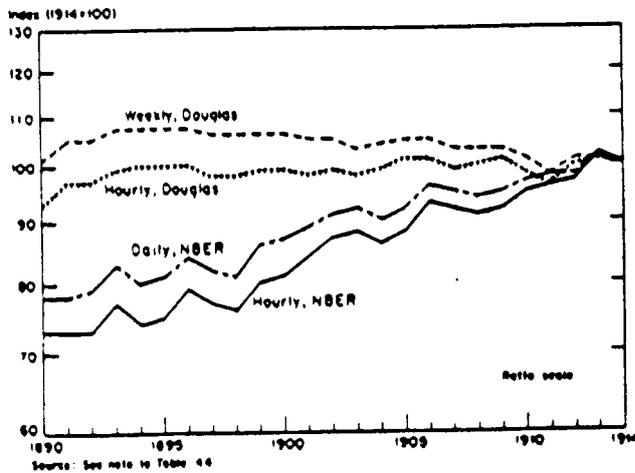


CHART 43. RELATIVE MOVEMENT OF REAL ANNUAL EARNINGS OF CLERICAL WORKERS

Source: Douglas
Comparison of Indexes of Real Earnings, 1890-1914

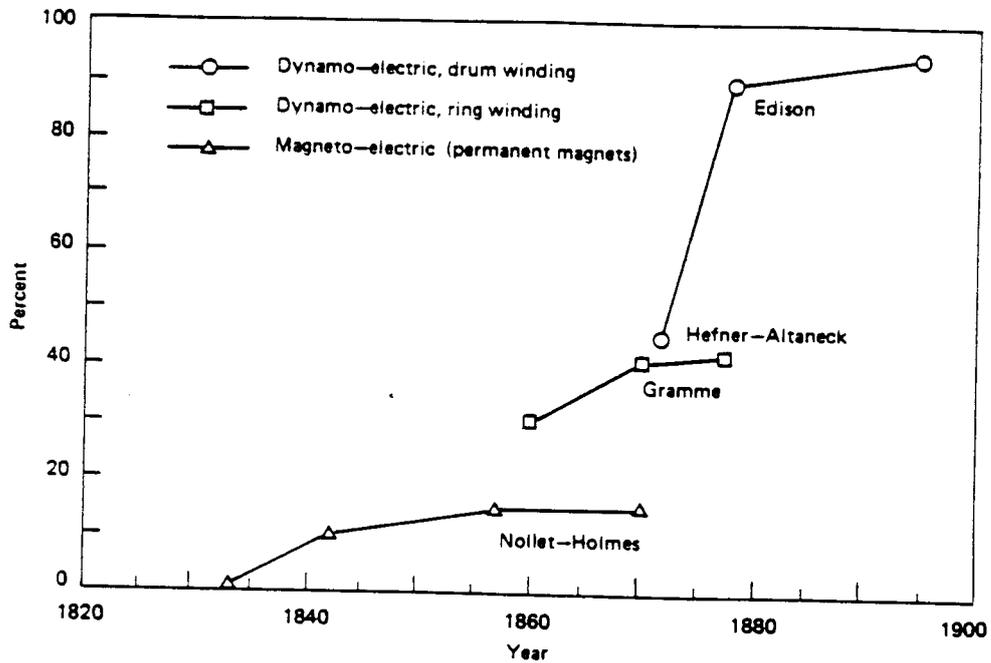


Source: Rees (1961), p.121
Alternative Indexes of Real Earnings
of Manufacturing Workers 1890-1974

Figure 4b

U.S. Real Wages and Real Annual Earnings Movements, 1890-1926,
according to Douglas and to Rees

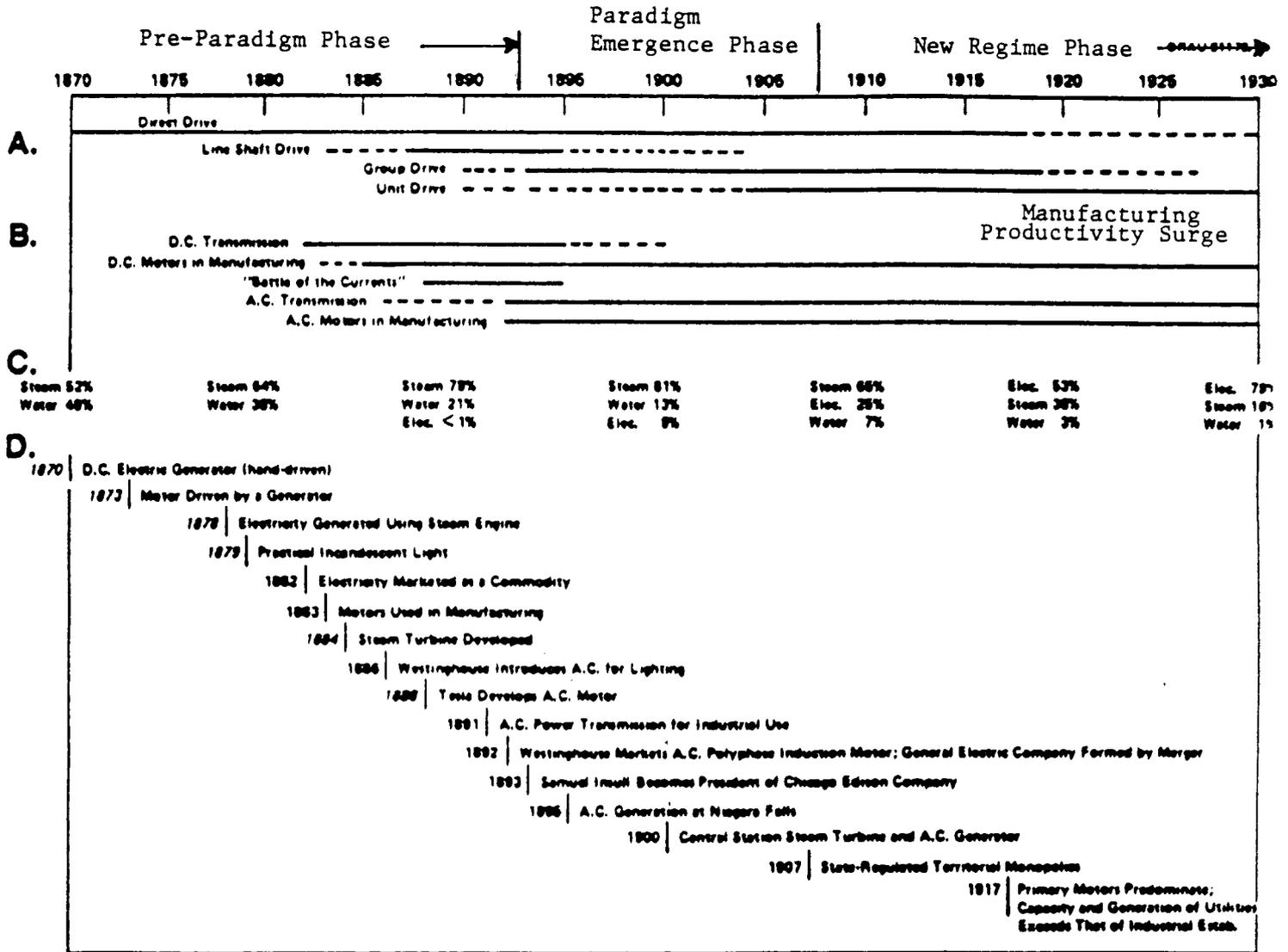
FIGURE 5



Efficiency of electric generators: electric power output per unit of mechanical power input.

Source: Ayres (1989), p. 33

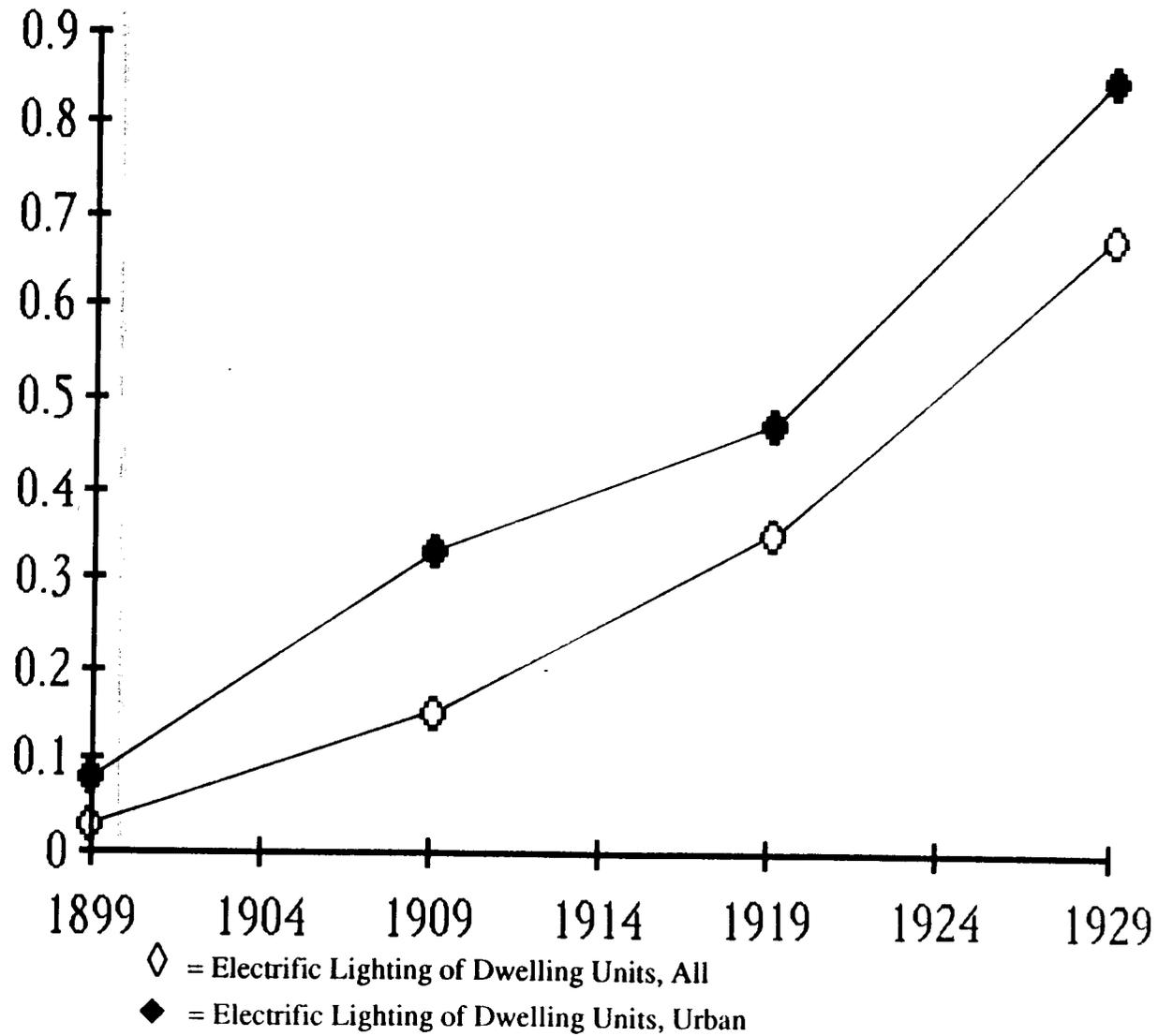
FIGURE 6



Chronology of electrification of industry: (A) Methods of driving machinery; (B) Rise of alternating current; (C) Share of power for mechanical drive provided by steam, water, electricity; (D) Key technical and entrepreneurial developments.

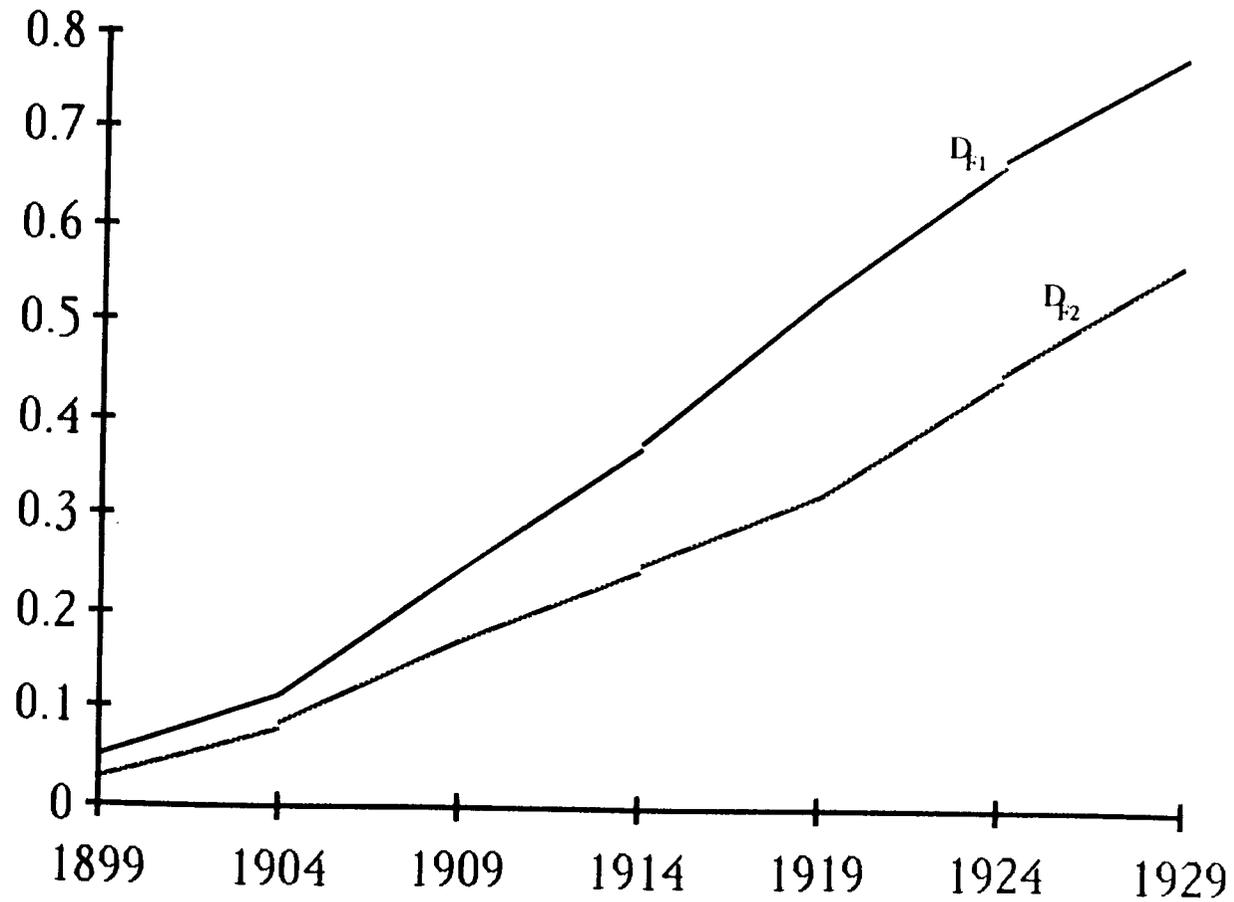
Source: Warren D. Devine, Jr., "From Shafts to Wires: Historical Perspective on Electrification", The Journal of Economic History, Vol. XLIII, No. 2 (June 1983) page 351 and 354, respectively.

Figure 7. Diffusion of Electric Power in the U.S., 1899-1929
Household Electrification



Source: Table 3

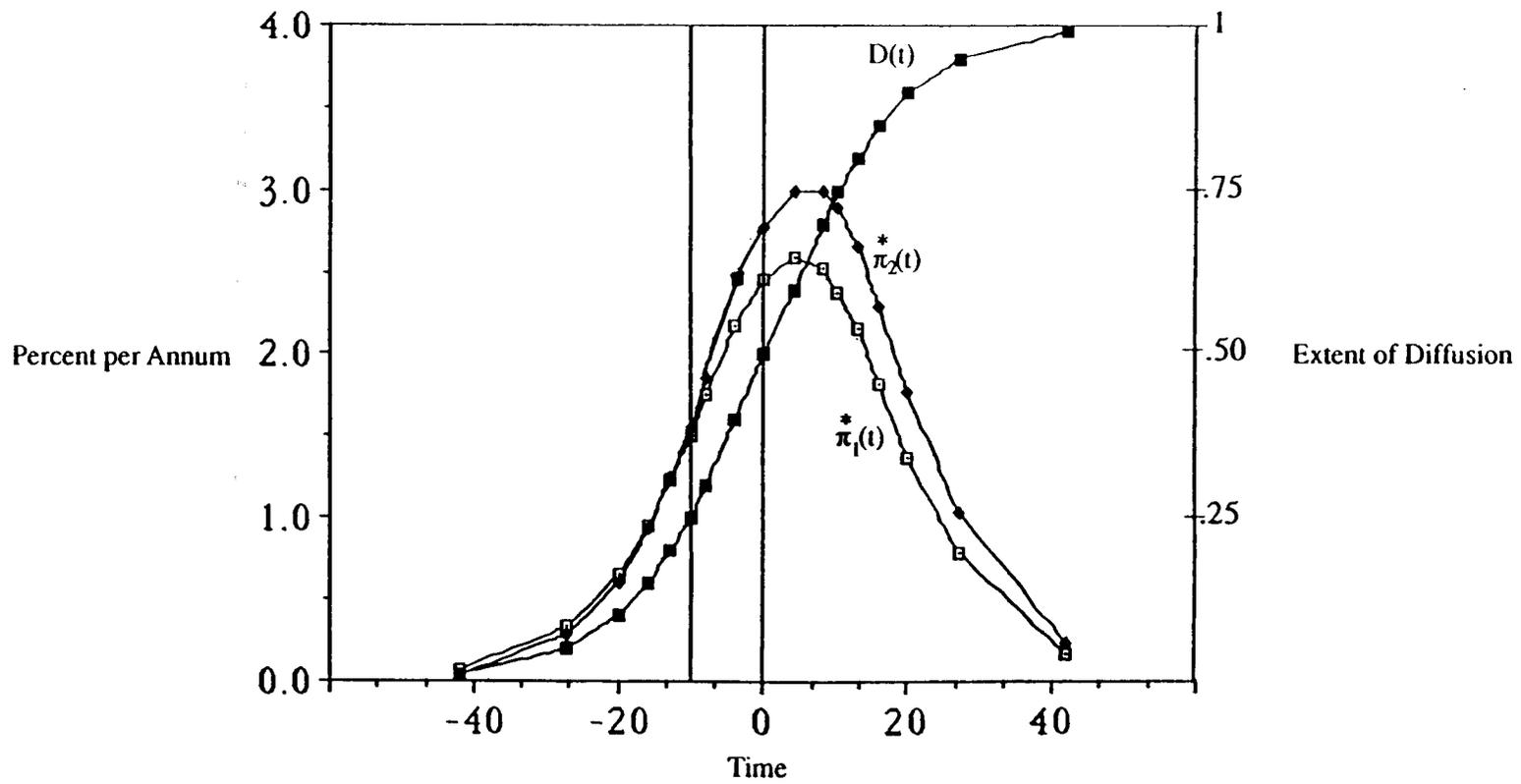
Figure 8. Diffusion of Electric Power in the U.S., 1899-1929
Factory Electrification



D_{F1} = Electrification of Mechanical Drive in Manufacturing Establishments
 D_{F2} = Penetration of Secondary Electric Motors in Manufacturing Establishments

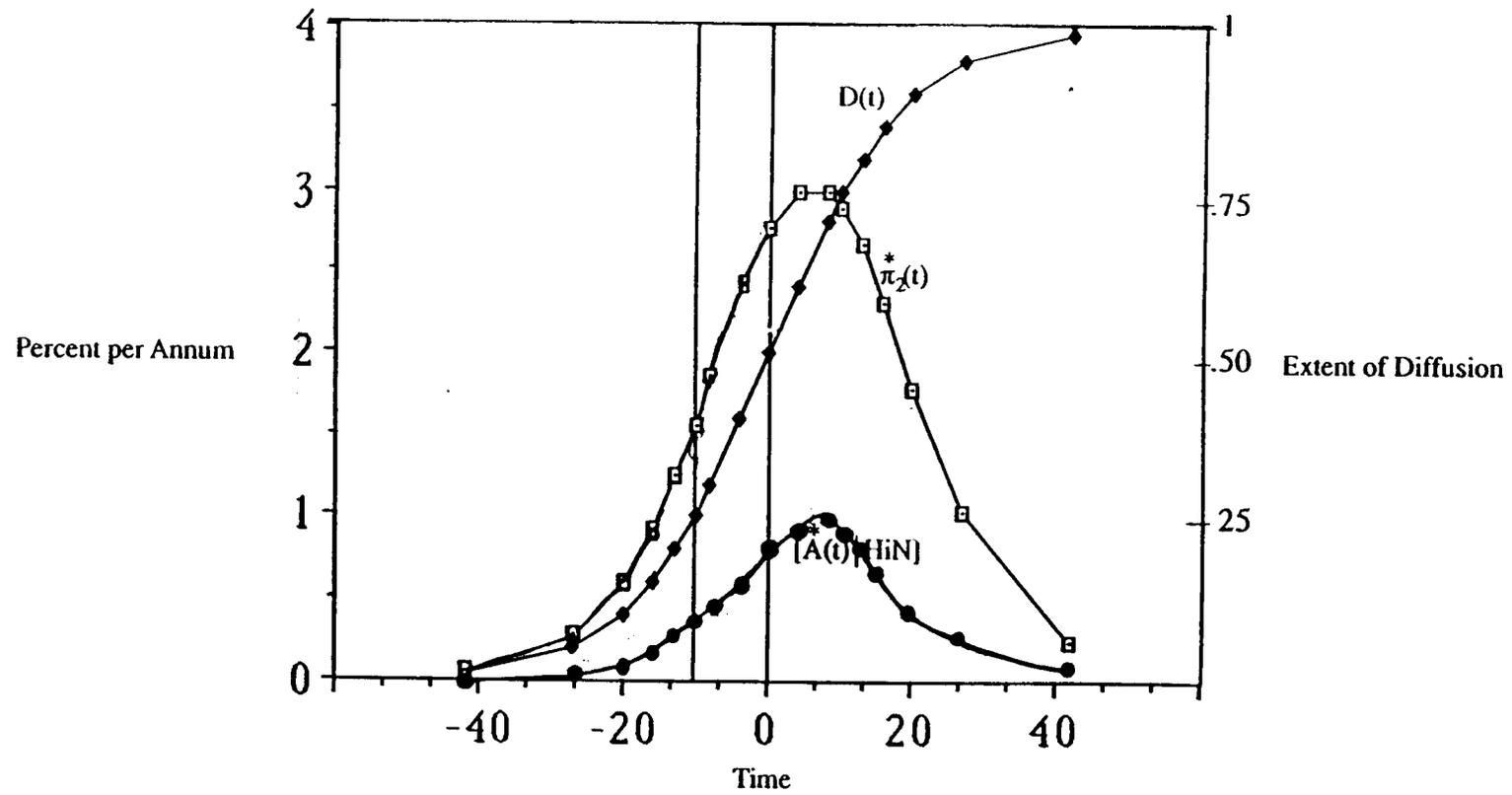
Source: Table 3

Figure 9. Labor Productivity Growth Rates Along the Diffusion Path



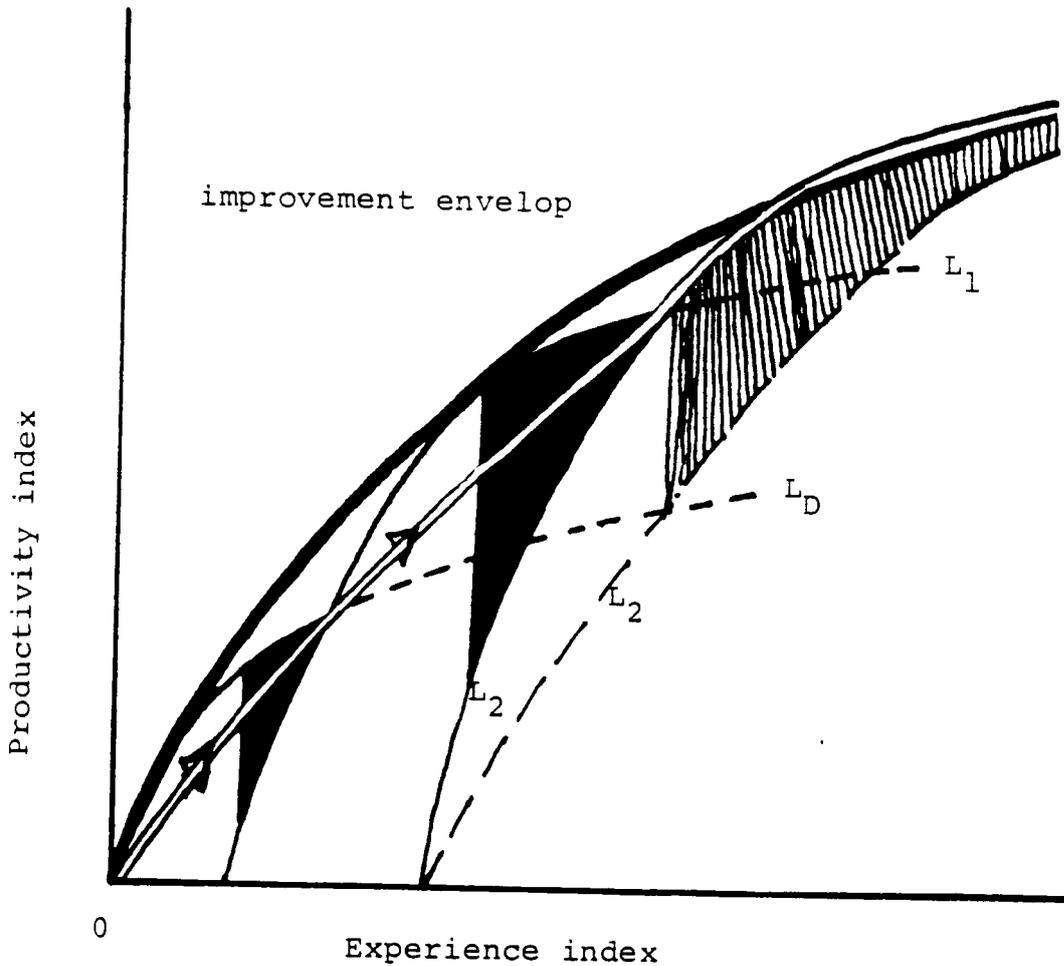
Source: Table A1

Figure 10. Labor Productivity and Total Factor Productivity Growth Rates Along the Diffusion Path



Source: Table A1

FIGURE 11



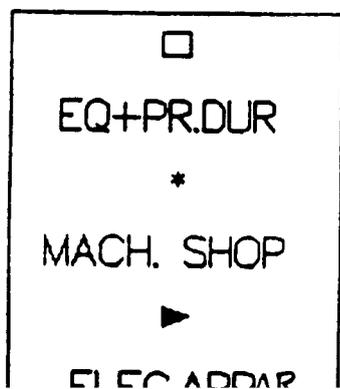
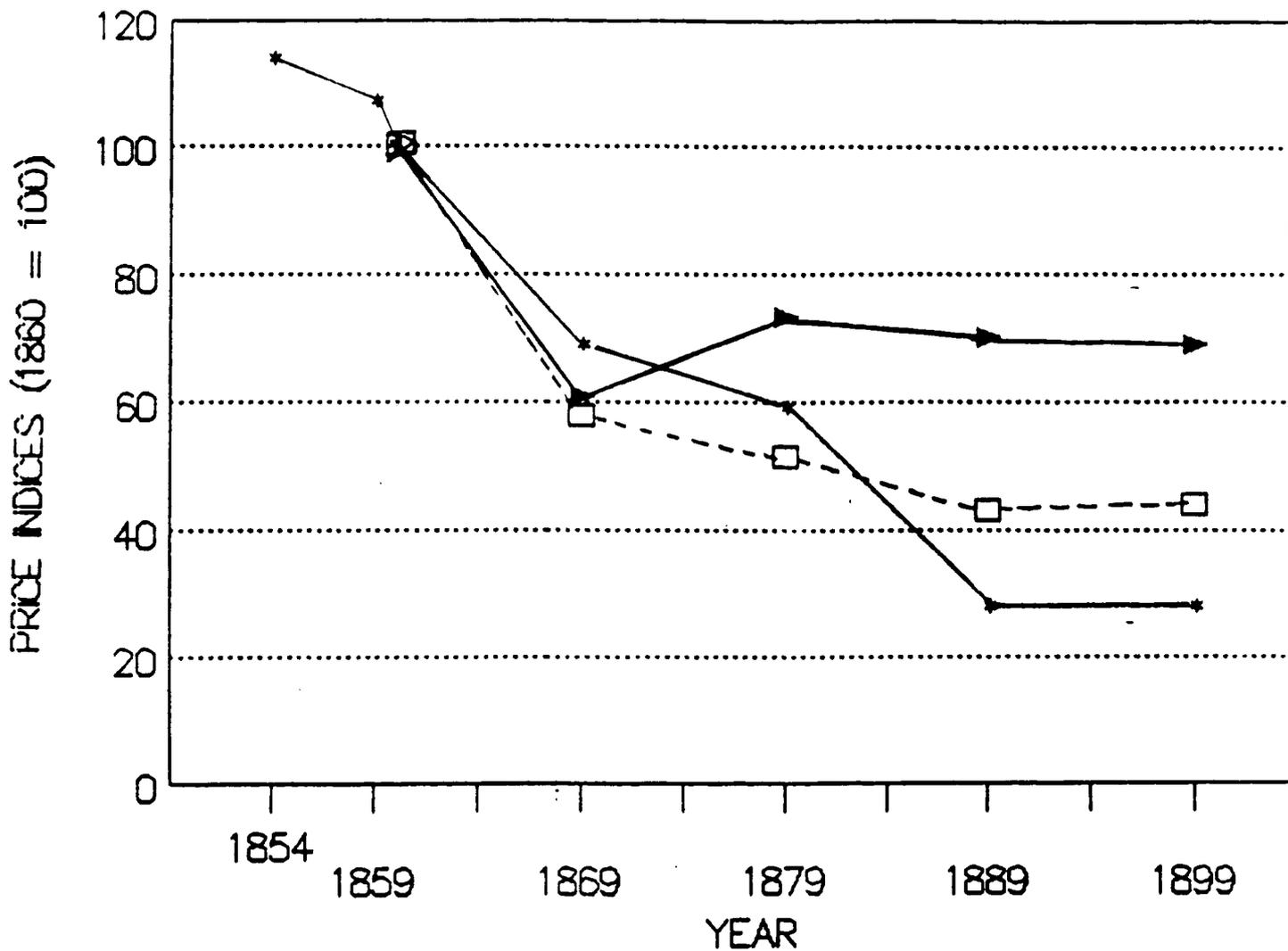
The rate of improvement realized in the early phase of the technology's evolution is slowed by investments in switching to better specific improvement curves.

Note: The dark areas represent undiscounted "learning investments", whereas the light shaded region is the benefits derived by sequentially switching to new and better versions of the technology, rather than trying to "catch-up" by an eventual, discrete jump.

FIGURE 12

BRADY U.S. DURABLE EQUIPMENT INDEXES, 1854-1899,

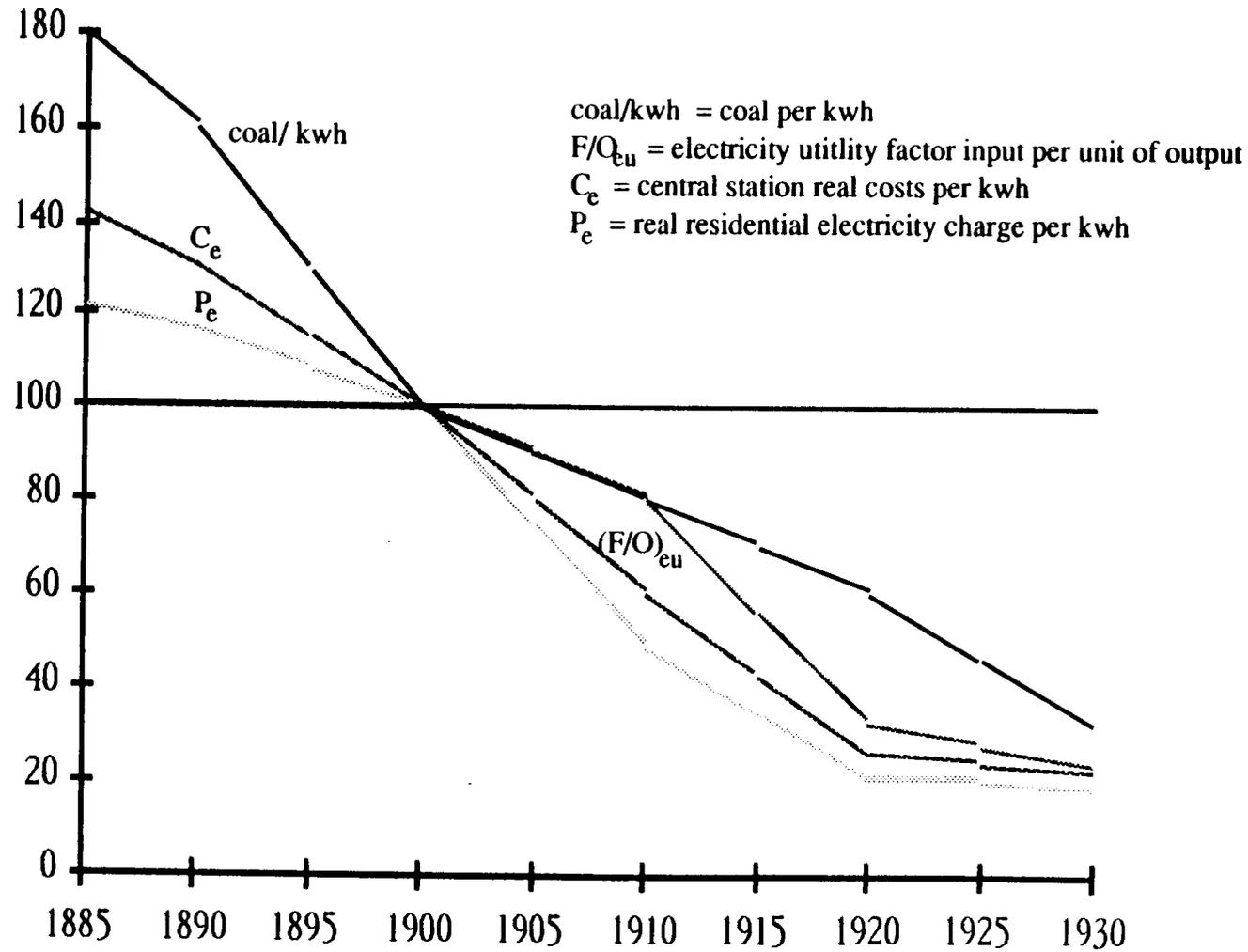
Deflated by David-Solar CPI Index



Sources:

Brady (1966), p. 111 for prices of equipment and producer durables, machine shop products, electrical apparatus; David and Solar (1977) Table 1, p. 16, for U.S. consumer price index.

Figure 13. Indexes of Real Cost of Electricity Supply in U.S., 1885 - 1930

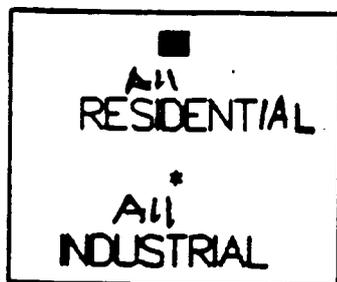
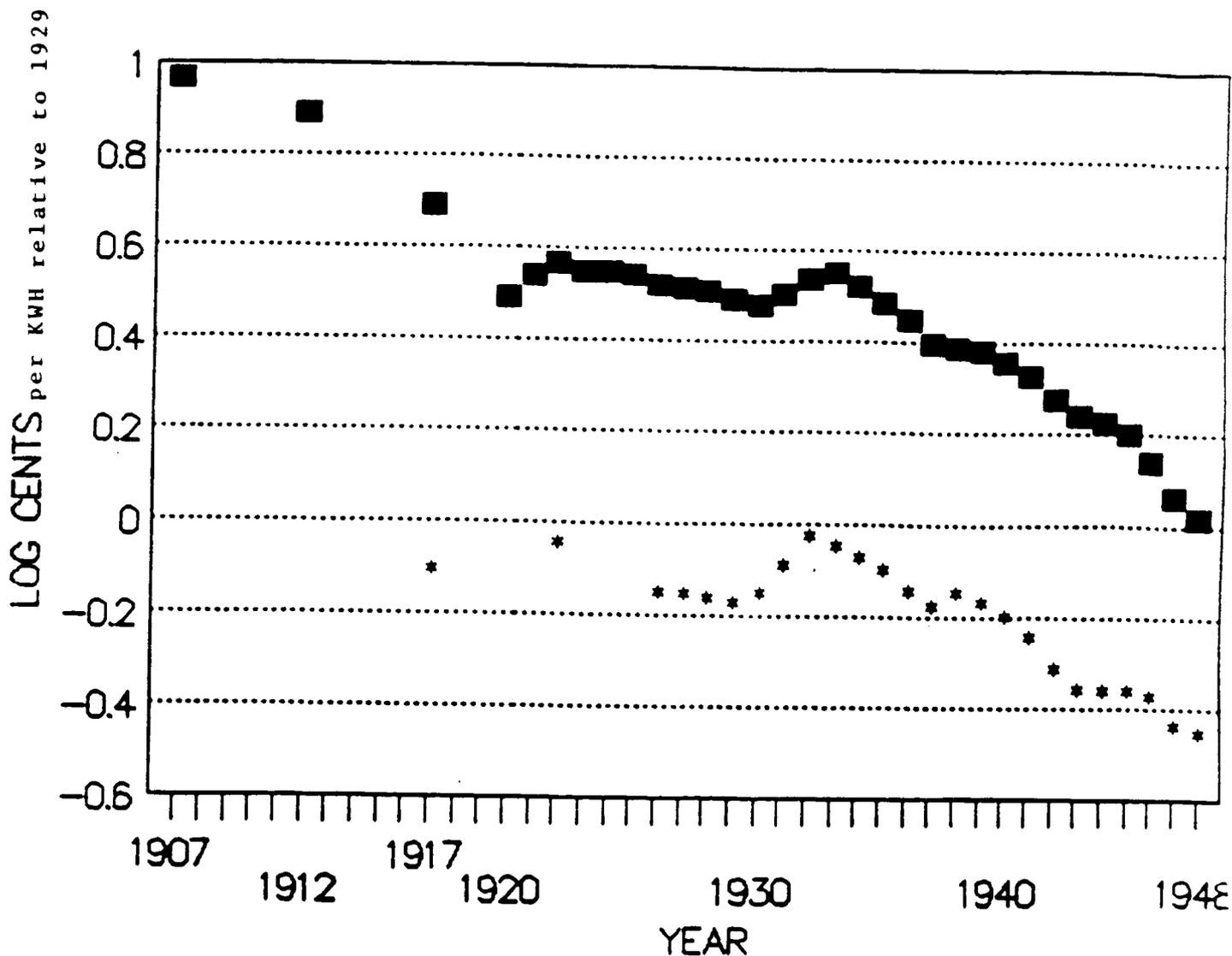


Source: Table 4

FIGURE 14

LOGARITHM OF INDEX OF U.S. REAL ELECTRICITY COST PER KW HOUR, 1907-1948

(Index of Charges/CPI: 1929 = 100)



Source: See same sources as cited for Table 4, column 4.