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EARLY TWENTIETH CENTURY PRODUCTIVITY GROWTH DYNAMICS: AN INQUIRY INTO THE ECONOMIC HISTORY OF "OUR IGNORANCE"

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Early Twentieth Century Productivity Growth Dynamics: An Inquiry into the Economic History of “Our Ignorance”

by

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Abstract

A marked acceleration of total factor productivity (TFP) growth in U.S. manufacturing followed World War I. This development contributed substantially to the absolute and relative rise of the domestic economy's aggregate TFP residual, which is observed when the "growth accounts" for the first quarter of the twentieth century are compared with those for the second half of the nineteenth century. Two visions of the dynamics of productivity growth are germane to an understanding of these developments. One emphasizes the role of forces affecting broad sections of the economy, through spillovers of knowledge and the diffusion of general purpose technologies (GPTs). The second view considers that possible sources of productivity increase are multiple and idiosyncratic. Setting aside possible measurement errors, the latter approach regards sectoral and economy-wide surges of TFP growth to be simply the result of aggregating over many essentially independent underlying cost reductions, some of which carried more weight than others. Although there is room for both views in an analysis of the sources of the industrial TFP acceleration during the 1920's, we find the evidence more compelling in support of the first approach. The proximate source of the TFP surge lay in the switch from declining or stable capital productivity to a rising output-capital ratio, which occurred at this time in many branches of manufacturing, and which was not accompanied by slowed growth in labor productivity. The 1920's saw critical advances in the electrification of industry, the diffusion of a GPT that brought significant fixed capital-savings. But the same era also witnessed profound transformations in the American industrial labor market, following the stoppage of mass immigration from Europe; rising real wages provided strong impetus to changes in workforce recruitment and management practices that were underway in some branches of the economy before the War. The productivity surge reflected the confluence of these two forces.

Early Twentieth Century Productivity Growth Dynamics:
An Inquiry into the Economic History of "Our Ignorance"

A marked acceleration of total factor productivity (TFP) growth in U.S. manufacturing followed World War I. This development often is overlooked by modern productivity analysts and economic historians alike. Yet, it contributed substantially to the absolute and relative rise of the domestic economy's aggregate TFP residual which is observed when the "growth accounts" for the first quarter of the twentieth century are compared with those for the second half of the nineteenth century. In directing closer attention to the surge of industrial productivity growth during the 1920's we hope not only to arrive at a fuller account of that particular episode in the American economy's development, but to contribute to a deeper general understanding of the phenomenon of recurrent prolonged swings in the TFP growth rate that is a feature of the long-term growth records of the advanced industrial economies.

Two visions of the dynamics of productivity growth are germane to an understanding of such movements. The first would emphasize the role of innovations whose resource-saving effects impinged upon many branches of manufacturing concurrently, especially through spillovers of knowledge and the diffusion of general purpose technologies (GPTs) into practical use. The second view considers the variegated possible sources of measured productivity increase, each of which might be relevant to one or another particular industry or industrial sub-group at some period. Setting aside possible measurement errors, this latter approach would regard sectoral and economy-wide surges of TFP growth as simply the result of aggregation over many essentially independent underlying sources of cost reduction, some of which happened to carry more weight in the total than others. These visions are elaborated below, in section 1 of the paper.

Although there is room for both views in an analysis of the sources of the industrial TFP acceleration during the 1920's, we have found the evidence to be more compelling in support of the first approach. The proximate source of the TFP surge lay in the switch from declining or stable capital productivity to a rising output-capital ratio, which occurred at this time in many branches of manufacturing, as will be seen from the data assembled in section 2. This change, however, was not accompanied by slowed growth in labor productivity, as would be expected were the onset of a trend towards "capital-shallowing" to have been a reflection of the substitution of labor for capital inputs. Indeed, across the manufacturing sector during the 1920's, faster growth of capital productivity went hand in hand with faster growth of labor productivity. The implied shift in production conditions can be traced to critical advances that were taking place at the time in the electrification of industry, a phase in the diffusion of a GPT that made possible significant fixed capital-savings.

But, from detailed examinations of that process whose highlights we review in section 3, it is evident that realization of the productivity-enhancing potentialities of "the dynamo revolution" involved a confluence of many other complementary technological and organizational advances; their implementation had awaited the stimulus eventually provided by the buoyant macroeconomic conditions of the 1920's. The post World War I era also witnessed the results of profound structural transformations in the American industrial labor market, following the stoppage of mass immigration from Europe. Rising real wages provided strong impetus to changes in workforce recruitment and management practices that previously were being tried to a more limited extent in some branches of the economy. We argue (in section 4) that the induced diffusion of these organizational adjustments directly supported the growth of industrial output per man-hour, and also spurred wider applications of electric power – particularly to tasks formerly performed largely by unskilled foreign-born workers. Recruitment of native born workers who had graduated from high schools was a significant aspect of the upgrading of the industrial labor force in a number of technologically more sophisticated branches of manufacturing. But we read the limited evidence available on this point to be consistent with the view that the enhanced "worker-qualities" most sought by industrial employers at this time were those of intelligence, diligence and general reliability – for which high school attendance and graduation may well have served as good signals – rather than specific cognitive knowledge.

1. "Measures of Ignorance" and Mysteries of TFP Growth Variations

The economics profession has been both bemused and perplexed by total factor productivity (TFP) growth throughout the five decades or so since the concept was introduced and its quantitative significance was discovered. That between one-half and two-thirds of the growth of the U.S. economy's aggregate real output in the twentieth century remained unaccounted for by conventional measures of the growth of labor and capital inputs was shocking news. Good news, if it truly reflected the reduction of the real cost of goods and services enjoyed by consumers currently and in the future. Yet at the same time vaguely disturbing, inasmuch as it seemed to leave so much of modern material progress hostage to developments about which economists had comparatively little to say.

Moses Abramovitz (1956) expressed dismay on the latter score when announcing his discovery, in a famous passage that continues to deserve quotation:[1]

> "This result is surprising in the lopsided importance which it appears to give to productivity increase, and it should be, in a sense, sobering, if not discouraging, to students of economic growth. Since we know little about the causes of productivity increase, the indicated importance of this element may be taken to be some sort of measure of our ignorance about the causes of economic growth in the United States and some sort of indication of where we need to concentrate our attention."

But, Abramovitz went on immediately to suggest that the absolute and relative size of this unexplained, residual source of growth might reflect not only "the gradual growth of applied knowledge," but the effects of economies of scale and deficiencies in the accounting made for the growth of economically costly inputs. He therefore called for the development of more sophisticated indexes of improved labor quality, and allowance for the contributions made to productive capacity growth by "capital formation" of unconventional sorts, "principally those for health, education and training, and research." In the intervening decades an enormous body of methodological and empirical work has been devoted to the subject of productivity measurement, and much progress may fairly be claimed to have been made in implementing the research program to which Abramovitz pointed.

Two principal responses to the brute fact of the TFP residual may be discerned in the writings of economists who followed in the tracks of the pioneer generation. One group was disposed towards the side of Abramovitz's suggested agenda for research that would

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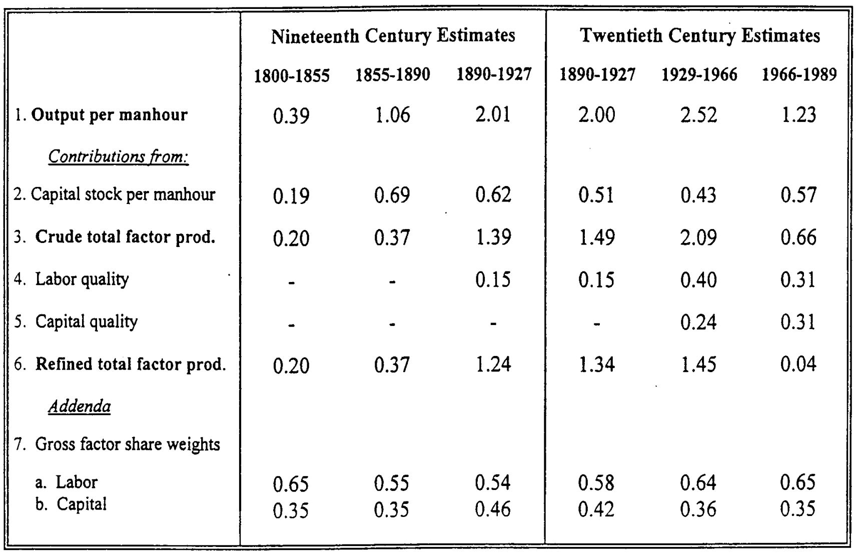
[1] "Resource and Output Trends in the United States since 1870," *American Economic Review*, 46(2), May 1956: pp. 5-23, is reprinted in M. Abramovitz, *Thinking About Growth, and Other Essays on Economic Growth and Welfare*, Stanford, CA: Stanford University Press, 1989. The passages quoted in the text above appear in the latter at pp. 133-135.

dispel “ignorance” by correcting “errors and omissions,” specifically those resulting in understatements of the growth of costly inputs. Following the lead of Dale Jorgenson and his collaborators, this gave rise to efforts to account for the growth of real output as completely as possible by reference to costly inputs of resources, minimizing the magnitude of the embarrassing residual.[2]

Even so, such “refinements” as can be made to allow for costly improvements in the quality of labor and capital services input manage to shrink the residual TFP growth rate down to a size that remains only preponderant, rather than overwhelmingly preponderant in relationship to the trend growth rate of labor productivity in the opening three-quarters of the twentieth century. This may be seen from growth accounts for the twentieth century US private domestic economy presented in Table 1: compare the “crude” TFP growth rates for 1890-1927 and 1929-1966 (line 3), which represent roughly 75-80 percent of the corresponding annual growth rates of output per manhour (line 1), with the 67 to 60 percent proportional contribution made by the “refined” estimates of the same residuals (line 6).

Moreover, other analysts, influenced by Robert Solow’s (1957) seminal contribution to the empirical analysis of aggregate production function relationships, increasingly came to associate the upward course of TFP indexes with efficiency growth due to “technical progress” – the effects of what Abramovitz had referred to as “the gradual advances of applied knowledge.”

Table 1.



	Nineteenth Century Estimates			Twentieth Century Estimates		
	1800-1855	1855-1890	1890-1927	1890-1927	1929-1966	1966-1989
1. **Output per manhour**	0.39	1.06	2.01	2.00	2.52	1.23
Contributions from:						
2. Capital stock per manhour	0.19	0.69	0.62	0.51	0.43	0.57
3. **Crude total factor prod.**	0.20	0.37	1.39	1.49	2.09	0.66
4. Labor quality	-	-	0.15	0.15	0.40	0.31
5. Capital quality	-	-	-	-	0.24	0.31
6. **Refined total factor prod.**	0.20	0.37	1.24	1.34	1.45	0.04
Addenda						
7. Gross factor share weights						
a. Labor	0.65	0.55	0.54	0.58	0.64	0.65
b. Capital	0.35	0.35	0.46	0.42	0.36	0.35

The popularity of a conceptualization of technological change as a process that would raise the efficiencies of all the productive inputs in equal proportion encouraged that direct association. It did so by providing a theoretical foundation for formally identifying the rate of growth of TFP with the rate of (Hicks neutral) change of technical efficiency,

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[2] On occasion such efforts were carried to excess, as when Jorgenson and Griliches (1967) proposed to include measures of long-term increases in capital-utilization rates among the inputs in growth accounting. In the view of Denison (1972), this improperly removed from the TFP residual the effects of gains in utilization intensity that resulted from technical improvements affecting machine speeds, reductions of down-time for scheduled maintenance and repairs that were not reflected in the prices of more reliable equipment, better plant management practises, and the like. On the so-called “capital-utilization controversy” see *U.S. Survey of Current Business* (1972); Foss (1997): pp. 117-120.

reflected in shifts in the aggregate production function rather than factor-substitution movements along its surface.[3]

Having been brought up on this interpretation of the movements in measured TFP, many economists in more recent years found it rather paradoxical, if not utterly baffling, that the growth accountants' residual should have all but vanished since the early 1970's at the very same time that a wave of major innovations was appearing – in microelectronics, in communications technologies based on lasers and fibre-optics, in composite materials, and in biotechnology. Indeed, the notion that there is something anomalous about the prevailing state of affairs drew much of its initial energy from the apparent failure of the wave of innovations based on the microprocessor and the memory chip to elicit a surge of growth in productivity from those very sectors of the U.S. service economy that were investing so heavily in computers and office equipment.[4]

There thus was general consternation, rather than professional celebration, when the measure of "our ignorance" shrank to the meager dimensions that appear in the figures for TFP growth in the U.S. economy during the trend period 1966-1989. Table 1 shows the absolute magnitude of the residual collapsing from levels of 1.5-2.1 percentage points per annum during 1890-1966 to 0.7 percentage points on a "crude" accounting, and all but vanishing (0.04 percentage points) on a "refined" reckoning.[5]

Despite the attention directed to the so-called productivity paradox, it remains the case that a very substantial degree of real ignorance persists about the dynamic processes that reflect themselves in variations of the trend growth rate of total factor productivity, whether at the aggregate or the sectoral level. The existence of such movements in the long-run growth records of the advanced industrial economies has not passed entirely unnoticed. By the end of the 1960's the role of unprecedentedly rapid TFP growth in post World War II economic growth among the OECD countries was widely recognized. Even so, economists and economic historians continue to labor with less than complete success

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[3] Global "Hicks neutrality" is defined as a shift in the production function that leaves the ratio of the marginal productivities of the inputs unchanged for all factor input combinations. A less restricted (local) Hicks neutrality condition is one in which for a given set of marginal product ratios of the inputs, the shift in the production technology leaves the input proportions unchanged. When relative rates of factor remuneration are equal to relative marginal productivities (as required for cost minimization), Hicks neutral technological change leaves (optimized) factor input proportions undisturbed at the pre-existing relative input prices. Harrod neutrality, by contrast, specifies that the capital-output ratio remains undisturbed by technological innovation, for any given marginal productivity of capital; and conversely. The popularity of the Cobb-Douglas form of production function derives in some part from the algebraic fact that efficiency changes that are specific to, and hence augment particular inputs, always can be expressed as equivalent to an equi-proportional (i.e., Hicks neutral) shift in the efficiency of all inputs combined. In other words, for the Cobb-Douglas function, the input efficiency change can be reinterpreted as being either Hicks neutral or Harrod neutral. Against these theoretically convenient assumptions of neutrality, Abramovitz and David have argued that there is much micro- and macro-level evidence suggesting the importance of historical changes in the *bias* in technological and organizational innovations. See Abramovitz and David (1973, 1996, 1998); Abramovitz (1993); David (1977).

[4] E.g., Roach (1987, 1988); Baily and Gordon (1988). For further discussion, see David and Steinmueller (1999).

[5] Indeed, on a still more comprehensive accounting in which intangible human and non-human capital inputs – reflecting investments in education and training and R&D – are considered, the contraction of the super-refined residual is sufficient to push the TFP growth rate estimate for 1966-1989 well into the negative zone. See Abramovitz and David (1998), Tables 1:IV, and 2:IV. Specifically, the comprehensive measurement of inputs with corresponding adjustment of the (augmented) real GDP growth rate, results in a TFP growth rate of -0.14 percentage points per annum during 1966-1989, compared with 1.0 percentage points as the average annual rate over the period 1929-1966. The latter finding lends some indirect support to recent contentions that the official measures of real output growth in the U.S. private domestic economy may be biased downwards by at least 0.2 percentage points per annum, due to the failure of the price deflators to fully reflect quality improvements in new goods and services. This state of affairs is not entirely without precedent in the history of the American economy, but nothing resembling it has been experienced since the era of the Civil War (1855-1871).

to explain how that Golden Age of growth came to be so "golden", and why it gave way during the 1970's and 1980's to what only can be labeled the Tarnished Age of TFP growth.[6]

Moreover, very few economists to date have tried to approach the problem by identifying the *origins* of historical eras of high productivity growth. Indeed, few appreciate the fact that stands out boldly from Table 1's comparison of the growth accounts for the nineteenth century trend periods (1800-1855 and 1855-1890) with those for the era that followed: the expansion of the residual during the 1890-1927 interval constituted a profound discontinuity in the U.S. long-term growth record. When viewed in this perspective, the greatly slowed pace of productivity increase that has marked the past three decades represents a reversion towards the aggregate economic growth performance that characterized the period 1855-1890. As we remain puzzled about where the TFP residual went, and whether it will re-emerge in the foreseeable future, perhaps it will be illuminating to try to learn whence it came from in the first place.

Our focus in the remainder of this paper therefore is confined to the comparatively brief watershed era that saw the TFP residual's rise. The four decades between 1890 and 1930 brought many fundamental structural transformations in the American economy, and witnessed changes in the pace of aggregate and sectoral productivity advance that were dramatic by any prior or more recent standard. But, perhaps due to the understandable obsessive attention devoted to the events immediately preceding and following the crisis of 1929, the antecedent developments affecting productivity have been by and large overlooked by economic historians and economists alike – even though they were a harbinger of the form of economic growth that was resumed in full-blown fashion following World War II.

Uncovering a Forgotten Puzzle: The Post World War I Productivity Acceleration

As a result, a striking and rather intriguing feature of the U.S. pre-1929 productivity growth record that was first remarked upon by Solomon Fabricant almost forty years ago, subsequently has remained in obscurity. In his Introduction to John Kendrick's (1961) study of productivity trends in the U.S., Fabricant noted (p. xliii):

> "A distinct change in trend appeared sometime after World War I. By each of our measures, productivity rose, on the average, more rapidly after World War I than before....The change in trend...is one of the most interesting facts before us. There is little question about it. It is visible not only in the indexes that Kendrick has compiled for the private domestic economy....It can be found also in his figures for the whole economy, including government, as well as in his estimates for the groups of industries for which individual productivity indexes are available."

At the heart of this discontinuity in the historical record of productivity growth lay the particularly marked post-1919 acceleration that was evident in Kendrick's (1961) indexes of labor productivity and TFP for the manufacturing sector. This point eluded Fabricant's commentary, but it is quite evident that the jump in the TFP growth rate that occurred during the decade of the 1920's was greatest in this, the dominant member of the commodity producing sectors. Whereas Kendrick's estimates put the decadal growth of

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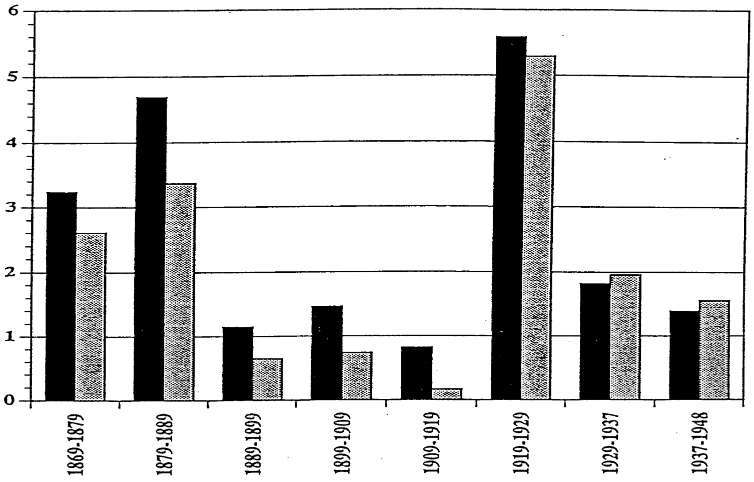
[6] See, e.g., Feinstein, Temin and Toniolo (1997); Crafts and van Ark (1997).

TFP at approximately 22 percent for the whole of the private domestic economy, the corresponding figure for manufacturing was 76 percent, and for mining it was 41 percent, leaving the farm sector in last position with a relatively low gain of 14 percent. Outside the bounds of commodity production, the transportation sector's TFP rose during this decade by 36 percent; the communications and public utilities industries' 28 percent increase also outstripped the performance of the private domestic economy, implying that the harder to measure productivity gains in the trade and services segments were undergoing a still more sluggish rate of TFP improvement than the 22 percent found for the aggregate economy.

Looking more closely at the timing of labor productivity and TFP movements in manufacturing, depicted by Figure P1, the surge during the decade 1919-1929 stands out starkly and the rates for the following sub-periods remain substantially above those for the three decades between 1899 and 1919.

Figure P1.



Average Annual Growth Rates of U.S. Manufacturing Sector's Labor Productivity (Black Columns) and Total Factor Productivity (Gray Columns)

These figures, which were derived by David (1991, Table 2) on the basis of underlying output and labor input data alternative to those used by Kendrick (1961) for the census years 1869 through 1909, also confirm Fabricant's perception of a break in trend following World War I. We may note, however that they indicate rather more rapid manufacturing productivity growth during the immediate post Civil War decades, and a correspondingly more pronounced "productivity pause" in the 1890-1914 era.[7] The resulting time path of the TFP index over the whole of the interval from 1869 to 1949 resembles the "lazy S" seen in Figure P2.

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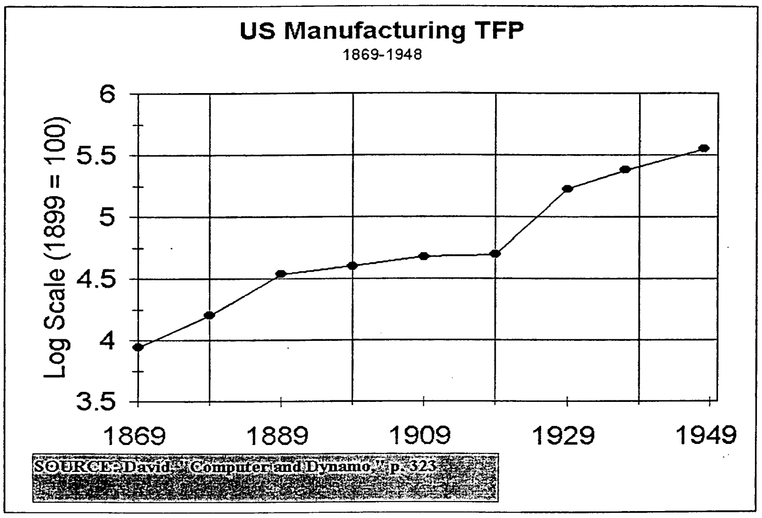
[7] David (1990, 1991) drew attention to the 1890-1914 U.S. productivity growth pause at the aggregate level and in manufacturing, but apart from that discussion, only Robert Gordon, in recent years, has commented upon the post World War I productivity surge and Fabricant's (1961) remarks.

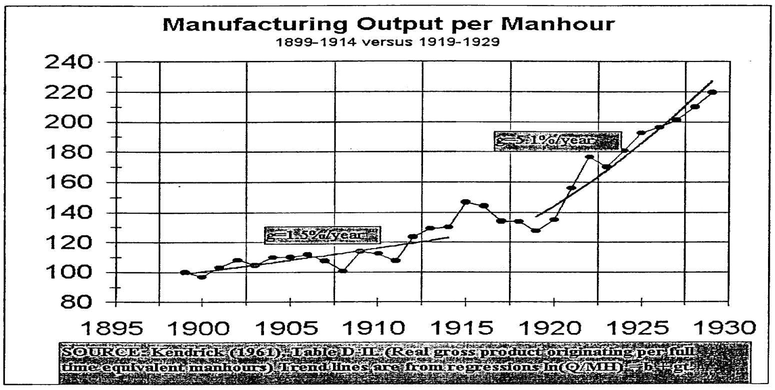
Figure P2.



SOURCE: David, "Computer and Dynamo," p. 323

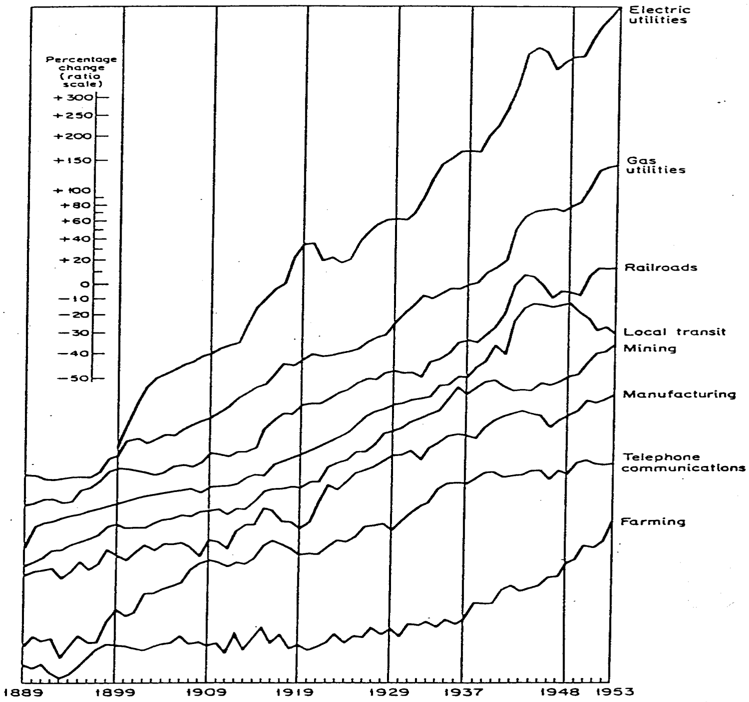
Focusing on the twentieth century portion of the statistical record, we may dispose of such doubts as may arise about the robustness of the trend break that followed World War I. The year 1919 was a low point in the business cycle, whereas 1929 was a peak. Rather than placing too much weight on the changes recorded between those cyclically non-comparable years, the available annual series for manufacturing output per man-hour permit estimation of the trend rates of growth for the periods before and after the 1915-1918 wartime interval. The series and the two trend lines fitted by logarithmic regressions are presented in Figure P3. These results confirm the discontinuity: the trend growth rate of labor productivity jumped from 1.5 percentage points per annum to 5.1 percentage points. A glance at Figure P4, which displays the logarithmic plot of the annual indexes tracing the movements of output per unit of labor input in each of the major sectors of the private economy, serves much the same purpose, providing visual confirmation that only the mining sector came close to matching the abruptness of the trend discontinuity that separated the pre-War and post-War eras. Having established that Fabricant had indeed identified a phenomenon worthy of more serious attention than it has received, we must now turn to consider how best to understand it.

Figure P3.



SOURCE: Kendrick (1961), Table D-II. (Real gross product originating per full time equivalent manhours) Trend lines are from regressions ln(Q/MH) = b + gt.

Figure P4.



2. Thinking About TFP Growth: Global or Localized, Yeast or Mushrooms?

How should we think about TFP surges in the economy, or in a major sector such as manufacturing such as occurred in the U.S. in the 1920's? Perhaps most familiar is the aggregate-level conceptualization of the sources of input efficiency growth that Arnold Harberger (1998) characterized in his Presidential Address to the American Economic Association as a "yeast like" process of uniform expansion. According to this conceptualization, TFP growth is identified with, and taken to result directly from, very general and broad advances in technologically applicable knowledge. Against this, Harberger contends that his vision of "a mushroom process" fits more readily the notion that TFP growth reflects "real cost reductions stemming from 1001 different causes." Mushrooms, offer a particularly suitable metaphor for the growth process in his view, because "they have the habit of popping up, almost overnight, in a fashion that is not easy to predict." What are we to make of this challenging vision, and how far can it help us to understand the early twentieth century surge of productivity growth in the U.S. economy?

The more familiar, "yeasty" conceptualization appears on its face to be more-or-less compatible with the conventional neoclassical production function approach to aggregate productivity analysis, although it is modifiable, perhaps, by allowing for the possibility that endogenous as well as autonomous technical progress may be responsible for the shifts thereof. But, equally, the vision of a loaf of bread dough ballooning outward uniformly under the fermenting agency of yeast, also could accommodate the notion that aggregate TFP growth is produced by the effects of Smithian division of labor, specialization and scale economies deriving from the expansion of the economy as a whole. Within such a framework the observed variations in the rate of advance of knowledge, or in conditions affecting its dissemination and diffusion into practical application, appear to be the most salient candidate sources of instabilities in the measured rate of productivity growth over the near-to and medium-run. But, the gap between best practice and average practice is viewed as approaching an equilibrium, given the constancy of the underlying rate of embodied efficiency growth; and so changes in that gap are unlikely to figure as explanations of more sustained variations in the observed growth rate of productivity.

On such a view, the equilibrium gap between best and average practice itself reflects the long-term steady state rate of savings (equal to investment) and the depreciation rate. The latter, in turn, would have to adjust to the rate of capital-embodied technical progress, designed obsolescence and durability, and consequently also is not supposed to undergo endogenous fluctuations due to supply-side forces. Endogenous growth theorists have not said much about such temporal variations, which they would presumably seek to trace to changes in institutions and policies affecting the formation of human capital, R&D investment, and market opportunities for industrial specialization.[8]

The foregoing are not the only possibilities envisioned by the "yeast" conceptualization. In an alternative formulation of the way production relationships change, the global shifting of an aggregate production function disappears from the scene. TFP increase results instead from localized advances in technological and organizational practice, arising from constrained "learning by doing" or bounded knowledge searches conducted in particular industries and sectors. The advances achieved in that fashion are retained when they prove to be well-suited to the local economic context, but some among these may prove to be especially susceptible to extension and generalization for application in a widening sphere of production activities. Responses to particular factor market conditions, regionally and temporally specific in nature, can take this form, as David (1975) and Wright (1990, 1998) have suggested in regard to different phases of U.S. industrial development. Nathan Rosenberg's (1963) idea of technological transfer and convergence, whereby many industries come to adopt the same production methods and product design approach, equally fits within this vision. This also is the conceptualization that the theory of general purpose technologies draws upon, as in the work of Timothy Bresnahan and Manuel Trajtenberg (1996), and the contributors to the volume recently edited by Elhanan Helpman (1998).

The global change vision of TFP growth that we have sought to adumbrate in the foregoing discussion lends itself more readily to formulations in which technological progress is Hicks neutral; whereas allowance for the localized character of technical and organizational innovations opens greater possibilities for biased (non-neutral) innovations. Progress taking the latter form might well emerge at a global level through the persistent, self-reinforcing exploration of certain technological trajectories. Rapid improvement of efficiency achieved along the latter paths would tend to have a self-reinforcing effect, rendering such production regimes increasingly dominant under a wider variety of input price conditions and production scales. In other words, learning that was neutral within a particular (localized) region of the factor input combination space could give rise to a global bias in factor savings (David 1975, Ch. 1).

Thus, to give some illustrative concreteness to the point, nineteenth century U.S. mechanization that was raw-materials-using as well as capital-using was promoted by the natural resource abundance of that region of recent European settlement. The unit process for continuous production systems was fixed capital-using and labor-saving, and it came to be widely diffused from petroleum to chemicals, etc. The fixed transfer-line system of assembly, beginning with disassembly operations in meat-packing, and in Pullman car construction, but brought to an advanced state by Ford at Highland Park, Michigan, also was fixed capital-using and labor saving in relation to batch production systems, yet it was

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[8] See e.g., P. Romer (1990, 1996), and Crafts' (1996) exploratory efforts to apply the new growth theory historically.

susceptible to improvements in throughput speed that made elements of the Ford "factory regime" applicable in a wide range of industrial settings (Hounshell 1984, Ch. 6, 7).

In juxtaposition to the "yeasty" vision of sources of productivity increase spreading more-or-less uniformly throughout the economy and its major sectors, Professor Harberger essays quite another vision involving "mushroom-like growth" at the micro-level. Here the picture is one of TFP levels shooting upwards only during certain times, and at particular points in the field of firms and industries. These upsurges are highly localized, but being idiosyncratic to the business context they are largely independent rather than interrelated developments that, in addition, do not generate important knowledge spillovers or allied non-pecuniary externalities. Such variations in the pace of TFP growth as might be observed at a more aggregative level reflects nothing that could properly viewed as an underlying generic or global phenomenon; the representative firm conceptualization of the production function thus would appear to "mushroom-fancying" analysts to be an uninstructive framework for empirical investigations of economic growth.

Professor Harberger's association of this vision of "mushroom-like growth" with the idea that TFP reflects myriad and idiosyncratic sources of cost savings at the (firm and) industry levels, only a few of which have great leverage over the aggregate, goes further than issuing a direct challenge to the conceptualization of TFP growth as involving various kinds of knowledge spillovers. Curiously enough, this vision coincides closely with that projected by some evolutionary economists, such as Richard Nelson and Sidney Winter (1982) and Stan Metcalfe (1997), who see TFP growth at the aggregate level as arising from micro-level innovations of a stochastic nature that are selected for their profit-generating potential by specific firms. Where they depart from Harberger's conceptualization is in emphasizing the process whereby selected innovations become established as the routines of business entities that, by ploughing back their profits, accordingly grow in the weight they carry in industry patterns of factor use. In the latter view what will be observed at the level of aggregate production relations can be understood only by analysis at the micro-level – which is one message also conveyed by Harberger's vision of "mushrooming" TFP growth. Of course, if one admits the possibility of purposive imitation among the firms, we return to the model of localized technological and organizational innovation with spillovers and eventually widespread diffusion. Whether or not there is a high degree of concentration of TFP gains and cost savings in some sub-group of activities is then likely to be a matter of the speed of diffusion and the choice of the time interval over which the measurements are made.

The key feature of the "mushroom-like" conceptualization of productivity growth that seems most sharply divergent from a "yeast-like" vision is its supposition of a high degree of independence, or orthogonality, between the conditions that give rise to real cost reductions in different branches of the economy. The rejection of spillovers and externalities in the advance of knowledge is one aspect of this. But another would seem to be a denial of the process of convergence, or confluence, in trajectories of technological advance that give rise to synergetic, or cross-catalytic effects. For a recent illustration of such phenomena one need look no farther than the effects of the convergence first of computing and telecommunications technologies, and to consider within the latter not only the use of microprocessors for digital switching but the fantastic expansion of bandwidth by use of laser-pumped optical transmission. To these counter-examples also could be added the convergence of computer and telecommunications technologies with the digitization of graphical images and sound, which are transforming the production and distribution of the entertainment media business. Were that not sufficient to raise doubts about the universal validity of the proposition that TFP growth can be traced to independent, essentially isolated developments, the point should be made that significant advances in the efficiency of complex production systems are more likely to come about through the confluence of distinct but complementary developments.

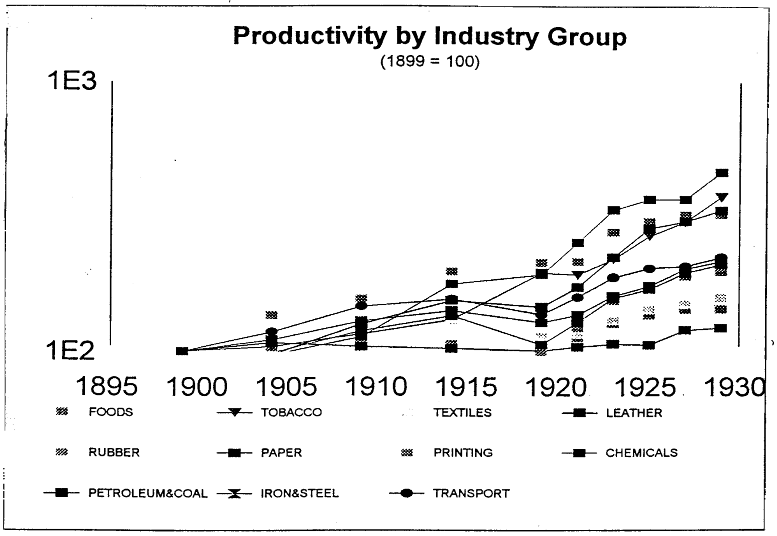
Indeed, such technical complementarities may themselves engender feedback effects that reinforce the convergence among them. A striking historical illustration of enhanced system-level real cost savings is provided by Fishlow's (1966) study of the innovations underlying the rise of productivity in the U.S. railroad transport sector during the late nineteenth and early twentieth centuries. Accelerated TFP growth came about in this instance through the convergence or "clustering" of diverse complementary developments that permitted the application of greater locomotive power to achieve higher train speeds and greater haulage capacities, thereby increasing the intensity with which both rolling stock and infrastructure could be utilized. But those gains were rendered realizable only through the introduction of more durable, wear-resistant steel rails, automatic air-braking, and block signaling and switching technologies; and they were enabled to affect the operating productivity of railroads as fully as they did because the introduction of automatic coupling and uncoupling raised the speed and efficiency with which trains were assembled and disassembled at the endpoints of their journeys, cutting the idle time of rolling stock.

Nevertheless, we hardly can rely solely on general theoretical considerations, or historical illustrations from other industries in different periods as our basis for arguing that Harberger's (1998) vision of "mushroom-like" growth at the micro-level has only very limited validity as a guide to understanding the dynamics of the industrial productivity surge that marked the post-World War I period. The main empirical apparatus that Harberger proposes in supporting his new vision involves conducting a more disaggregated examination of productivity movements, in order to determine whether TFP increases during a given period were highly concentrated in a handful of disparate branches of production rather than being very evenly distributed across the industrial landscape. Unfortunately, due to the limitations of the available data needed to ascertain TFP growth rates for very narrow segments of U.S. manufacturing prior to 1939, exactly the same approach cannot be applied in the case at hand. But it is quite feasible for use to look more closely beneath the sectoral growth rates of manufacturing labor productivity.

A Closer Look at the Pre-1929 Pattern of Productivity Changes in U.S. Manufacturing

What emerges very clearly from our quantitative inquiry is the widespread industrial participation in the accelerated growth that marked the period after 1919. In Figure P5 the index numbers of real output per man-hour for 11 industry groups observed at quinquennial intervals have been graphed on logarithmic scales. In virtually each group the upward slope became more pronounced during the 1920's than it had been during the preceding decade, and in comparison to the trend established between 1900 and 1915. It will be seen in the next section from the data assembled in Table 4 that 13 of the 14 major industry groups represented there also participated in the acceleration of the pace of TFP growth between the decades 1909-1919 and 1919-1929. Transportation equipment was the exception, only because automobile manufacturing experienced an even faster pace of productivity gains in the earlier decade.

Figure P5.



The empirical center-piece of Harberger's (1998) vision of the growth process is his analysis of the extent to which, in any period of interest, the observed TFP increases (or real cost reductions) remain concentrated in a comparatively small portion of the overall economy, or a major sector therein such as manufacturing. He presents calculations for the post-World War II U.S. showing that the fractions of manufacturing industry which by themselves were able to account for the full amount of real cost reduction achieved over successive five year intervals between 1970 and 1990 ranged downwards from 50 percent of total value added in manufacturing to as small a share as 12 percent. Since those figures are based on the same eighteen industry groups that we list in Table 2, it is illuminating to carry out a similar assessment of the degree of concentration of labor productivity advance (reductions in real unit costs of labor) during the 1920's. We can say at the outset that the divergence from Harberger's (1998, p. 6) findings is great indeed, because all eighteen industries enjoyed positive productivity change in our period; consequently, contributions from virtually the entire ensemble are required to produce the aggregate gain.

The approach taken in developing Table 2 is a minor variant on Harberger's scheme of calculations, for, as is explained by the Notes and Sources to the Table, we examine the concentration in the growth of labor productivity achieved by the eighteen industry groups, whose estimated value added in 1929 represented about 93 percent of value added in the entire manufacturing sector. What has been done, in effect, is to find the weighted average growth rate over the 1919-1929 interval for this ensemble of industry groups, using the individual industry shares of 1929 value added (in Column 2) to weight the industry-specific productivity growth rates (as shown in Column 1). The industry groups are arrayed in the table in descending order of their pace of productivity growth, and, starting with the Transportation Equipment group at the top, we can cumulate the proportions of total group value added (in Column 2) and the weighted average rate of the ensemble (in Column 3) that are being added by each group as one proceeds down the ranking.

Table 2.

Industry Group	Average Annual Growth Rate of Real Output per Manhour, 1919-29 (Percentage Points)	Cumulative Proportion of 18 Groups' 1929 Aggregate Value Added	Cumulative Proportion of Weighted Average Labor Productivity Growth Rate for 1919-29	Labor Productivity Acceleration: Change in Average Annual Growth Rate from 1909-19 to 1919-29 (Percentage Points)
Transportation Equipment	9.11	.079	.141	1.45
Petroleum and Coal Products	9.00	.108	.192	7.24
Rubber Products	8.38	.127	.224	0.54
Chemicals and Allied Products	8.22	.188	.322	8.48
Tobacco Products	7.24	.201	.349	1.16
Stone, Clay and Glass Products	6.33	.238	.384	5.29
Primary Metal Industries	5.76	.337	.496	6.12
Food and Kindred Products	5.38	.455	.620	5.38
Fabricated Metal Products	5.11	.509	.674	3.09
Paper and Allied Products	5.06	.537	.701	4.54
Furniture and Fixtures	4.34	.558	.719	4.73
Apparel and Related Products	3.98	.626	.772	0.64
Electric Machinery	3.98	.674	.809	4.01
Printing and Publishing	3.75	.753	.868	0.48
Non-electric Machinery	2.97	.842	.919	2.28
Lumber and Products	2.97	.888	.947	3.98
Leather and Products	2.54	.915	.963	1.61
Textile Mill Products	2.45	1.000	1.000	0.72
Weighted Average of 18 Industries	5.36			
Total Manufacturing Sector	5.59			4.45

Notes and Sources for Table 2: Productivity Growth by Industry Groups, 1919-1929

Note[a]: This weighted average growth rate is Σ p(i) · s (i), as defined in the sources for column (3).

Sources

Column (1) and **Column (4)**: Computed from real output per manhour indexes in Kendrick (1961), Table D-IV, for each industry group; from Kendrick (1961), Table D-I for manufacturing sector as a whole.

Column (2): Cumulative proportions for the (ordered) industry groups were obtained by first summing the 1929 (current dollar) value added figures for the 18 groups, obtained from U.S. Commerce Department, Historical Statistics of the U.S. (1975), Series 65, to obtain the total Σv(i) = V. Proportionate industry group shares, found as s(i) = v(i)/V, were cumulated, thus: C_s(j) = C_s(i) + s(j).

It was necessary to estimate missing 1929 value added figures for the following specific industry groups, by extrapolating from the 1937 entry the earliest available value added figures presented by the Historical Statistics of the U.S. (1975), Series P-65.

Primary Metals: extrapolated on index of raw steel output (Series P-265), multiplied by the price index of steel rails (Series E-130).

Fabricated Metal Products: extrapolated on a weighted index of rolled iron and steel, and copper products (Series P-270-271), multiplied by the index of wholesale prices of metal products (Series E-47).

Electrical Machinery: extrapolated on index of value of output of electrical equipment (Series P-355).

Non-Electrical Machinery: extrapolated from Series P-65 entry for 1937 on index of value of output of industrial machinery and equipment (Series P-353).

Tobacco Manufactures: the 1931 entry from Series P-65 was used.

Column (3): Cumulative proportions of the weighted average of labor productivity growth rates (in Col. 1) were derived by first computing the industry group's 1919-29 growth contribution on a 1929 base: p(i) = y(i) · s(i), where y(i) is the growth rate from **Col. (1)** and s(i) is the 1929 value added share defined for **Col. (2)**. The weighted average rate is found as the sum: Σp(i); the proportional share is P(i) ≡ [p(i)/Σ p(i)], and these were cumulated, thus: C_p (j) = C_p (i) + P (j).

The pairs of corresponding cumulative proportions can be displayed graphically as a Lorenz curve, the curvature of which provides a visual indicator of the degree of concentration. The very flatness of the curve shown in Figure P6, which never rises far above the (45-degree) line that indicates complete absence of concentration, makes immediately apparent the marked divergence of these results for the 1920's from the general tenor of the findings that Harberger presents to support his characterization of industrial productivity growth in the 1970's and 1980's as having been more like "mushrooms" than "yeast."

Although matching the level of aggregation chosen by Harberger (1998), the industry groups in Table 2 are still quite broad, and some of them subsume rather heterogeneous collections of manufacturing branches. A still more disaggregated view of the labor productivity growth path between decadal benchmarks therefore is presented in Figure P7, which exhibits the logarithms of output per man-hour indexes for twelve selected branches of manufacturing that are found within some of the major industry groups. Yet again the contrast between pre- and post-World War I experience is found to have been widely shared.

Figure P6.

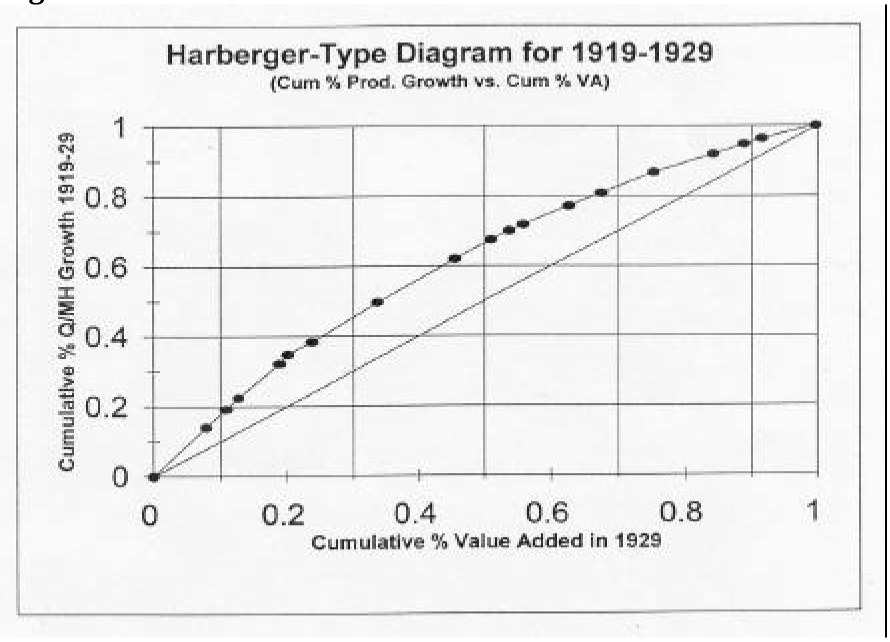
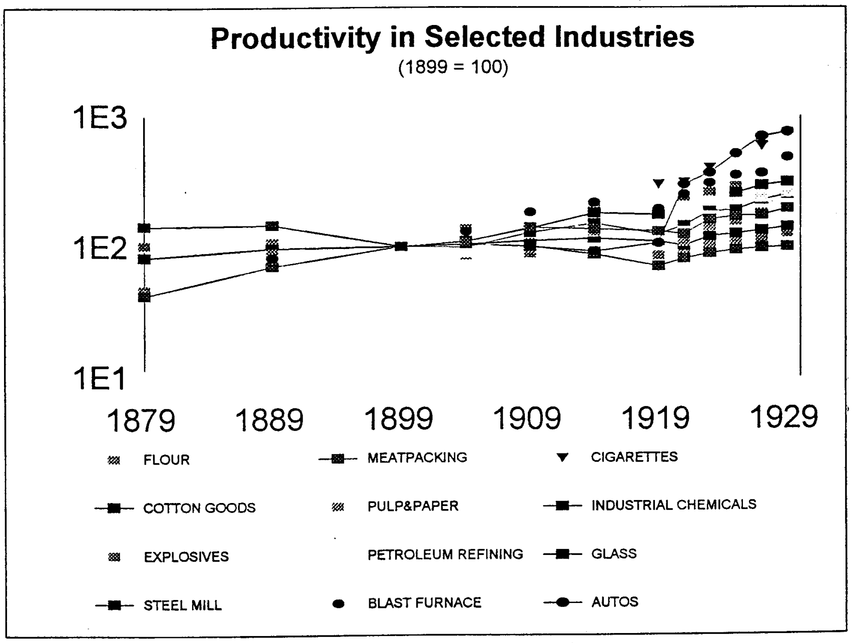
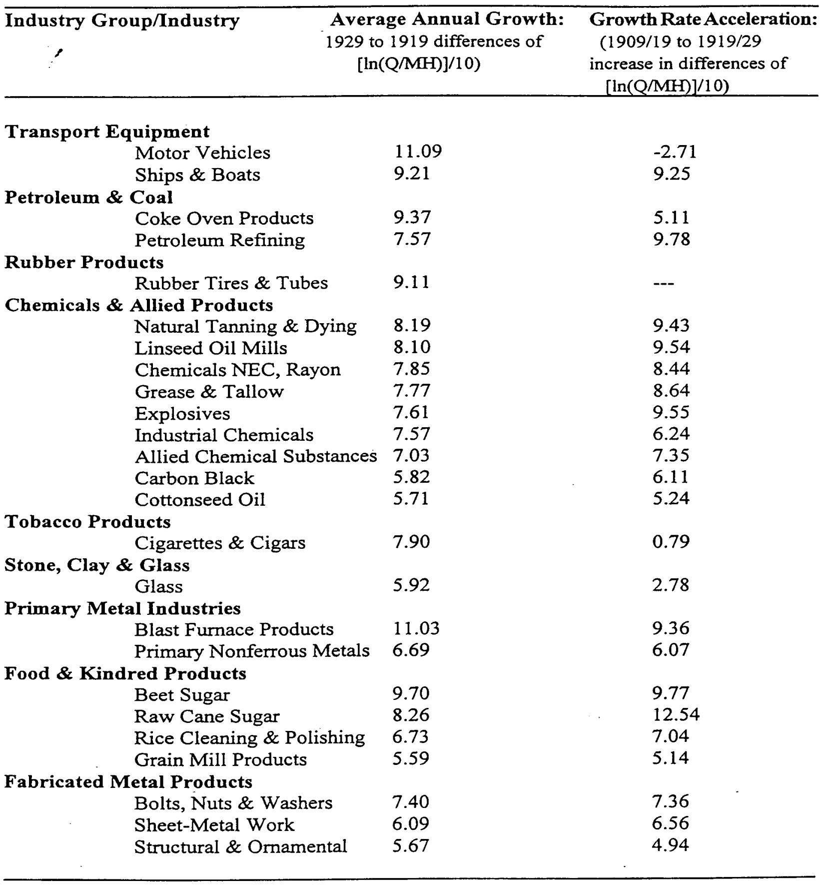


Figure P7.



One further, and rather more systematic demonstration can be made of just how widely distributed was the participation by detailed industrial branches in the wave of rapid labor productivity advance that marked the 1920's. As was seen from Table 2, the weighted average annual growth rate of output per man-hour for the eighteen major industry groups stood at 5.36 percentage points during that decade, and the eight groups whose productivity growth was most rapid all enjoyed annual growth rates that were above that average, the slowest being Food and Kindred Products which had averaged a rate of 5.38 percentage points per annum.[9] Table 3 takes us within these fast labor productivity growth groups to find out whether these high group averages reflected the impacts made upon each by a single high-flying sub-branch – the sort of super-fast-rising "mushrooms" that Harberger's model envisages as springing up randomly across the industrial landscape. For this purpose we have listed in the first column of Table 3 all the sub-branches that experienced faster productivity growth than the average for the manufacturing sector as a whole. In all there were twenty-two such branches of manufacturing arrayed under the eight group headings, and, except for Rubber Products, Tobacco, and Stone Clay & Glass, there were at least two high flying members within each group and as many as nine, in the case of the Chemicals and Allied Products group.

Table 3.



Industry Group/Industry	Average Annual Growth: 1929 to 1919 differences of [ln(Q/MH)]/10)	Growth Rate Acceleration: (1909/19 to 1919/29 increase in differences of [ln(Q/MH)]/10)
Transport Equipment		
Motor Vehicles	11.09	-2.71
Ships & Boats	9.21	9.25
Petroleum & Coal		
Coke Oven Products	9.37	5.11
Petroleum Refining	7.57	9.78
Rubber Products		
Rubber Tires & Tubes	9.11	---
Chemicals & Allied Products		
Natural Tanning & Dying	8.19	9.43
Linseed Oil Mills	8.10	9.54
Chemicals NEC, Rayon	7.85	8.44
Grease & Tallow	7.77	8.64
Explosives	7.61	9.55
Industrial Chemicals	7.57	6.24
Allied Chemical Substances	7.03	7.35
Carbon Black	5.82	6.11
Cottonseed Oil	5.71	5.24
Tobacco Products		
Cigarettes & Cigars	7.90	0.79
Stone, Clay & Glass		
Glass	5.92	2.78
Primary Metal Industries		
Blast Furnace Products	11.03	9.36
Primary Nonferrous Metals	6.69	6.07
Food & Kindred Products		
Beet Sugar	9.70	9.77
Raw Cane Sugar	8.26	12.54
Rice Cleaning & Polishing	6.73	7.04
Grain Mill Products	5.59	5.14
Fabricated Metal Products		
Bolts, Nuts & Washers	7.40	7.36
Sheet-Metal Work	6.09	6.56
Structural & Ornamental	5.67	4.94

We may go a step farther by checking whether Table 3 reveals that no more than a single sub-branch within each group achieved a rate of productivity growth that stood about the average rate for the group. Those would constitute "the fastest of the fast," and it is true that in the cases of three of the industry groups there was a solitary member of that elite class. But there were pairs in the cases of Transport Equipment, Chemicals and Allied

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[9] It might be noted from Table 2 that whereas the 1929 value-added weighted average growth rate for the 18 industries was 5.38 percent per annum, average annual labor productivity growth in the entire manufacturing sector was 5.6 percent. This implies that changes in the structure of the manufacturing sector during 1919-29 (measured by the shares of value added) could not have been contributing substantially to the high sectoral productivity growth in that decade.

Product, Primary Metals, and as many as four of these "super-fast-rising mushrooms" had sprung up within the Food and Kindred Products group.

The upshot of the immediately preceding discussion is that an understanding of the forces that underlay the post-1919 industrial productivity surge is more likely to involve the identification of some broad, generic developments that were impinging widely upon U.S. manufacturing activities – at least more likely than would be true of other, less extraordinary periods, and certainly more likely than would be suggested by the vision of the growth process that Harberger has proposed. Perhaps what this implies is that the generality of participation in quickening productivity growth is a feature of surge-like movements that are discerned at higher levels of aggregation, because it is on those occasion that the "yeast process" has come to dominate the "mushroom process" that prevails during episodes of "productivity pause".

If we can accept that broad but nevertheless quite plausible conjecture as a working hypothesis, our explanation of productivity dynamics in the early twentieth century U.S. should be focused upon more global developments, and particularly those that entailed profound structural changes, and the emergence of widely applicable innovations. Some clues to the nature of those developments are to be found in the new constellation that appeared during this period in the behavior of the partial productivity measures for industry groups within manufacturing.

The scatter diagram displayed in Figure P8, relating the growth of capital and labor productivity by industry, shows a moderate positive correlation between the two over the course of the 1919-1929 interval. The cross-section relationship parallels the time-series association that emerges during the 1905-1927 period in these partial productivity variables for manufacturing as a whole, and for the private domestic economy as well. Thus, we are not dealing here with the growth accounting situation envisaged by modern growth theory, where the growth of labor productivity can be partitioned between the additive effects of technological and organizational innovation that are supposed directly to raise the efficiency of labor inputs, and such contributions as result from the rate of "capital-deepening" in response to falls in the relative rental rate on capital. Rather than capital-deepening, reflected in a rise in real capital inputs per unit of real output, manufacturing industries both in aggregate and at the industry group level were undergoing "capital-shallowing" or rising capital productivity after 1919.

As will be discussed more fully in section 4, a long period of stasis in the real unit costs of industrial labor during 1890-1914 came to an end with the outbreak of World War I and the ensuing rapid rise in the price of labor inputs vis-à-vis the prices of both capital inputs and gross output was sustained during the post-War decade. The change in relative factor prices thus was in a direction that would tend to induce the substitution of capital for labor within the pre-existing set of production technologies. Therefore, it is particularly striking that after 1919 the rise of capital-intensity in U.S. manufacturing proceeded at a greatly *retarded* pace. Between the 1889 and 1909 census benchmark dates, the ratio of capital inputs per unit of labor input was rising at the average rate of 2.6 percentage points per year, and the pace quickened to 2.8 percent per annum over the decade 1909-1919. But during the 1920's, despite the upsurge of real wage growth, the growth in capital-intensity slowed to 1.2 percentage points per annum, well below half its previous pace.[10] This change, and the emergence of "capital-shallowing" with which it was linked, represented a

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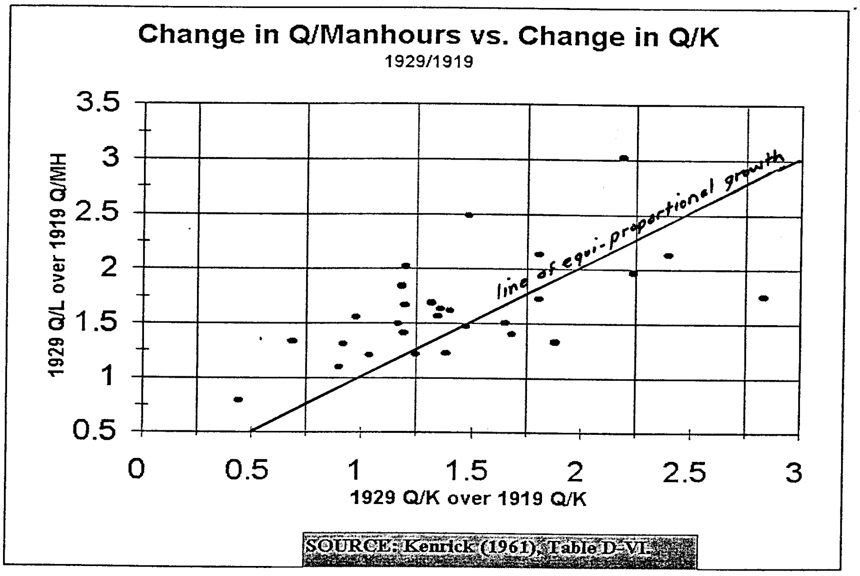
[10] The figures cited are based upon Kendrick's (1961; Table D-I) indexes of manufacturing capital input and labor input (which in this period closely tracks manufacturing manhours).

new departure, reflecting the diffusion of the new production regime in manufacturing that was based upon applications of the electric dynamo.

Figure P8.



SOURCE: Kenrick (1961), Table D-VI.

3. Electrifying Manufacturing

In the dynamo revolution, as David (1990, 1991) has pointed out, one may recognize the emergence of an extended trajectory of incremental technical improvements, the gradual and protracted process of diffusion into widespread use, and the confluence with other streams of technological innovation, all of which are interdependent features of the dynamic process through which a general purpose engine acquires a broad domain of specific applications. Successful exploitation of the new technology's evolving productivity potential over the period from the early 1890's to 1929 entailed the production and financing of investment projects whose novelty – in terms of scale, technical requirements, or other characteristics – posed significant challenges for the existing agencies supplying capital goods and the established capital market institutions. Although their realization was delayed for decades after the engineering possibilities were first appreciated, these developments finally bore fruit in the surge of TFP growth in the manufacturing sector that was concentrated in the post-World War I era.

The Pace of the Dynamo Revolution in Theory and Practice

The history of electrification[11] from 1900 onwards lends considerable plausibility to the "regime transition thesis" advanced by Freeman and Perez (1986). Addressing the modern productivity paradox, these writers suggested that the pace of TFP growth well might remain sluggish for an extended duration because the emergence and elaboration of a new techno-economic regime based on computer and communications innovations – supplanting the mature, ossified Fordist regime of mass production – would, more than likely, be a protracted and historically contingent affair. In much the same fashion as the

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[11] See e.g., Hughes (1983), Schurr et al. (1991), on the U.S. experience; see Byatt (1979), on Britain; Minami (1987), on Japan.

present-day enthusiasts of the information age have heralded the revolutions to be wrought by the advent of universal access to massive amounts of computing power, at the opening of the twentieth century there were farsighted electrical engineers who already had envisaged many of the profound transformations that the dynamo revolution would bring to factories, stores, and homes. But the materialization of those presbyopic visions was less imminent than it appeared to be to many at the time.

Certainly, the transformation of industrial processes by the new electric power technology was a long-delayed and far from automatic business. It did not acquire real momentum in the U.S. until after 1914-17, when the rates charged to consumers of electricity by state-regulated regional utilities fell substantially in relationship to the general price level, and central station generating capacity came to predominate over generating capacity in *isolated* industrial plant. Particularly rapid gains in the efficiency of electricity generation during 1910-1920 underlay these developments.[12] This closely reflected the fact that the number of kilowatt-hours of power per dollar of central station generating costs (in constant prices) was increasing at the average rate of 9.4 percent per year, whereas over the two preceding decades (1890-1910) it had been rising at 5.0 percent per annum. To realize the economies of scale that were attainable with immense central power plants that used high-speed steam turbines to drive massive alternating current generators required more than the very substantial direct investments represented by such facilities. For one thing, it necessitated the integration and extension of power transmission networks over an expanded territory. Within a larger service area the greater diversity of electricity users contributed to mitigating the peak-load problem; load-balancing improved the utilization of fixed capacity, to which the cost structure of the industry was extremely sensitive.

But this was not simply a matter of technology. Significant adaptations in other dimensions affecting business practice were called for. In the American setting, two “social innovations”, pioneered by Samuel Insull at the Chicago-based Commonwealth Edison Co. greatly facilitated the channeling of investment into the formation of regional electric utilities during the century’s second decade.[13] One was an adjustment of the political environment, advantageously affecting the terms on which long-term monopoly franchises could be secured, and reducing the transaction costs entailed in obtaining franchises to operate in many contiguous communities.[14] This change was largely accomplished during the period 1907-1914, through a campaign (on the part of the National Electric Light Association) to transfer regulatory authority over the electricity supply business from municipal and town governments to specially created state public utility commissions. The second “innovation” was the application (first by Insull, in creating the Middle West Utilities Co. in 1912) of the holding company form of corporate organization to the problem of financing both the acquisition and the incremental investment needed to physically integrate numerous small, local utility operations within an extensive, centrally managed regional network.[15]

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[12] See David (1991): Table 4 and Figure 14. Also Schurr et al. (1991). Estimates of TFP growth in the electric utility industry made by Kendrick (1961: Table H-VI) show a sharp acceleration during 1909-1919.

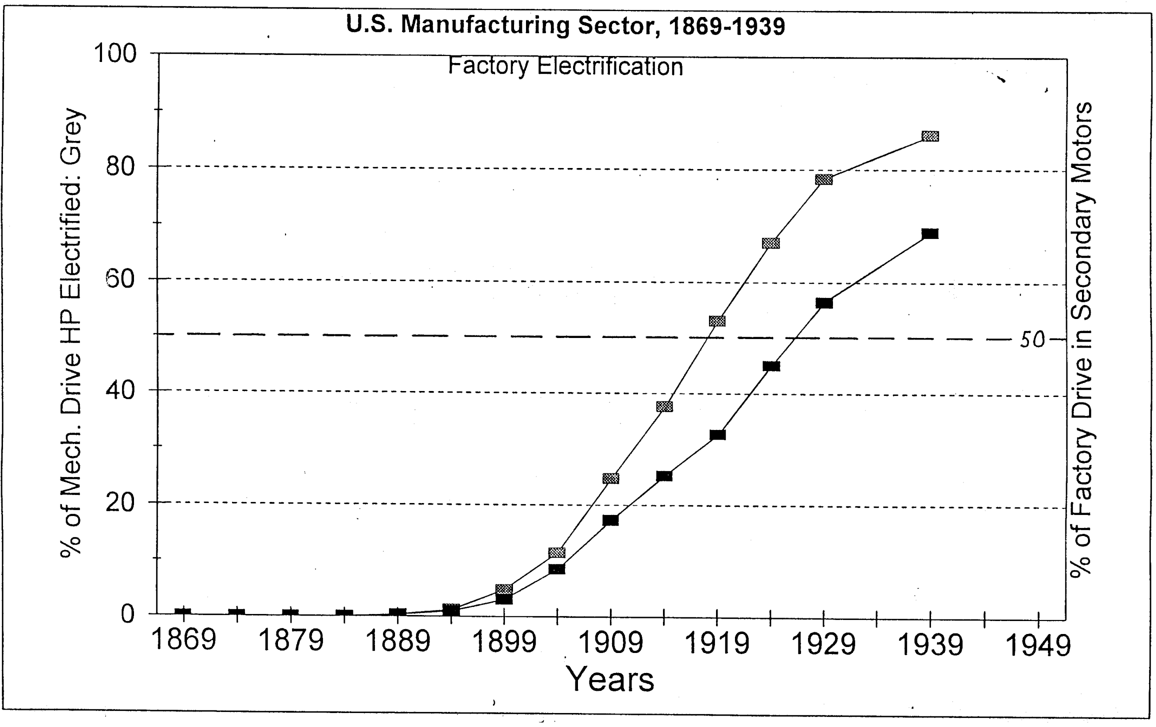
[13] See Platt (1991): esp. Ch. 7, on Insull, the Commonwealth Edison Company and the formation of regional network in the Midwest.

[14] See MacDonald (1962): pp. 82-89, 114-17, 177-78.

[15] The success of the campaign to shift regulatory authority to the state level owed much to its coincidence with the political movement for civic reform, and the waning enthusiasm for municipal ownership of utilities, following the

Factory electrification did not reach full fruition in its technical development and in its impact on productivity growth in manufacturing before the early 1920's, at which time only slightly more than half of factory mechanical drive capacity had been electrified, as may be seen from Figure E1. This was four decades after the first central power station opened for business.

Figure E1.



The proximate source of the delay in the exploitation of the productivity improvement potential incipient in the dynamo revolution was, in large part, the long time it took before substantial gains were being achieved from year-to-year in the proportion of mechanical drive that was electrified, especially by the substitution of purchased current for factory-generated power. The delay, in turn, was attributable to the unprofitability of replacing still serviceable manufacturing plants embodying production technologies adapted to the old regime of mechanical power derived from water and steam.

Thus, it was the American industries that were enjoying the most rapid expansion in the early twentieth century – tobacco, fabricated metals, transportation equipment, and electrical machinery itself – that afforded greatest immediate scope for the construction of new, electrified plants along the lines recommended by progressive industrial engineers.[16] More widespread opportunities to embody best-practice manufacturing applications of electric power awaited the further physical depreciation of durable factory structures, the locational obsolescence of older-vintage industrial plants sited in urban core areas, and,

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collapse of the market for municipal bonds in the Rich Man's Panic of 1907. This suggests the historically contingent character of some of the developments that shaped the evolution of the electricity supply industry and its consequences for the transformation of manufacturing technology. On financial holding companies in the utility industry, see MacDonald (1962): Ch. 5.

[16] See DuBoff (1979): p. 142; Minami (1987): pp.138-41.

ultimately, the development of a general fixed capital formation boom in the expansionary macroeconomic climate of the 1920's.

From the beginning of the century onward, there were farsighted electrical engineers who envisaged many sources of cost-savings that would result from exploiting the flexibility of a power transmission system based on electric wires, especially the efficiency gains that would be obtained by replacing the system of shafting and belts with the so-called "unit drive" system. In the latter arrangement individual electric motors were used to run machines and tools of all sizes.[17] But, as will be seen, the benefits of the unit-drive system would be reaped fully by building a new kind of factory, whereas the persistence of durable industrial facilities, embodying older power generation and transmission equipment, had some perverse consequences for average capital productivity that are worth noticing. During the phase of the U.S. factory electrification movement extending from the mid-1890's to the eve of the 1920's, the "group drive" system of power transmission had remained in vogue.[18]

With this system – in which electric motors turned separate shafting sections so that each motor would drive related groups of machines – the retrofitting of steam- or water-powered plants typically entailed adding primary electric motors to the original stock of equipment. From photographs of the Ford Co.'s Highland Park Plant taken shortly after its opening in 1913, one can see that even in this relatively new plant overhead group-drive equipment had been installed alongside the old mechanical system of power transmission using shafts and belting (see Hounshell 1984, pp. 232, 250). Owners of pre-existing factories rationally could ignore the sunk costs of the installed shaft and belting equipment, and act on a calculation that 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, by contrast, have to reckon that the original (belt and shaft) power transmission equipment, and the primary engines that powered them, remained in place as available capacity. The effect of the incremental investments in electrification using group drive would be to raise the capital-output ratio in manufacturing, thereby militating against rapid gains in measured TFP.[19]

During the initial phase of the dynamo revolution in industry, while electric motors driven by purchased energy still represented only 10-15 percent of total manufacturing horsepower, as was the case during 1919-1925 (Gould 1946), the rising proportion of total factory drive capacity that took the form of secondary motor horsepower reflected the diffusion first of the group drive system, and later of the unit drive system. As may be seen from Figure E1, secondary electric motor capacity as a proportion of electric and non-electric direct drive horsepower rose from 33 percent to 56 percent between 1919 and 1929.

The advantages of the unit drive for factory design turned out to extend well beyond the savings in inputs of fuel derived from eliminating the need to keep all the line

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[17] For further description see Devine (1983), pp. 362ff; David (1991); Schurr et al.(1991): esp. Ch. 1, pp. 29-30 and 292-293.

[18] This would be so especially if the energy input savings, and the quality improvements from better machine control were left out of the productivity calculation. See Duboff (1979): p. 144; Devine (1983): pp. 351, 354.

[19] This sort of overlaying of one technical system upon a pre-existing stratum is not unusual during historical transitions from one technological paradigm to the next. Examples could be cited from the experience of the steam revolution (von Tunzelmann 1978: pp. 142-43, 172-73). 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 (see, e.g., Baily and Gordon 1988: pp. 401-02).

shafts turning, and the greater energy efficiency achieved by reducing friction losses in transmission. Factory structures could be radically redesigned once the need for bracing, to support the heavy shafting and belt-housings for the transmission apparatus that typically was mounted overhead, had been dispensed with. This afforded (1) savings in fixed capital through lighter factory construction, and (2) further capital savings from the shift to building single-story factories, whereas formerly the erection of more costly multi-story structures had been dictated by the desirability of reducing power-losses in turning very long line shafts, and the problems of variation in machine speed that increased with the length of those shafts. Single-story linear factory layouts, in turn, permitted (3) closer attention to optimizing materials handling, and flexible reconfiguration of machine placement and handling equipment to accommodate subsequent changes in product and process designs within the new structures. Related to this, (4) the modularity of the unit drive system and the flexibility of wiring curtailed losses of production incurred during maintenance, rearrangement of production lines, and plant retrofitting. With fully electrified factory drive, the entire power system of the plant no longer had to be shut down in order to make changes in one department or section of the mill.[20]

Although all this had been clear enough in principle *c*. 1903-5, the relevant point is that its implementation on a wide scale required working out the details in the context of many kinds of new industrial facilities, in many different locales, thereby building up a cadre of experienced factory architects and electrical engineers familiar with the new approach to manufacturing. The decentralized sort of learning process that this entailed was dependent upon the volume of demand for new industrial facilities at sites that favored reliance upon purchased electricity for power. It was, moreover, inherently uncertain and slow to gain momentum, owing in part to the structure of the industry responsible for supplying the capital that embodied the new, evolving technology. The business of constructing factories and shops remained extremely unconcentrated and was characterized by a high rate of turnover of firms and skilled personnel. Difficulties in internalizing and appropriating the benefits of technical knowledge acquired in such circumstances is likely to slow experience-based learning. A theoretical analysis of an interdependent dynamic process involving diffusion and incremental innovations based upon learning-by-doing demonstrates that where the capital goods embodying the new technology are competitively supplied and there are significant knowledge spillovers among the firms in the supplying industry, the resulting pace of technology adoption will be slower than is socially optimal.[21]

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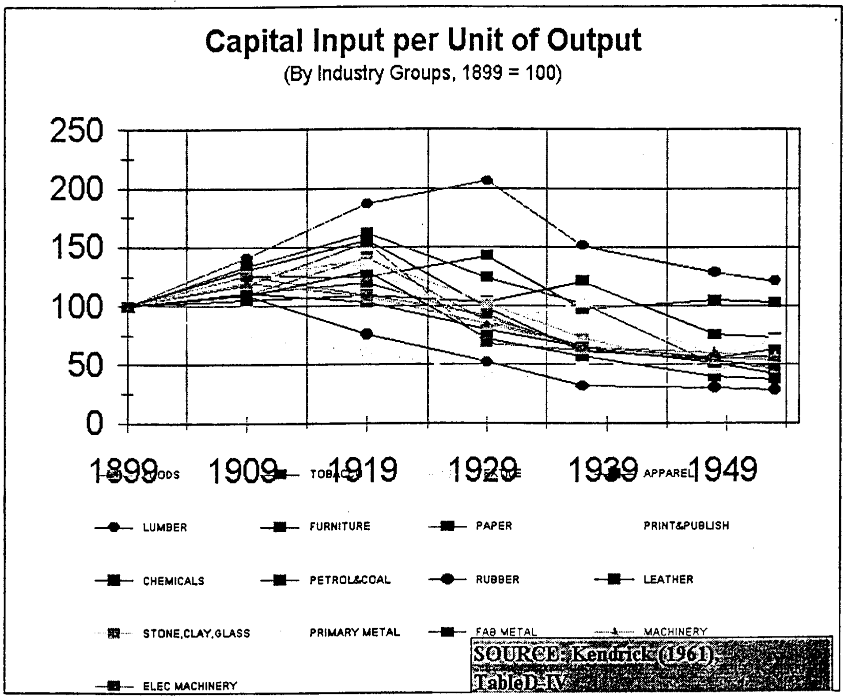
[20] For further discussion of the technical implication of the unit drive system, see Schurr et al. (1991): esp. Ch. 1, pp. 29-30 and 292-293.

[21] See David and Olsen (1986, 1992) for further discussion.

Figure E2.



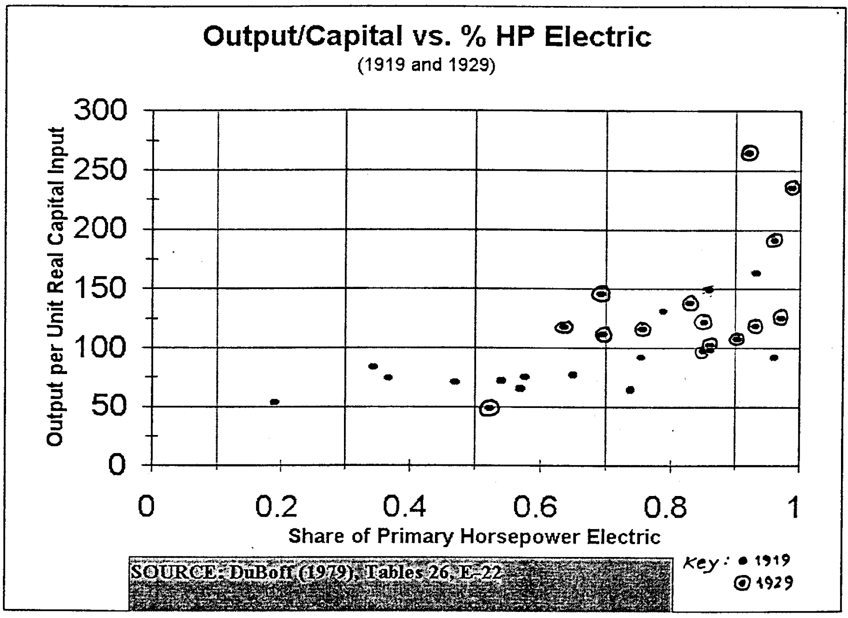
SOURCE: Kendrick (1961): Table D-IV

The replacement of prime movers by purchased electricity, and shafts and belting by wires as the means of power transmission within the factory, came as part of a package ultimately involving new plant design and the necessary relocation of manufacturing to suitable greenfield sites outside the old urban core districts. That in turn entailed the provision of suitable transport services via surfaced roads and motor trucks to industrial sites not served by the existing railroad network. While new investment was entailed in all this, much of it was undertaken outside manufacturing, whereas within that sector there were readily quantifiable resource savings. These are noticeable in the behavior of capital productivity measures. From Figure E2 it is evident that in all save two of the seventeen industry groups shown, the Kendrick (1961) index of capital input per unit of output was declining during the decade 1919-1929; whereas during this ratio had been rising in every one of the industries during 1899-1909, and in twelve of the seventeen cases during 1909-1919. Was there an immediate connection between the reversal of the prior trend toward capital-deepening, and the factory electrification movement in the 1920's?

Of course, by supplanting equipment that previously supplied mechanical drive, the switch to purchases of electric energy from central power stations lowered the capital requirements in manufacturing establishments in a direct way, an instance of sectoral capital-savings achieved through out-sourcing. But rather than interpreting the purely organizational aspect of that change as a source of enhanced overall manufacturing efficiency, it would be more satisfactory to work with a measure of TFP growth in manufacturing that adjusted for the growth of energy inputs purchased from outside the sector, just as has been the practice in examining the acceleration of TFP at the individual industry level. A rough adjustment of this kind can be made, which, naturally, shrinks the size of the multifactor productivity residual. But, rather surprisingly, the estimated amount by which the total input efficiency growth rate for the decade 1919-29 *exceeds* that for the preceding decade remains little changed, at 5.3 percentage points per annum.[22]

But, beyond the real cost savings that were achieved through the substitution of purchased (electric) energy for capital equipment in the form of prime movers in manufacturing plants, the foregoing discussion points to some overall capital-saving effects that accompanied the diffusion of the unit drive system and the new plants that were being designed around it during this era. Quantitative confirmation of this association can be found from the scatter diagram displayed in Figure E3: there is indeed a positive correlation across industrial groups between the average productivity of capital and the share of primary horsepower that was electrified in 1919. Furthermore, this association was more pronounced among the industry groups for which the later share ranged upwards from the 50 percent mark. By 1929, it can be seen, all of the industry groups had moved into the latter range, and the rising slope of the cross-section relationship became still more pronounced.

Figure E3.



SOURCE: DuBoff (1979), Tables 26, E-22

As one may see from Figures P8 or E4, during the 1920's the rates of change in the average productivities of capital and labor inputs for all the manufacturing industry groups lay in the positive quadrant, and in the industry cross-section there was a positive association between them. Since a positive relationship has been observed between capital productivity and the electrification of primary power, one might suppose that the weighted sum of the partial productivity growth rates, i.e., the value-added TFP growth measure, also would be positively associated with increasing electrification of primary horsepower. But that particular relationship turns out to be quite loose in the industry cross-section, which ought not to be so surprising, as correlation relationships are not transitive.

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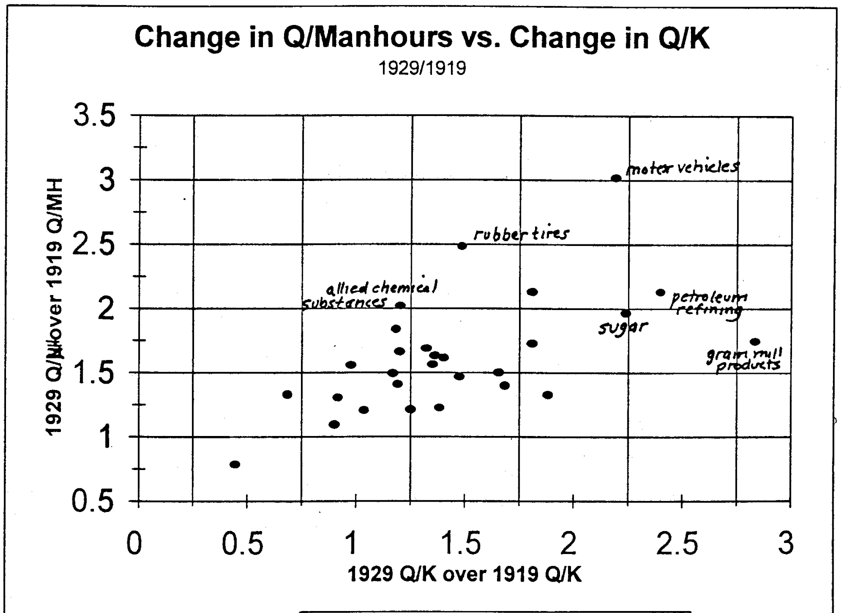
[22] See the estimates of TFP adjusted for purchased energy inputs, in Woolf (1984).

Figure E4.



SOURCE: Kenrick (1961), Table D-VI.

In any case, since purchased electric power was a (costly) replacement for primary power-generating facilities in the plant, the productivity growth measures of interest here are those in which TFP has been adjusted to take account of purchased energy inputs. These are available for 14 of the major industry groups that are listed in Table 4. The first column of entries in the table shows the percentage point per annum *acceleration* in the adjusted TFP residual between the 1910's and the 1920's. The second column presents the corresponding proportionate increase of secondary electric motor capacity installed by the industry between 1919 and 1929.[23] The existence of a positive rank correlation is directly visible when the two columns are compared, and a statistically significant relationship is found between the two variables – described by the linear regression line among the scatter of points in Figure E5.[24]

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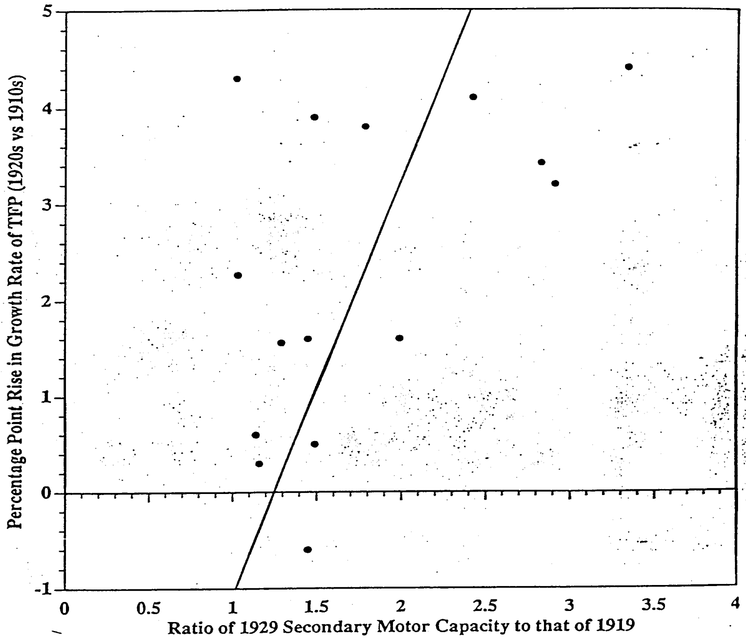
[23] Making use of this cross-section relationship, David (1991) found that approximately half of the 5 percentage point acceleration recorded in the aggregate TFP growth rate of the U.S. manufacturing sector during 1919-1929 (compared with 1909-1919) could be accounted for statistically simply by the growth in manufacturing secondary electric motor capacity during that decade. The alternative cross-section regression results presented below suggest a somewhat different imputed effect electrification during the 1920's.

[24] The regression results are those given by David (1991): p. 343, n. 17. From the scatter in Figure E5 the reader might surmise that although the relationship is significant at the 95 per cent confidence level. The proportion of the variance that is explained (adjusted for degrees of freedom) is only 0.251.

Figure E5.



What is implied when this simple cross-section relationship within the manufacturing sector is taken in conjunction with the 1.8-fold increase observed during the 1920's in the share of aggregate direct factory drive represented by secondary motor capacity? The predicted extent of the acceleration of adjusted TFP is about 2.4 percentage points for the sector as a whole, or slightly under one half of the estimated jump (of 5.3 percentage points) that occurred in the correspondingly adjusted TFP growth rate for the U.S. manufacturing sector between 1909-1919 and 1919-1929. Of course, such a calculation only can be accepted at face value if one thought that the temporal process surrounding the diffusion of the unit drive system, and reflected by the penetration of secondary motor capacity in factory drive, had involved little else than a shifting of the whole sector along the cross-section regression line.

As simplistic a view of the matter as that may be, the very substantial putative effect of the widening adoption of the unit drive system is impressive, the more so because it hardly comprehends the full productivity ramifications of the dynamo revolution in the industrial sector during the 1920's. A further important source of measured productivity gains during this era can be identified in 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.[25] Although these developments did not involve the replacement of shafts by wires, they were bound up indirectly with the new technological regime built up around the electric dynamo. Advances in automatic process control engineering were dependent upon use of electrical instrumentation and electro-mechanical relays. More fundamentally, electrification was a key complementary element in the foregoing

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[25] See Lorant (1966): Chs. 3, 4, 5; Foss (1970): Pt. 2, sections 1 and 3 on shift-working and capital utilization in manufacturing circa 1929.

innovations, because pulp-and paper-making, chemical production, and petroleum refining were the branches of manufacturing that made particularly heavy use of electricity for process heat. The same was true also of the primary metals, and 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.[26]

Table 4. The Growth of Secondary Electric Motor (HorsePower) Capacity and the Acceleration of Multifactor Productivity in U.S. Manufacturing, 1909-1929

Industry	Percentage Points of Change in Multifactor ProductivityGrowth Rate, 1909-19 to 1919-29	Ratio of Secondary Electric Motor HP Capacity in 1919 to 1919	Proportion of Primary HP Capacity Electrified in 1919
Paper products	4.40	3.34	0.34
Leather products	4.30	1.02	0.74
Stone, clay, glass	4.10	2.42	0.54
Lumber products	3.42	2.83	0.19
Chemicals	3.80	1.78	0.65
Petroleum and Coal products	3.20	2.91	0.57
Machinery, electrical	2.27	1.03	0.96
Iron and steel	1.60	1.99	0.37
Food products	1.60	1.45	0.47
Machinery, non-electrical	1.56	1.29	0.76
Non-ferrous metals	0.60	1.14	0.85
Rubber	0.50	1.49	0.79
Printing and publishing	0.30	1.16	0.93
Transportation equipment	-0.60	1.45	0.86

Sources:

Col 1. From Woolf (1984), Table 2, estimates adjusted for energy inputs. Estimates in column (1) for Electrical and Non-electrical machinery were obtained by combining Kendrick's figures using (balue added) weights of 0.333 and 0.667, 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 column estimates.

Cols. 2 and 3 From DuBoff (1979), Tables E-12C, D; Table 26, respectively.

Has the TFP Surge Been Underestimated? Unmeasured Quality Changes

It might appear from the foregoing discussion that we are in danger of explaining too much of the observed quickening of manufacturing TFP growth that occurred in the 1920's simply by reference to the direct and indirect effects of electrification. But that impression may be somewhat illusory, inasmuch as there were important unmeasured gains in the quality of many of the new products that issued from America's factories during this decade. Quite apart from the new makes of automobiles, we should keep in mind the amazing range of new consumer durables, many of which themselves were electricity-driven; as well as many new kinds of producers' equipment, ranging beyond electric motors, to motor trucks and buses, diesel locomotives, aircraft, and so on. Thus, the true surge in output and hence in total factor productivity growth may be considerably underestimated by the available estimates.

But on the other side of the ledger, it is equally worth remarking that electrification itself brought unmeasured improvements in the working conditions to which manufacturing employees were exposed. As has been pointed out earlier in our discussion, the initial commercial applications of the dynamo during the 1890-1914 era were concentrated in the fields of lighting equipment and urban transit systems. Notice, then, that qualitative improvements in characteristics such as brightness, ease of maintenance, and fire safety were especially important attributes of incandescent lighting for factories, as

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[26] See Jerome (1934): pp. 62-63, 252-253; DuBoff (1979): pp. 179-181.

well as for shops and homes – the early electric lighting systems having been designed to be closely competitive with illuminating gas on a cost basis. Productivity growth in newspaper publishing was mainly realized in the form of higher throughput rates which permitted *faster* dissemination of news to the public. Likewise, the contributions to the improvement in economic welfare in the form of faster trip speeds and shorter passenger waiting times afforded by electric streetcars, and later by subways – not to mention the greater residential amenities enjoyed by urban workers who were able to commute to the central business district from more salubrious residential neighborhoods – all of which remained largely uncaptured by the conventional indexes of real product and productivity.[27]

Measurement biases of this kind persisted in the later period of factory electrification, most notably in regard to some of the indirect benefits of implementing the unit drive system. One of these was the improvement in machine control achieved by eliminating the problem of belt slippage and installing variable speed D.C. motors. This change yielded better quality, more standardized output without commensurately increased costs, as Warren Devine (1983: pp. 363ff) has noticed. Factory designs adapted to the unit drive system also brought improvements in working conditions and safety. Lighter, cleaner workshops were made possible by the introduction of skylights where formerly overhead transmission apparatus had been mounted. And there were gains from the elimination of the myriad strands of rotating belting that previously swirled dust and grease through the factory atmosphere; and which, when not enclosed within safety screening, would maim or kill workers who became caught up in them. To the extent that growing concerns with workman's compensation costs, fire hazards from open gas flames and dust particle explosions, and other safety considerations led manufacturing employers to value the benefits that factory electrification would bring in these regards, we would expect that the prices paid for newly designed plant might reflect some of these dimensions of quality improvement. But, although the measured flow of capital services would be raised on the latter account, our conventional concept of manufacturing output is not comprehensive enough to accommodate the idea that improved working conditions, and reduced hazards of losses from accidents and fire, also were forms of "output" being produced jointly with marketed goods. This potential source of downward measurement bias should be added to allowances for improvements in the quality of marketed output, in order to arrive at a full picture of the growth of overall productivity in manufacturing. But the effect of doing so would not appear greatly to diminish our assessment of the quantitative impact contributed by the transition to the dynamo regime.

The transition has been seen to have been complex, involving more than the installation of electric motors in factories. Advances in electrical engineering, in factory architecture, and in motor-truck transportation, converged with the alteration of the power technologies and the organization of work in manufacturing establishments to reduce real costs across a wide array of America's manufacturing industries during the 1920's. While the developments just reviewed may be said to form the core of the industrial dynamo revolution, they were not a self-contained dynamic process. Rather, there were other, equally profound changes taking place during this era that interacted with the diffusion of the dynamo and contributed to raising the productivity of the resources engaged in manufacturing. Among these, the transformation in the labor market and its consequences for the character of the U.S. industrial workforce, and the personnel management practices of manufacturing firms, must command center stage in the remaining discussion.

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[27] See e.g., Wright (1895): p. 350; Byatt (1979): pp. 29-45.

4. The "New Era" in the U.S. Labor Market and Its Productivity Consequences

When Harry Jerome and his colleagues surveyed American manufacturing during the 1920's, one development they found across a wide range of industries was the use of electrification to save labor in the physical handling of materials. As Jerome (1934, p. 179) wrote: "even the most diverse industries have one operation in common – handling. In all it is necessary to move materials from one processing operation to the next." Although handlers numbered less than one-fifth of nonsupervisory workers, fully *half* of all reported labor-saving changes were in handling rather than processing operations (p. 189). Directly and indirectly, the application of electrical technology lay at the heart of these innovations in industrial practice: the use of electric trucks and tractors come in for particular emphasis (see Jerome's discussion), as do electric cranes and hoists, and continuous conveyor belts that by that time were mainly run by electricity. Central to the cost reductions in handling operations was the *rearrangement* of the factory layout made possible by electrification, serializing machines and processes by rerouting the flow of materials, and thereby reducing or eliminating "back-tracking" (pp. 190-191). All of this was an integral part of the shift toward more continuous operation and more intensive utilization of the capital stock; but elimination of handling labor had its greatest impact on labor "of the unskilled type" (p. 190).

Now if we ask ourselves whether electrification *per se* was strictly necessary for these labor-saving changes, the answer must be no, not exactly. Labor-saving technology was a hallmark of American manufacturing from early in the nineteenth century, and firms had long searched for ways to increase machine speeds using steam and water power; doubtless they would have continued to do so, had electric power never appeared on the scene. But during the 1920's the electrification movement in U.S. manufacturing industries was in full swing, and, as it also happened, changes in the labor market offered powerful incentives to channel the impact of that in an unskilled-labor-saving direction. Thus we can understand the extraordinary performance of that decade most accurately as the product of a true *confluence* between these two streams of technological development.

Perhaps the clearest single indicator of the contemporary change in the labor market is the sharp increase in the real hourly wage in manufacturing, as depicted in Figure L1. The data displayed are from the comprehensive real wage study by Paul Douglas (1927, 1930).[28] Douglas's cost-of-living index has been questioned by Albert Rees (1961), on the basis of better evidence on rents and the prices of new consumer goods. But measures of workers' economic welfare are not our primary concern at present. The bottom line to employers was the price of an hour's labor relative to the cost of materials and products in the economy, and for this purpose an all-commodity *wholesale* price deflator yields a more appropriate index. By this measure, the real wage was virtually flat across the entire period 1890-1914, as may be seen in Figure L1. Any analysis of the productivity revolution of the 1920's, however, must come to grips with the fact that the real price of labor in that decade was between 50 and 70 percent higher than it had been a decade before. The subsequent absolute rise of the real price of industrial labor also was translated into a dramatic relative increase in the level of annual real earnings of manufacturing workers vis-à-vis those in transportation and service sector employments, which is reflected by the movement of the series in Figure L2. There is a clear parallel between this alteration of the structure of real earnings in the post World War I era, on the

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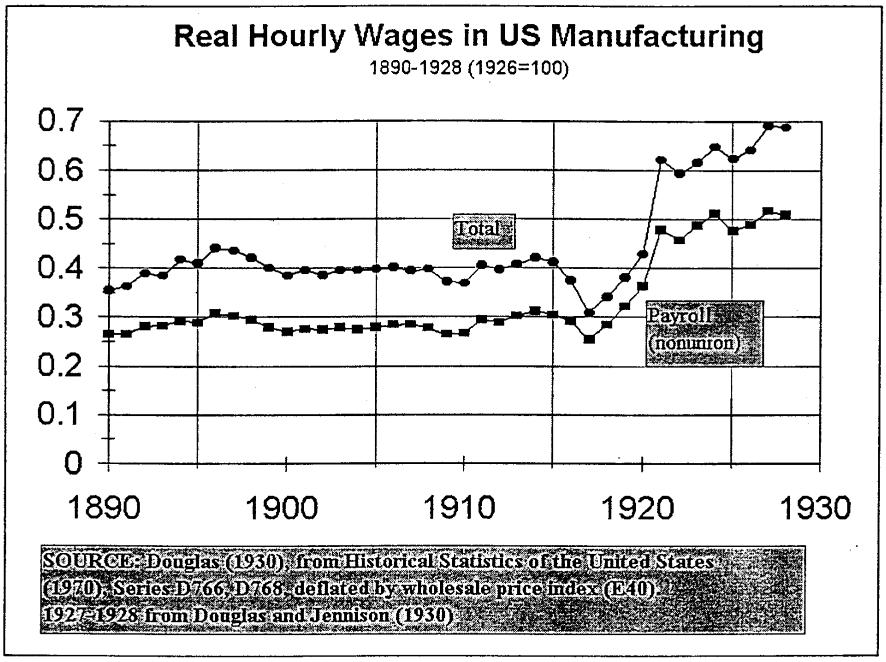
[28] The standard Douglas wage series extend only through 1926, as reported in Douglas (1930). We have extended them through 1928, using the data in Douglas and Jennison (1930).

one hand, and the fact that the upsurge of productivity growth during that period was concentrated in the manufacturing sector

Figure L1.



SOURCE: Douglas (1930), from Historical Statistics of the United States (1970), Series D766, D768, deflated by wholesale price index (E40). 1927-1928 from Douglas and Jennison (1930)

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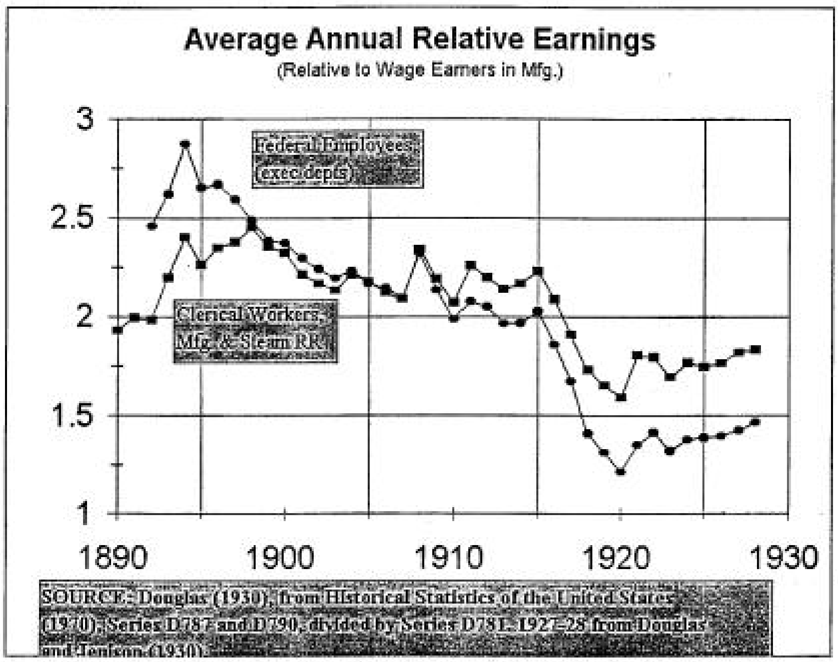
Figure L2.



SOURCE: Douglas (1930), from Historical Statistics of the United States (1970), Series D787 and D790, divided by Series D781. 1927-28 from Douglas and Jenison (1930)

What was the cause of the striking change in relative wages and earnings? The one-time jump in real hourly industrial wages between 1920 and 1921 could be viewed as the artificial result of accidents of timing and price adjustment. Labor markets were extremely tight under wartime conditions, but nominal wages and prices chased each other somewhat inconclusively between 1914 and 1919. Then the postwar boom ended with the collapse of commodity prices at the end of 1920, but as nominal wages were relatively sticky, the wage-price ratio leapt sharply upwards. A lag in nominal adjustments, however, can hardly be the full explanation for the pattern displayed; had real wages been above sustainable levels for accidental reasons in 1921, we would expect to see them decline gradually toward a lower equilibrium level thereafter. Instead, we see that the new real wage plateau was not only maintained during the 1920's, but actually continued to drift upwards between 1921 and 1928.

Evidently, there were important "real" forces affecting the industrial labor market in this era. To most observers, the immediately apparent real change was the cutting off of the mass European immigration that had supplied the bulk of the labor for American factories for the previous half century or more. Immigration averaged more than one million arrivals per year during the decade prior to 1914, and the foreign born comprised the majority of the wage-earners in such basic industries as iron and steel, farm machinery, automobiles, cotton goods, clothing, oil refining and meatpacking. But these flows were reduced to a trickle with the outbreak of the war, and this closure was then decisively ratified by legislation in 1920 and 1924. Thus, employers could not anticipate being able to push real manufacturing wages back down to prewar levels, because they could no longer deploy immigrant workers in massive numbers for this purpose.

This interpretation is consistent with the observation that the greatest upward pressure on wage rates was felt at the low end of the wage distribution. The labor scarcities of 1916-1919 generated a sharp compression of wage differentials in general, and these were only partially restored during the 1920's. Figure L2 displays this pattern for two "middle class" occupational categories, clerical workers in manufacturing and steam railroads, and federal government employees, relative to wage earners in manufacturing. It is evident that manufacturing labor had become very expensive at the time of the productivity revolution, especially relative to office workers and managers.

Not only did relative wages rise during the 1920's, but behavioral patterns in the labor market also changed markedly. One manifestation of the new regime was the radical reduction in rates of turnover. Brissenden and Frankel (1920) estimate that separations per 100 employees averaged nearly 100 during 1910-1914 – i.e. one worker left for every one who stayed on the job. But according to Berridge (1929), the rate fell to less than 40 separations per hundred employees between 1923 and 1928. The bulk of the decline was in voluntary quits, but worker dismissals by firms also was cut in half between the two periods. These shifts are not artifacts of changes in macroeconomic conditions. Careful econometric studies demonstrate that when account is taken of the normal responsiveness of turnover to such factors in unemployment and wage dispersion, the bulk of the decline remains unexplained (Sundstrom 1986; Owen 1995), an apparent change in prevailing labor market norms.

Indeed, economic historians have debated alternative interpretations of the fall in turnover rates. Jacoby (1983) argues that the primary cause was a decline in labor mobility as a consequence of changes in the composition of the industrial labor force. In comparison to their prewar counterparts, the manufacturing wage-earners of the 1920's were more mature; more likely to be married with dependents; had more years of schooling in America and a better command of English; they were more committed to America as a place to live, and to industrial work as a lifetime occupation. Not every item on this list is objectively measurable, but each one is a logical consequence of a fundamental shift from an immigrant to a native-born labor supply.

In contrast, Owen (1995) argues that turnover behavior must be understood in the light of the active efforts by employers to stabilize their workforces, by increasing the costs of separation to workers and by offering opportunities for advancement and enhanced job security with increases in tenure. Beginning with the War, growing numbers of employers established personnel departments for precisely this purpose, centralizing decisions over hiring and firing (as opposed to the arbitrary discretion exercised under the "foremen's empire"), and using tenure as a criterion in compensation, promotion and layoff decisions. Jacoby (1983) estimates that the share of large industrial firms with personnel departments grew from less than 7 percent in 1915 to 25 percent in 1920. Remarkably, this share did not decline when wartime labor pressures eased; it continued to expand through the decade, reaching 34 percent in 1929. Personnel department objectives were reinforced by a diverse range of incentives and inducements, from savings and insurance plans, to health benefits, recreational opportunities and representation schemes loosely known as "welfare capitalism."[29]

It seems evident to us that this is a context where the classic assumption of independence between the supply and demand sides of the market does not do justice to the situation. The objective conditions of labor supply in the open market were of course generally beyond the power of individual firms to alter. But to employers entering that market on a probabilistic basis, the range of feasible options was altered by the change in composition of the underlying pool. Not every firm would want to make such a change, but for those who saw the possibility of a positive return to stabilizing and upgrading their labor forces, the prospects for doing so were now enhanced. For others, the reality of coping with a high, sticky real wage level may have left them with little choice but to raise their hiring standards and retain workers longer. Such decisions by firms, in turn, created incentives for mature heads of households to commit to industrial work; and for younger men to make plans for marriage and family in this context. Reinforcing changes on both sides of the market can generate something like a "regime change" establishing a new set of relationships that we may call the High Wage Economy.

Organizational Adjustments and Workforce Upgrading in the High Wage Economy

Economists are not in the habit of accepting the self-serving claims of private business firms at face value, and, unquestionably, there was a fair quotient of public-relations salesmanship in the popular High Wage talk of the 1920's. Why then do we take this rhetoric seriously? For one thing, one cannot escape the objective evidence that many firms were in fact investing substantial resources in implementing personnel plans and cultivating their workforce. The encouragement to do so came not just from self-promoting efficiency experts, but from the highest levels of government; most prominently, from Herbert Hoover, first as Secretary of Commerce and later as President. Behind the high wage philosophy was a broadly-based political coalition, including political reformers, "progressive" businessmen, and self-interested adult male workers. Exhortations to hire more selectively and invest more in those hired were reinforced by a range of public policies that pointed in the same direction. For example, legal changes in the areas of industrial safety and liability increased the effective costs of hiring and training (Owen 1995, p. 824). Restrictions on the use of "child labor" and continuing increases in the age of compulsory schooling delayed the age of first employment by something between two

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[29] For general discussions, see Slichter (1929), Fairris (1997).

and five years relative to prewar norms (Osterman 1981, p. 54). Goldin (1990) shows that "marriage bars" restricting the employment of married women diffused extensively through the economy in the 1920's, in private as well as public sector employment.

Many of these political and ideological currents represent trends that had been underway for a much longer historical period, perhaps thrust into culmination more decisively and discontinuously than otherwise would have occurred. Because the High Wage transition reached its historic peak under a very different ideological and political aegis in the subsequent decade, there has been a tendency on the part of labor historians to view the private-order labor initiatives of the 1920's as a sham, motivated mainly by the desire to discourage independent unions. The mature, stable workforce certainly did have enhanced potential for collective organization, as employers learned in a big way during the 1930's, and preempting unions surely was part of the basis for welfare capitalism in the 1920's. But that does not mean that the programs were empty or ineffectual. A study by Fairris (1997) reports a strong association between productivity growth, reduction in injury rates, and the prevalence of company unions in an industry.

How much of the observed increase in real wage levels and in productivity can be "accounted for" by compositional changes in the labor force, such as age, sex, marital status, language, and education? Perhaps surprisingly, such a calculation has yet to be carried out. To do so is not straightforward, because the census did not record many of these personal characteristics by industry and employment categories. Industry and Labor Department surveys are generally incomplete in their coverage, or lack comparability with prewar data. We presently are working to develop a set of labor force estimates that would fill this gap. In advance, however, we offer our expectation for the results: Some part of the rise in real manufacturing wages may be "accounted for" by compositional changes in the work force, particularly in certain industries. It follows that some part of the acceleration of productivity growth may be interpreted as a one-time transition to a higher productivity *level*, associated with upgrading. But we do not expect that the full increase in real wages, nor the full dynamic effect on productivity *change*, can be factored out in this way. Our reasoning is, that the learning to make more productive use of longer-term, better-educated workers, was as much a part of the ongoing effort to adjust technical practice to potential, as was any other part of the process of technological change. During the 1920's, that adjustment was in its infancy, but it was definitely underway.

Synergies Between the New Era Labor Regime and the Dynamo Revolution

The foregoing discussion raises an obvious question: Was there any inherent association between the rise in the effective utilization of capital – facilitated by electrification – and the acceleration of labor productivity, reflecting the upgrading of labor standards in response to increased relative wages and conditions of labor supply? The connection may not have been close. Each of the two processes had its own historical trajectory, and each had distinct economic effects. The first-order impact of electrification was to raise capital productivity; the first-order impact of labor upgrading was on labor productivity. The acceleration in the growth of *total factor* productivity may thus be seen as the result of a fortuitous confluence of these two forces. Yet clearly the two were not completely independent. Both were facilitated by the favorable macroeconomic conditions of the 1920's, including the high rate of investment in new plant and equipment, and new flexibility in plant location and design, which made it possible to implement reorganization of job assignments and labor systems as well as physical arrangements.

Indeed we would go further, in arguing that there were positive micro-level interactions between electrification and rising labor productivity in the 1920's. The scatter diagram displayed in Figure E4 relating the growth of capital and labor productivity during the decade shows there was a measure of positive correlation in the strength of the two tendencies across the array of industries (already noted in connection with the discussion of Figure P8). Was this association purely accidental, or were there underlying connections between the sources of enhanced labor productivity and the capital-saving changes that were being effected? In this regard it is worth recalling (from Figure E4's labeled points) that in relatively high capital-intensity manufacturing operations such as grain-milling, sugar refining and petroleum refining, where great use never had been made of labor, productivity growth was skewed more strongly towards relatively rapid capital-savings; whereas in the comparatively more labor-intensive batch-process manufacture of allied chemical substances, rubber tires, and motor vehicles, the skew was more towards rapid rates of reduction in unit labor inputs.

We suggest that the correlation evident from Figure E4 was not a product of mere coincidence; that the technological and organizational development that underlay the sudden appearance of gains in capital productivity during the 1920's also exerted a positive influence on the efficacy of labor time, at least in some of the industries responsible for the decade's remarkable record. Although our discussion must be more conjectural at this point than we would wish, the following three possibilities deserve notice:

(a) The flow of materials through the plant, both in directness of the layout and the speed and reliability of transmission, reduced the amount of worker down-time during the day, and hence increased the effective rate of utilization of labor capacity. Electrification facilitated the mechanization of routine unskilled tasks, such as materials handling.

(b) Improved internal coordination and throughput increased the vulnerability of plant systems to disruption at particular points, and increased the potential costs of such disruptions. Hence, the new systems placed a premium on mature, reliable, longer-term employees, and the upgrading of hiring standards.

(c) Localization of electric power supply through unit drive is likely to have increased the scope for individual specialization and exercise of discretion, making it possible to utilize more highly trained workers effectively, and to develop new skills on the job.

These points of connection presumably affected different industries in very different ways, depending on the prior evolution of their technologies and labor force characteristics. They have in common an increased focus on the selection and retention of workers. But in some cases the selection took the form of brutally increased machine-tending responsibilities, as in the "stretch-out" system in cotton textiles. In other cases electrification may have increased the exercise of cognitive skills and discretion by individual workers, as with the teletype operators and pressman employed in the printing and publishing industry. In examples of each type, new technology facilitated increased labor productivity by facilitating worker selection, monitoring and control of performance.

The emphasis placed on new hiring standards for worker selection and retention raises the question of the role of rising levels of schooling in the productivity revolution. A recent study by Goldin and Katz (1998) identifies the era surrounding World War I as the origin of "technology-skill complementarity," the widely observed modern tendency for new technologies disproportionately to favor the employment of more highly trained and educated labor. Correspondingly, Goldin (1998) documents the spectacular, uniquely American rise of the "high school movement" after 1910, as graduation from high school ceased to be the exception and began to be the norm – at least outside of the South. The male high school graduation rate, for example, stood at 10-15 percent for the cohort born in the 1890's, but rose to nearly 50 percent for those born after World War I.[30] Working backward from the comprehensive schooling data presented in the 1940 census, Goldin and Katz (1998) show that the diffusion of high school graduates among manufacturing industries was extremely uneven. Those industries drawing upon new emerging science-based technologies, such as aircraft, electrical machinery, and petroleum refining, employed large numbers of high school graduates in both blue- and white-collar jobs, and it appears that this pattern goes back at least as far as the 1910's. Goldin and Katz do not advance this analysis as a cause of the productivity revolution of the 1920's. But the historical association between the two sets of phenomena is so suggestive, that such a proposed hypothesis would seem to be only a matter of time.[31] Can the human capital formed in the high school revolution explain the manufacturing productivity revolution of the 1920's?

Having framed this hypothesis, we must say that we regard it with some skepticism. At best, there may have been a positive correlation between productivity growth rates and those industries identified as "high-education" industries by Claudia Goldin and Lawrence Katz (1998, p. 708), and compiled here in Table 5.

Nonferrous metals, Dairy products, and Petroleum Refining are three examples of industries in this top education bracket (more than one-third of employees high school graduates in 1940), and all had productivity growth rates in excess of 5.0 percent per year for the 1920's. But productivity performance was also strong in many industries that made little use of high school graduates. Some of the most spectacular productivity growth was recorded in Tobacco Products (chiefly cigarettes), Rubber Products (chiefly tires and tubes), Iron and Steel (chiefly blast furnaces), and Transportation Equipment (chiefly automobiles), all of which grew at better than 8 percent per year during the 1920s, with little benefit from workers with high school diplomas. Thus, upgrading of educational standards for manufacturing employment to the high school level may have contributed something, but it could not have been the full story for the productivity revolution of this decade.

Could the contribution of secondary education to manufacturing productivity be concealed in the industrial firm's white collar workforce? Using the available data for 1940, Goldin and Katz report that employment of high school graduates in blue collar jobs was positively correlated with rising employment of high-school-educated white collar workers, both observed in industries drawing on new science-based technologies. Yet Fabricant's data for the 1920's shows that average productivity growth for "total" manufacturing employees was almost precisely equal to productivity growth for wage-earners alone (5.0 percentage points per year). In manufacturing as a whole, the shares of employment in the two categories show almost no change between 1919 and 1929, although the non-production workforce had grown more rapidly during the preceding decades.

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[30] See Goldin (1998): p. 366.

[31] Abramovitz and David (1998), Table 2: IV, present comprehensive growth accounts for the U.S. private domestic economy that show the rise in intangible capital per manhour (mostly due to investment in education) during 1890-1927 that accounted for a 0.42 percentage points per annum of the corresponding real output per manhour growth rate of 2.2 percentage points. But this contribution would have represented over one-third of the trend acceleration in labor productivity growth between 1855-90 and 1890-1927.

Table 5.
High School Graduates Distribution Among Male Blue Collar Workers (Ages 18-34) by Manufacturing Industry Groups, U.S. 1940

Percentage Range of H.S. Graduates among Craftworkers, Operatives and Laborers	Industries in Range
	Part A: High-Education Blue-Collar Workforce Industries Accounting for Top 20% of total employees in sample of 2-digit manufacturing industries, ranked from top down:
52.4 - 44.7	Aircraft and parts; Printing and Publishing
43.4 - 40.3	Office machinery; Petroleum refining; Dairy products; Scientific and photographic equipment; Electrical machinery.
35.6 - 32.6	Paints and varnishes; Shipbuilding; Clocks, watches, jewelry; Misc. machinery; Nonferrous metals
	Part B: Low-Education Blue-Collar Workforce Industries accounting for the bottom 20% of total employees in sample of 2-digit manufacturing industries, ranked from bottom up:
10.7 - 13.8	Cotton manufactures; Logging; Tobacco; Sawmills and planing mills
15.6 - 17.1	Not specified textile mills; Silk and rayon manufactures; Carpets and rugs; Cut-stone and stone products; Misc. fabricated textiles and textile goods
18.8 - 22.8	Hats, except cloth and millinery; Dyeing and finishing textiles; Misc. wooden goods; Footwear industries except rubber.
27.4	Mean of all workers in sample of 31,500

Notes and Sources: Compiled from C. Goldin and L.F. Katz, "The Origins of Technology - Skill Complementarity," Quarterly Journal of Economics, 113, August 1998, Table 2. The 20% cutoff applies to all workers in the sample of 31,500, not just male blue collar workers.

What about the cognitive content of new manufacturing jobs? Goldin and Katz draw upon detailed job descriptions and qualifications, developed by the Bureau of Labor Statistics between 1918 and 1921, emphasizing the increasing role of schooling-based skills. Examples of key terms include "knowledge of weights and measures," "record-keeping and computations," "knowledge of how to set machines and test results," "special ability to interpret drawings," "well-versed in grammar, spelling, punctuation;" one even encounters references to scientific knowledge such as "ability to mix the chemicals," "knowledge of electricity," or "general knowledge of photography." These occupational descriptions do make interesting reading, and they clearly confirm the Goldin-Katz result that there were distinct industry clusterings in job requirements and qualifications. In older industries such as meatpacking and cotton manufactures, virtually no jobs are listed as having any required level of schooling at all. A typical entry in meatpacking identifies "good health and a willingness to work in a meat-packing house" as all that was looked for in an applicant for a general butcher's job. Even the "most important and skilled worker in the weaving room" (the loom fixer) was expected to have no more than a common school education. In these industries, it was well accepted that a high school diploma was as good as a bus ticket out of town and out of that line of work. For newer industries drawing on newer technologies, in contrast, the job descriptions imply that positive value was invested in a wider range of individual traits and qualifications.

What is striking, however, is just how limited the expected levels of cognitive mastery actually were, even in the newest and most scientific industries. Medicinal Manufacturing, for example, was clearly a modern industry with a science-based technology. But the great majority of job listings for this industry called for only a common school education; examples include finishing worker, ten types of pharmaceutical workers, plaster maker, and veterinary hospital attendant. For the job called "chemical worker," the occupational requirements manual states that "schooling depends on the aptitude of the employee, preferably, at least, a common school and some high school training." In electrical manufacturing, the majority of jobs asked only for common school education, sometimes with additional technical training; another handful of job categories were listed as "high school preferable;" and no more than a small elite class of jobs specifically called for high school graduates. Looking ahead from the perspective of 1918-1921, it appears to us that a wide range of schooling-enhanced traits were represented in standard manufacturing job descriptions – some cognitive, some attitudinal and behavioral – but for most jobs common school education was thought to be adequate. Actual command of scientific knowledge as a job requirement was limited to a tiny fraction of the overall work force, and these positions typically required post-secondary training if not professional degrees.

To be clear on this point, we are by no means denying a linkage between the productivity revolution of the 1920's and the roughly coincident extension of high school education in the country at large. Yet, we see the connection as broad and simultaneous in character, part of the general transition to a more stable, carefully selected, high-wage, high-productivity labor force. It is hardly surprising that new and more rapidly growing industries adapted their hiring criteria and job descriptions to match the curriculum of high school education. But only in part did such an adaptation represent required cognitive dimensions of the job. Of equal prominence in the job qualifications are phrases representing individual attributes of patience and reliability that might well be confirmed by receipt of a high school diploma. Drawing from the manual for Office Employees, we find that a file clerk "should be a keen observer, possess a good memory and a mind for detail. Should be thoroughly conscientious, accurate, and alert." A ledger clerk should possess "good penmanship; neatness; accuracy...should know how to use an adding machine." A mail clerk should display "carefulness; accuracy; honesty; knowledge of different classes and rates of mail matter and office routine." An order clerk should demonstrate "intelligence; accuracy; ability to learn readily the products sold by the firm." And so on.

Employers probably were on sound ground in assuming that traits such as these were likely to be well-represented in high school graduates. More questionable is the assumption that extending years of public schooling should be seen as a direct response to more demanding cognitive requirements of the workforce, generated by new manufacturing technologies. In explaining cross-state variation in the spread of high school education, Goldin (1998) reports that the relative importance of manufacturing in a state was in fact a negative influence. Furthermore, in his study of evolving employment relations in Philadelphia, Walter Licht (1992) reports that increases in the compulsory school-leaving age were never welcomed by either employers or by the bulk of the students; these policy changes were part of the broad policy trend to exclude teenagers from the labor force, and for the most part not a response to rising educational demands by employers. The one education policy initiative explicitly intended to improve the match between high school studies and job requirements, vocational training, was universally regarded as unsuccessful in the U.S. during the 1920's, as has been the case also in more recent decades (Osterman 1981).

5. Conclusion

In concluding, we must acknowledge the conjectural nature of much of the argument about the micro-level connections between factory electrification, labor force upgrading and the acceleration of productivity growth in U.S. manufacturing. To understand fully the dynamics of the 1890-1914 TFP growth pause, and the post-1919 surge, it will be necessary to integrate studies of changes at the plant level with analyses of the diffusion both within industries and across industry boundaries of the new regime of production. Further, it seems likely that this line of inquiry would in turn necessitate some re-examination and improvement of the available measures of industrial outputs and inputs, with an eye to making proper allowances for hitherto neglected quality changes that are distorting the details of our quantitative picture of the productivity surge.

We also should notice that the 1920's saw the consolidation of still other technological and organizational innovations whose proximate origins can be traced back to developments in the pre-World War I era, particularly those involving the use of telecommunications, information processing, storage and retrieval, and applications of statistical analysis for business management and control. These have been the subject of recent attention in historical studies carried out by James Beniger (1986), JoAnne Yates (1989), Margaret Leverstein (1998), and others.[32] It is plausible to think that in addition to their direct effects, among which the introduction into manufacturing enterprises of non-production employees with higher levels of educational attainment certainly figured prominently, these aspects of "the information and control revolution" in industry may have had synergetic productivity interactions with the developments that have been examined here.

While the existence and nature of those particular links remain to be identified through further historical research, enough has been said here to support the central contention that major surges of productivity advance are likely to be traceable not so much to the concatenation of many individual, independent and industry-specific "causes," as to the confluence of generic developments that were interrelated. Those inter-connections have been seen to run either through the logic of technical and organizational complementaries, or through the spillovers generated in the process of applying a general purpose technology, or commonalities in the modes whereby firms adjusted their internal organizational routines in response to major alterations in the structure of the markets for their (labor) inputs. The "mushroom" metaphor may fit better in earlier or later eras of much retarded aggregate productivity growth; but that particular conceptualization does not explain why TFP growth for the economy as a whole goes through alternating periods of productivity surge and slowdown.

Our discussion carries the further implication that there are some serious distortions of reality in the conceptualization of economic growth that is conveyed by the conventional "growth accounting" approach. The aim in exercises of that kind – whether pursued for a specific sector or for the economy as a whole – is to quantify the contributions made from distinct and independent "sources." But the particular historical episode upon which we have focused provides a clear illustration of the salient limitations of that approach to understanding productivity growth dynamics. The patent non-neutrality of innovation during this era (in both the Hicksian and Harrodian senses) makes it theoretically unjustified to try to separate sharply the effects of technological and organizational advances from those of changing factor proportions, in the way that growth accountants often give an impression of having done. Furthermore, non-neutrality vitiates the basis for identifying the TFP residual – however so refined a measure thereof may have

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[32] See e.g., the contributions to the volumes edited by Bud-Frierman (1996), and by Lamoureaux, Raff and Temin (1998).

been obtained – with “the rate of innovation” taking place in the economic entity concerned.

Thus, the acceleration of TFP growth in U.S. manufacturing industries during the 1920’s has been seen to have reflected a general weakening, and in many industries an outright reversal, of the previous bias towards capital-deepening. And the timing of that change in the nature and direction of implemented innovations, as distinct from such quickening as may have occurred in the pace of “advances in knowledge,” was bound up directly and indirectly with the coincident transformation of labor market conditions and the long-anticipated industrial application of the “unit drive” system of factory electrification.

Might there have been some background conditions, left implicit by our discussion, that made this all possible in the U.S. during the “New Era,” and more so there than elsewhere? That, too, must be acknowledged. The industrial concentration movement of the pre-1908 years might have played such a role, preparing the ground by stabilizing the corporate competitive environment and so making it possible for the larger firms to extend their planning horizons and undertake longer-term adjustments to the altered structure of the post-World War I labor market. A sharp jump in real wage costs, however, would not necessarily stimulate a takeoff in labor productivity growth, especially not if that required heavy investment in new plant and equipment. Thus, there may also have been have been a somewhat fortuitous link between the ability of the buoyant macroeconomic conditions after 1921 to stimulate new fixed investments in industrial plant and equipment, and the micro-level sources of reduction in marginal capital-output ratios. Further study in a comparative context may illuminate these and other historical circumstances that made possible the episode of remarkable productivity performance that we have here identified.

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