The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox

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Many observers of recent trends in the industrialized economies of the West have been perplexed by the conjecture of rapid technological innovation with disappointingly slow gains in measured productivity. A generation of economists who were brought up to identify increases in total factor productivity indexes with "technical progress" has found it quite paradoxical for the growth accountants' residual measure of "the advance of knowledge" to have vanished at the very same time that a wave of major innovations was appearing—in microelectronics, in communications technologies based on lasers and fiber optics, in composite materials, and in biotechnology. Disappointments with "the computer revolution" and the newly dawned "information age" in this regard have been keenly felt. Indeed, the notion that there is something anomalous about the prevailing state of affairs has drawn much of its appeal 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 the sectors of the U.S. economy that recently have been investing so heavily in electronic data processing equipment (see, for example, Stephen Roach, 1987, 1988; Martin Baily and Robert Gordon, 1988). This latter aspect of the so-called "productivity paradox" attained popular currency in the succinct formulation attributed to Robert Solow: "We see the computers everywhere but in the productivity statistics."

If, however, we are prepared to approach the matter from the perspective afforded by the economic history of the large technical systems characteristic of network industries, and to keep in mind a time-scale appropriate for thinking about transitions from established technological regimes to their respective successor regimes, many features of the so-called productivity paradox will be found to be neither so unprecedented nor so puzzling as they might otherwise appear.

I

My aim here simply is to convince modern economic analysts (whether perplexed by the productivity slowdown, or not) of the immediate relevance of historical studies that trace the evolution of techno-economic regimes formed around general purpose engines.[1] The latter, typically, are key functional components embodied in hardware that can be applied as elements or modular units of the engineering designs developed for a wide variety of specific operations or processes. Accordingly, they are found ubiquitously distributed throughout such systems when the latter have attained their mature, fully elaborated state. James Watt's (separate condenser) steam engine design springs to mind readily as an example of an innovation that fulfilled this technological role in the first industrial revolution. My particular line of argument will be better served, however, by directing notice to the parallel between the modern computer and another general purpose engine, one that figured prominently in what sometimes is called the "second Industrial Revolution"—namely, the electric dynamo. (But, see also Herbert Simon, 1986.)

Although the analogy between information technology and electrical technology

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[1] This paper draws upon material developed in a longer work—my 1989 paper.

would have many limitations if taken very literally, it proves illuminating nonetheless. Computer and dynamo each form the nodal elements of physically distributed (transmission) networks. Both occupy key positions in a web of strongly complementary technical relationships that give rise to "network externality effects" of various kinds, and so make issues of compatibility standardization important for business strategy and public policy (see my 1987 paper and my paper with Julie Bunn, 1988). In both instances, we can 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 (see Timothy Bresnahan and Manuel Trajtenberg, 1989). Moreover, each of the principal empirical phenomena that make up modern perceptions of a productivity paradox had its striking historical precedent in the conditions that obtained a little less than a century ago in the industrialized West, including the pronounced slowdown in industrial and aggregate productivity growth experienced during the 1890-1913 era by the two leading industrial countries, Britain and the United States (see my 1989 paper, pp. 12–15, for details). In 1900, contemporary observers well might have remarked that the electric dynamos were to be seen "everywhere but in the productivity statistics!"

II

At the turn of the century, farsighted engineers already had envisaged profound transformations that electrification would bring to factories, stores, and homes. But the materialization of such visions hardly was imminent. In 1899 in the United States, electric lighting was being used in a mere 3 percent of all residences (and in only 8 percent of urban dwelling units); the horsepower capacity of all (primary and secondary) electric motors installed in manufacturing establishments in the country represented less than 5 percent of factory mechanical drive. It would take another two decades, roughly speaking, for these aggregate measures of the extent of electrification to attain the 50 percent diffusion level (see my 1989 paper, Table 3, for estimates and sources). It may be remarked that, in 1900, an observer of the progress of the "Electrical Age" stood as far distant in time from the introduction of the carbon filament incandescent lamp by Edison, and Swann (1879), and of the Edison central generating station in New York and London (1881), as today we stand from comparable "breakthrough" events in the computer revolution: the introduction of the 1043 byte memory chip (1969) and the silicon microprocessor (1970) by Intel. Although the pace of the computer's diffusion in the business and public sectors of the industrialized societies during the past two decades has been faster than that recorded for the dynamo during its comparable early phase of adoption, it has been estimated that only 10 percent of the world's 50 million business enterprises today are using computers, and only 2 percent of the world's business information has been digitized (see Peter Lewis, 1989).

The history of electrification after 1900 (see I. C. R. Byatt, 1979; Thomas Hughes, 1983; Ryoshin Minami, 1987) lends considerable plausibility to the "regime transition thesis" of Christopher Freeman and Carlotta Perez (1990). They suggest that productivity growth has been sluggish, and very well might remain so 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) will, more than likely, be a protracted and historically contingent affair.

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 United States until after 1914–17, when regulated regional utility rates for electricity were lowered substantially in relationship to the general price level (see my 1989 paper: Table 4, Fig. 14), and central station generating capacity came to predominate over generating capacity in *isolated* industrial plants. Furthermore, factory electrification did not reach full fruition in its technical development nor have an impact on productivity growth in manufacturing before the early 1920s. At that time only slightly more than half of factory mechanical drive capacity had been electrified. (On the significance for derived productivity growth of attaining 50 percent diffusion, see my 1989 paper, Appendix A.) This was four decades after the first central power station opened for business.

The proximate source of the delay in the exploitation of the productivity improvement potential incipient in the dynamo revolution was, in large part, the slow pace of factory electrification. The latter, 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 (see Richard DuBoff, 1979, p. 142; and Minami, pp. 138–41). 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, ultimately, the development of a general fixed capital formation boom in the expansionary macroeconomic climate of the 1920s.

The persistence of durable industrial facilities embodying older power generation and transmission equipment had further consequences that are worth noticing. During the phase of the U.S. factory electrification movement extending from the mid-1890s to the eve of the 1920s, the "group drive" system of power transmission remained in vogue (see Duboff, p. 144; Warren Devine, 1983, pp. 351, 354). 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. While factory owners rationally could ignore the sunk costs of the existing power transmission apparatus, and simply calculate whether the benefits in the form of reduced power requirements and improved machine speed control justified the marginal capital expenditures required to install the group drive system, productivity accountants would have to reckon that the original belt and shaft equipment (and the primary engines that powered them) remained in place as available capacity. The effect would be to raise the capital-output ratio in manufacturing, which militated against rapid gains in total factor productivity (TFP)—especially if the energy input savings and the quality improvements from better machine control were left out of the productivity calculation.

This sort of overlaying of one technical system upon a preexisting stratum is not unusual during historical transitions from one technological paradigm to the next. Examples can be cited from the experience of the steam revolution (G. N. 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, for example, Baily and Gordon, pp. 401–02).

Finally, it would be a mistake to suppose that large potential gains from factory electrification were obtainable from the beginning of the century onward, just because there were farsighted electrical engineers who at the time were able to envisage many sources of cost savings that would result from exploiting the flexibility of a power transmission system based on electric wires, and the efficiency of 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 of all sizes (see Devine, pp. 362ff). 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 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 aim of reducing power losses in turning very long line shafts had dictated the erection of more costly multistory structures. 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; the entire power system no longer had to be shut down in order to make changes in one department or section of the mill.

Although all this was clear enough in principle, 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. For, 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 the technical knowledge acquired in such circumstances are likely to slow experience-based learning. A theoretical analysis of an interdependent dynamic process involving diffusion and incremental innovations based upon learning-by-doing (see my paper with Trond Olsen, 1986) 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.

III

The preceding review of the sources of "diffusion lags" bears directly on the relationship between the timing of movements in industrial productivity, and the applications found for electric power within the industrial sector. A somewhat different class of considerations also holds part of the explanation for the sluggish growth of productivity in the United States prior to the 1920s. These have to do more with the deficiencies of the conventional productivity measures, which are especially problematic in treating the new kinds of products and process applications that tend to be found for an emergent general purpose technology during the initial phases of its development. Here, too, the story of the dynamo revolution holds noteworthy precedents for some of the problems frequently mentioned today in connection with the suspected impact of the computer (see, Baily-Gordon; and Gordon-Baily, 1989): 1) unmeasured quality changes associated with the introduction of novel commodities; and 2) the particular bias of the new technology toward expanding production of categories of goods and services that previously were not being recorded in the national income accounts.

In the case of the dynamo, initial commercial applications during the 1890–1914 era were concentrated in the fields of lighting equipment and urban transit systems. Notice that qualitative characteristics such as brightness, ease of maintenance, and fire safety were especially important attributes of incandescent lighting for stores and factories, as well as for homes—the early electric lighting systems having been designed to be closely competitive with illuminating gas on a cost basis. 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 enabled to commute to the central business district from more salubrious residential neighborhoods), all remained largely uncaptured by the conventional indexes of real product and productivity.

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 yielded better quality, more standardized output without commensurately increased costs (see Devine, pp. 363ff). 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 also by the elimination of the myriad strands of rotating belting that previously swirled dust and grease through the factory atmosphere, and, where unenclosed within safety screening, threatened to maim or kill workers who became caught up in them.

These more qualitative indirect benefits, however, came as part of a package containing other gains that, as has been seen, took the form of more readily quantifiable resource savings. Consequently, a significantly positive cross-section association can be found between the rise in the industry's TFP growth rate (adjusted for purchased energy inputs) during the 1920s, vis-à-vis the 1910s, and the proportionate increase of its installed secondary electric motor capacity between 1919 and 1929. Making use of this cross-section relationship, approximately half of the 5 percentage point acceleration recorded in the aggregate TFP growth rate of the U.S. manufacturing sector during 1919–29 (compared with 1909–19) is accounted for statistically simply by the growth in manufacturing secondary electric motor capacity during that decade (see my 1989 paper, Table 5, and pp. 26–27).

But, even that did not exhaust the full productivity ramifications of the dynamo revolution in the industrial sector during the 1920s. An important source of measured productivity gains during this era has been found to be the capital-saving effects of the technological and organizational innovations that underlay the growth of continuous process manufacturing, and the spread of continuous shift-work, most notably in the petroleum products, paper, and chemical industries (see John Lorant, 1966, chs. 3, 4, 5). Although these developments did not involve the replacement of shafts by wires, they were bound up indirectly with the new technological regime build up around the 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 innovations because pulp- and paper-making, chemical production, and petroleum refining (like the primary metals, and the stone, clay and glass industries where there were similar movements towards electrical instrumentation for process control, and greater intensity in the utilization of fixed facilities) were the branches of manufacture that made particularly heavy use of electricity for process heat.

IV

Closer study of some economic history of technology, and familiarity with the story of the dynamo revolution in particular, should help us avoid both the pitfall of undue sanguinity and the pitfall of unrealistic impatience into which current discussions of the productivity paradox seem to plunge all too frequently. Some closing words of caution are warranted, however, to guard against the dangers of embracing the historical analogy too literally.

Computers are not dynamos. The nature of man-machine interactions and the technical problems of designing efficient interfaces for humans and computers are enormously more subtle and complex than those that arose in the implementation of electric lighting and power technology. Moreover, information as an economic commodity is not like electric current. It has special attributes (lack of superadditivity and negligible marginal costs of transfer) that make direct measurement of its production and allocation very difficult and reliance upon conventional market processes very problematic. Information is different, too, in that it can give rise to "overload," a special form of congestion effect arising from inhibitions on the exercise of the option of free disposal usually presumed to characterize standard economic commodities. Negligible costs of distribution are one cause of "overload"; information transmitters are encouraged to be indiscriminate in broadcasting their output. At the user end, free disposal may be an unjustified assumption in the economic analysis of information systems, because our cultural inheritance assigns high value to (previously scarce) information, predisposing us to try screening whatever becomes available. Yet, screening is costly; while it can contribute to a risk-averse information recipient's personal welfare, the growing duplicative allocation of human resources to coping with information overload may displace activities producing commodities that are better recorded by the national income accounts.

In defense of the historical analogy drawn here, the information structures of firms (i.e., the type of data they collect and generate, the way they distribute and process it for interpretation) may be seen as direct counterparts of the physical layouts and materials flow patterns of production and transportation systems. In one sense they are, for they constitute a form of sunk costs, and the variable cost of utilizing such a structure does not rise significantly as they age. Unlike those conventional structures and equipment stocks, however, information structures per se do not automatically undergo significant physical depreciation. Although they may become economically obsolete and be scrapped on that account, one cannot depend on the mere passage of time to create occasions to radically redesign a firm's information structures and operating modes. Consequently, there is likely to be a strong inertial component in the evolution of information-intensive production organizations.

But, even these cautionary qualifications serve only to further reinforce one of the main thrusts of the dynamo analogy. They suggest the existence of special difficulties in the commercialization of novel (information) technologies that need to be overcome before the mass of information-users can benefit in their roles as producers, and do so in ways reflected by our traditional, market-oriented indicators of productivity.

REFERENCES

Baily, Martin N. and Gordon, Robert J., "The Productivity Slowdown, Measurement Issues, and the Explosion of Computer Power," *Brookings Papers on Economic Activity*, 2:1988, 347–420.

Bresnahan, Timothy F. and Trajtenberg, Manuel, "General Purpose Technologies and Aggregate Growth," Working Paper, Department of Economics, Stanford University, January 1989.

Byatt, I. C. R., *The British Electrical Industry 1875–1914: The Economic Returns to a New Technology*, Oxford: Clarendon Press, 1979.

David, Paul A., "Computer and Dynamo: The Modern Productivity Paradox in a Not-Too-Distant Mirror," Center for Economic Policy Research, No. 172, Stanford University, July 1989.

______, "Some New Standards for the Economics of Standardization in the Information Age," in P. Dasgupta and P. L. Stoneman, eds., *Economic Policy and Technological Performance*, London: Cambridge University Press, 1987, ch. 7.

______ **and Bunn, Julie A.,** "The Economics of Gateway Technologies and the Evolution of Network Industries: Lessons from Electricity Supply History," *Information Economics and Policy*, Spring 1988, *4*, 165–202.

______ **and Olsen, Trond E.**, "Equilibrium Dynamics of Diffusion when Incremental Technological Innovations are Foreseen," *Ricerche Economiche*, October-December, 1986, *40*, 738–70.

Devine, Warren, Jr., "From Shafts to Wires: Historical Perspective on Electrification," *Journal of Economic History*, June 1983, *43*, 347–72.

DuBoff, Richard, *Electrical Power in American Manufacturing 1889–1958*, New York: Arno Press, 1979.

Freeman, Christopher, and Perez, Carlotta, "The Diffusion of Technical Innovations and Changes of Techno-economic Paradigm," in F. Arcangeli et al., eds., *The Diffusion of New Technologies*, Vol. 3: *Technology Diffusion and Economic Growth*: *International and National Policy Perspectives*, New York: Oxford University Press, forthcoming 1990.

Gordon, Robert J. and Baily, Martin, N., "Measurement Issues and the Productivity Slowdown in Five Major Industrial Countries," OECD, Directorate of Science, Technology and Industry, Paris, June 1989.

Hughes, Thomas P., *Networks of Power*: *Electrification in Western Society*, *1880–1930*, Johns Hopkins University Press, 1983.

Lewis, Peter H., "The Executive Computer: Can There Be Too Much Power?," *New York Times*, December 31, 1989, p. 9.

Lorant, John H., *The Role of Capital-Improving Innovations in American Manufacturing during the 1920's*, New York: Arno Press, 1966.

Minami, Ryoshin, *Power Revolution in the Industrialization of Japan*: *1885–1940*, Tokyo: Kinokuniya Co., 1987.

Roach, Stephen S., "America's Technology Dilemma: A Profile of the Information Economy," *Special Economic Study—Morgan Stanley*, New York, September 22, 1987.

______, "White Collar Productivity: A Glimmer of Hope?," *Special Economic Study—Morgan Stanley*, New York, September 16, 1988.

Simon, Herbert A., "The Steam Engine and the Computer: What Makes Technology Revolutionary?," *EDUCOM Bulletin*, Spring 1986, *22*, 2–5.

von Tunzelmann, G. N., *Steam Power and British Industrialization to 1860*, Oxford: Clarendon Press, 1978.