Productivity growth prospects and the new economy in historical perspective

Paul David

1. Introduction: getting the right questions about the "new economy"

Today there are many questions about the nature and the future of the so-called "new economy". The term "new economy" itself has acquired a variety of quite different connotations. For many commentators, it continues to refer primarily to the altered macroeconomic performance of the US economy during the 1990s, when an accelerating rate of growth of real GDP and a steadily falling unemployment rate, unexpectedly, did not give rise to inflationary pressures on wages and prices. Some connected this with evidence of the revival of labour productivity growth, which became increasingly visible in the aggregate statistics for the private sector, as the key development heralding an escape from the US economy's puzzling and worrisomely poor productivity performance of the preceding two decades.

For others, however, the productivity growth picture below the aggregate level was less than entirely clear, and the core of the "new economy" was bound up with the growth of output and employment in "hi-tech" industries, particularly those involving information technologies and computer-mediated telecommunications, and with the on-going restructuring of business organisations and markets that are driven by advances in the latter (ICTs). The high and rising stock market valuations of companies in this sector, and the wave of venture capital that poured into new enterprises launched after 1993 to exploit the commercial possibilities of the explosively expanding Internet, seemed for still other observers to be the very essence of what was new and positive in these developments. Indeed, in the exuberance that marked the century's close, the NASDAQ stock market index came to be identified with the "new economy", whereas the comparatively weak performance of the Dow Jones index was disparaged as representative of the "old economy".

This welter of associations only serves to multiply the potential issues that might be addressed in responding to such a question as "Whither the new economy?" Not the least among these is the logically anterior issue of whether or not, and in what sense (or senses) such a thing usefully can be said to exist. In June of 2000 the OECD was taking a "wait and see" position on the question of whether or not there was a new dynamic of growth among the world's industrial economies, particularly those in Europe. There appeared to be less doubt that if the "new economy" existed anywhere, it was thriving in the US (1). Nevertheless, by the following autumn, Internet business watchers, stock market analysts, and the surviving "dot-com" principals themselves no longer were so convinced, even on the latter point; the leading publication of the Silicon Valley trade press, *The Industry Standard*, offered its anxious readers an assortment of expert opinion on its question: "Has the death of the dot-coms been greatly exaggerated?" (6 November, 2000, pp. 133ff).

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1) See OECD (2000), page 1*: "The question in the title [Is There a New Economy?] is promoted, in particular, by the remarkable performance of the US economy in recent years....The answer is probably 'yes - in some respects'. Some of the features associated with the 'New Economy' can actually be observed: stronger non-inflationary growth linked to a rising influence of ICT. But this picture applies mainly to the United States and does not generalize across countries [in the OECD]."*

But, if one seriously sought to respond to even so seemingly specific a query as that, the nature of the answers would seem to turn upon the interpretation of the term "dot-coms". Were that label construed as referring to the mass of novel enterprises launched during the *fin du siècle* stock market run-up, the numbers and market valuation of which now dwindle by the day, it would be hard to be optimistic about the prospects for their collective survival. On the other hand, if the term "dot-com" is accepted as shorthand for the general class of Internet-based enterprises that enter e-commerce markets with new business models, then, it is unlikely that we have seen the last of them. That much seems sure, even though in the future their financial backers are going to have a very hard-eyed look at their business plans.

A more intriguing set of issues are those concerning the sustainability of the high and rising rates of aggregate productivity growth in the US economy. Is the latter, too, a phenomenon that will pass into the annals of history (along with "the dot-com bubble") as a remarkable but transient phase of the protracted economic expansion that is currently drawing to a close? This question, and particularly its connection with the role that digital information technologies are playing in transforming the structure of the US economy, has held my interest for quite some time now. Its significance for long-term economic growth and welfare improvements in American society is both obvious and important. I believe it should be regarded as no less compelling as a subject for the attention of economic analysts and others whose primary concerns lie with the implications of the ICT revolution for Europe's economic prospects. In any event, this is the topic that I tackle here: How ephemeral is the productivity surge that developed in the US during the 1990s?

2. Towards understanding the productivity growth revival of the 1990s

Labour productivity growth during 1995-98 exceeded that of the 1980s by 1 percent. The data for TFP growth records almost as big an acceleration.

A quick look at the recent US statistics of labour productivity growth and total factor productivity (TFP) growth, will suffice both to make that question more concrete, and to suggest the beginnings of an answer. According to the Bureau of Labor Statistics' estimates (see Table 1), the average rate increase of real output per person hour worked in the private business economy during 1995-98 was a full percentage point above the 1.5 percent per annum rate maintained during the first half of the decade (1990-95). Hence, it exceeded the average productivity growth rate that characterised the decade of the 1980s by essentially the same 1 percentage point margin. The corresponding data for TFP growth records almost as big an acceleration in absolute terms, that is, a jump of 0.8 percentage points. Relative to its previous level (of 0.5 - 0.6 percentage points), this measure of the pace of TFP growth therefore underwent a proportionate recovery in the late 1990s that was considerably more pronounced than the revival in the labour productivity growth rate (2).

In the private business non-farm sector the acceleration of the corresponding TFP measure (from the same BLS source) was slightly less pronounced between 1990-95 and 1995-98: the rate rose from 0.6 to 1.3 percent per annum. There had been a more substantial pick-up in the pace of TFP advance, however, amounting to a 0.3 percentage point rise between the average rates during 1979-90 and 1950-95. Thus, reckoning from the experience of the 1980s as a base, the following decade saw a quickening, two-step acceleration that cumulated into a 1 percentage point gain in the annual pace of TFP increase, accounting for nearly all the gain registered by the labour productivity growth rate of the private business non-farm sector.

2) As noted in Table 1, the most recent BLS TFPgrowth rates (cited above), are "semi-refined" whereas the "refined" data in Table 2 reflect full adjustments for the contribution to output growth attributable to changes in the composition of capital inputs.

Table 1. The US productivity growth revival of the late 1990s in perspective.

	1973-1979	1979-1990	1990-1995	1995-1998
BLS Measures	Average annual percentage growth rates of GDP productivity measures for the Private Business Economy			
Output per person hour	1.3	1.6	1.5	2.5
Capital services per person hour:	0.7	0.7	0.5	0.8
Information processing equipment and software	*0.3*	*0.5*	*0.4*	*0.8*
All other capital services	*0.5*	*0.3*	*0.1*	*0.0*
Labour input composition	0.0	0.3	0.4	0.3
Semi-Refined TFP Residual (a)	0.6	0.5	0.6	1.4

Notes: a) Compositional change corrections are made for labour inputs, but in the case of capital inputs the only compositional changes accounted for are those between IT and non-IT capital, and changes in the quality of the IT capital stock.

Source: Derived from US Department of Labor, *News Release USDL 00-267*, September 21, 2000.

The picture just drawn serves to focus our attention upon the prospects for future total factor productivity (or multifactor productivity) gains, because these were the proximate agencies responsible for returning labour productivity growth during 1995-98 to the long-term average pace that was achieved over the whole period stretching from 1948 to 1995 (3). The other side of this coin, however, is the duration and severity of the deceleration in the growth of measured TFP that had marked the decades following the 1960s. The latter experience is brought out more starkly by a slightly different, and more exacting set of BLS measures for "refined" TFP growth in the private business non-farm economy. Those figures (in Table 2) reflect a more complete correction for the effects of compositional changes in capital inputs, as well as in the labour inputs.

Table 2. The extended slowdown of US TPF growth after 1972

Annual Percentage Growth Rates of GDP Productivity Measures for the US Private Non-Farm Business Economy			
BLS Measures:	1950-72	1972-88	1988-96
Output per work hour	3.08	1.32	0.83
Crude TFP	2.38	0.94	0.70
Input quality effect	0.40	0.59	0.59
Refined TFP	1.98	0.35	0.11

Source: US Department of Labor, News Release 98-187, May 6, 1998.

3) The average annual rates reported for TFP during 1948-98 are 1.4 percent in the private business sector, and 1.2 in the private business non-farm sector; the corresponding rates for 1995-98 are 1.4 percent and 1.3 percent. See US Department of Commerce, News Release USDL 00-27, September 21, 2000.

As can be seen from Table 2, the revival in the 1990s was not sufficiently strong to erase the effects of the preceding "slowdown": the average annual growth rate of measured TFP for the period 1988-96 actually continued to fall to the negligible 0.11 percentage point level - lower than the average rate recorded for the long interval of the "productivity slowdown" itself (1972-88).

The foregoing observations permit an initial response to the original question: clearly, these productivity indicators for the US economy aren't going to go on *accelerating* in the way they have done since the early 1990s. The BLS has yet to release its estimates for TFP growth beyond 1998, and so we must wait a while to learn whether the acceleration continued throughout the twentieth century's final years. Nonetheless, while it is not inconceivable that a further acceleration by as much as 0.5 percentage points could have been achieved in the private business non-farm economy, it seems most unlikely that the higher growth rate which would have been established by such a change could be sustained as a new long-term trend.

One way to arrive at this conclusion is to notice that the result of such a scenario (i.e., continued acceleration) would be tantamount to the US economy staging a cumulative productivity revival amounting to 1.3 - 1.5 percentage points, thereby bringing the average annual rate of aggregate (refined) TFP growth all the way back up to the trend rate that had characterised the post-World War II era, the so-called "golden age of productivity improvements" (4). We know that in the latter era, however, many quite special conditions circumstances prevailed in both the US and the international economy which contributed to boosting productivity growth; that in their very nature those conditions were not self-renewing, and so gave way eventually to a subsequent macroeconomic environment characterised by reduced investment rates, sluggish productivity advance and recurring inflationary pressures (5).

Should we entertain the notion that the "Age of the Internet" will be another "golden age" of productivity improvement?

Should we entertain the notion that the consequences of the technologies of digital computing and computer-mediated communications - associated with the dawning of the "Age of the Internet" - constitute the basis for the return of another extraordinary episode, featuring a comparably strong surge of productivity advance? That, of course, is the view advanced by some advocates of the "new economy" hypothesis who see new information processing and telecommunications technologies as having played the central role in accelerating the US economy's growth while holding inflation in abeyance (6). The most recent Economic Report of the President placed itself quite forthrightly in this camp, declaring (7):

> *"At the heart of the New Economy lie the many dramatic technological innovations of the last several decades. Advances in computing, information storage, and communications have reduced firms' costs, created markets for new products and services, expanded existing markets, and intensified competition at home and abroad.... Indeed, the rapid growth of the information technology sector was one of the most remarkable features of the 1990s".*

4) This point (conveniently) holds in regard to the array of variant TPF growth measures in Tables 1 and 2. The "golden age" of post-WII growth referred to in the text is dated variously as 1948-73 and 1950-72.

5) See Abramovitz (1989), for a compact but comprehensive exposition.

6) Former Federal Reserve Board member Alan Blinder (2000), for example, noted the temporal coincidence in referring to the "tantalizing fact - that productivity accelerated at just about the time the Internet burst on the scene". But, he cautiously hesitated to infer that there was a causal connection: "Whether or not the Internet was the cause of the speedup in productivity growth will be a matter for economic historians to sort out some years from now....For now, however, it appears that the economy can sustain a higher growth rate than most people thought plausible just a year or two ago. In that limited respect, at least, we appear to be in a 'New Economy'".

7) Economic Report of the President, (2001); Chapter 3, page 95; on productivity growth, see Chapter 1, pp. 25-33.

Yet, that conclusion also has been criticized as lacking in solid empirical foundations, and not only by economists who have steadily expressed scepticism about the "ICT revolution", (8). Rather than engaging with the technical details of that debate, I want to devote the following sections of this paper to a somewhat more analytical look backward, before venturing upon some concluding conjectures about the road that lies ahead. This approach reflects more than the historian's characteristic diffidence when asked to predict. We are likely to form a better grasp of the present prospects for sustained rapid productivity growth, and hence for the continuation of the US economy's remarkable non-inflationary expansion in the years immediately ahead, by making the effort to delve first into the causes of the recovery in measured TFP growth that occurred during the second half of the 1990s. Furthermore, as will become evident, without a satisfactory account of what happened in the preceding period of the productivity slowdown, it is going to be difficult to understand the underlying sources of the revival.

3. Links between new technologies and sources of recent acceleration in measured TFP

There are at least three proximate sources of the revival of measured TFP growth that occurred during the later years of the 1990s that we may link with the effects of technological change, and, more specifically, with innovations in information processing and computer-mediated telecommunications. The connections to which I wish to draw attention here, however, are rather less direct than those, which economists typically emphasise when they interpret the TFP growth rate itself as measuring "the rate of technological innovation".

Some part of the apparent speed-up certainly was due to the strength of demand growth, fuelled by the higher gross private domestic investment rate, and the wealth effects upon consumption that derived from the stock market boom. The move toward more intensive utilisation of the employed labour force, and of the existing stock of plant and equipment, has contributed to increasing measured productivity. In one sense, this aspect of "the new economy" isn't really new, because there is a long historical record of pro-cyclical movements in the growth of TFP as well as of average labour productivity (9).

But, how large an effect this can be said to have contributed to the recent surge of productivity growth remains a matter of some controversy among economists. By extrapolating from the US historical record, Robert Gordon (2000a), arrived at estimates showing the "cyclical component" accounted for almost two-fifths of the post-1995 acceleration. For the non-farm private business economy, according to Gordon, this component contributed 0.5 percentage points of the 1.3

8) Paul Krugman's (2000a), enthusiasm about the reality of a technology driven surge in productivity did not suffice to quell his scepticism (2000b), about the soundness of the macroeconomic arguments advanced by believers in the existence of a "new paradigm". Robert Gordon (1999, 2000b), has maintained, on a variety of grounds, that the "information revolution" is not an economic phenomenon whose consequences will approach the magnitude of the transformations wrought by technological innovations in the late 19th and early 20th centuries. See also, for example, Cassidy (2000), for a review of the recent recurrence of ICT-scepticism. On a rather different level is Gordon's (2000a) observation that labor productivity growth failed to recover in many sectors of the US economy, so that the sharp acceleration of the late 1990s actually has been quite patchy, and concentrated heavily in the computer and telecommunications equipment, and software branches within manufacturing.

9) This has been recognized in the literature at least since Hultgren (1960); and, since Oi (1962), it has been explained in terms of the changing intensity with which "quasi-fixed" elements of the work force, as well as other fixed factors of production are utilised.

percentage point rise observed in the annual rate of growth of real GDP per hour; and the corresponding share was as much as three-fourths of the smaller (0.86 percentage point) acceleration experienced in the part of the non-farm private business sector not engaged in manufacturing durables.

Gauged by historical standards the strength and duration of the pro-cyclical upswing appear to be something new.

Jorgenson and Stiroh (2000b), however, take the view that Gordon's estimate over-states the "cyclical" correction, and therefore yields too low a residual figure for the "structural component" of the acceleration in the TFP growth rate. Disagreements of this kind reflect the deeper problem of extrapolating from statistical relationships that prevailed in the past, when the pace and manner in which technologies are diffused, and their effects upon the structure of the economy all have been changing. Gauged by historical standards the strength of the pro-cyclical upswing on this occasion, and the duration over which the productivity rises have continued to offset upward pressure on input costs, would appear to be *something new*. Moreover, there are some good reasons to believe that the large "cyclical component" arrived at by Gordon's calculations itself may reflect the application of digital information technologies (from computers and databases to broadband telecommunication networks).

For example, these applications contributed to reducing required levels of inventory holdings of both goods in process and finished products. In the durable goods industries the inventory-sales ratio has exhibited a secular decline since the early 1980s, but after the early 1990s its downward course became particularly pronounced (10). In addition, "smarter" scheduling of transportation and production operations, and better coordination of work within and among business firms, reduces the need to hold "inventories" of partially utilised workers and avoids plant and equipment being idled while awaiting the delivery of supplies. All of that makes possible the fuller utilisation of the capacity of the "fixed" inputs in production, and it shows up in measured TFP gains.

These sources of accelerated productivity growth, however, are the kind that are unlikely to be sustainable. In the first place, the aggregate demand may not keep up with the expansion of supply capacity, and the resulting accumulation of unwanted inventory holding is then likely to reduce utilisation rates. A further consideration, also suggesting the limited sustainability of rapid productivity gains achieved in response to demand pressures on capacity, is that the easier changes in the organisation of production and distribution tend to be the first ones to be exploited. As the low-hanging fruit get picked off first, so the incremental gains become smaller and smaller. Similarly, when experienced workers no longer will take on more overtime, new workers need to be found, hired and instructed, and that means the employing firms must incur the added fixed labour costs, which such activities impose.

The difficulty of making detailed time-series adjustments for the influence of such changes on measured productivity growth encourages cautious practitioners of the growth accountants' art to view their results as most reliable for gauging the longer-term trend rates, particularly those which emerge from

10) See McConnell and Perez-Quiros (2000), who attribute the decreased short-term volatility of real GDP growth in the US after 1983 to this development in the durable goods sector. Between the successive peak levels of the inventory-sales ratio in the years 1981-83, and 1991-92, the proportional decrease amounted to 10 percent, but the downward trend resumed thereafter and brought the ratio down by another 25 percent, to an unprecedentedly low level of 1.5 by 1998. Interestingly, the 1990s also witnessed the first persisting departure of the movements in the inventory-sales ratio for durable goods from the ratio for non-durable goods. The latter continued to fluctuate around a stationary level (approximately 1.14) throughout the 1990s.

comparisons between points in the growth record where the economy is found to have been operating at equivalently high rates of capacity utilisation. Applying growth accounting methods for the analysis of economic performance over comparative short time intervals, therefore, must be regarded as somewhat more of a "risky business" than casual readers of the results often are left to suppose (11).

There is a second "new" element to be noted in the recent US productivity growth story, one that is not unconnected with the strength and the nature of technological changes accompanying the recent economic expansion. A much larger share of aggregate production now involves intangible goods, such as software and other digital information-goods, whose unit costs of production tend to fall rapidly with growth in the volume of production. This has undoubtedly contributed to reinforce the pro-cyclical productivity effect. In this sense one may say that the information technology revolution has been contributing towards maintaining the importance of the sector of the US economy in which production is characterised by conventional, old-fashioned economies of scale. Of course, the downside is that this source of productivity growth is likely to be jeopardized by a weakening of demand and declining sales volumes in the new information-goods sector industries.

Much of what has been taking place within the time frame on which recent analysts have focused appears to reflect interactions between demand side and supply side changes and interactions among supply side phenomena.

Summing up the foregoing discussion, one may remark that trying to quantify the various "sources of growth" on the supply side, in the way that conventional growth accounting encourages us to do, is less than wholly enlightening about the behaviour of the economy over the short- and medium run, which is to say, within the course of normal 4-5 year business cycle movements (12). Much of what has been taking place within the time frame on which recent analysts have been focusing, appears to reflect interactions between demand side and supply side changes, and the interactions among various supply side phenomena. Under rather exacting assumptions, each of the latter factors could be quantified as neatly as they may be distinguished for purely conceptual purposes. But, in practice, the conditions required to separate them for purposes of measurement are more typically not fulfilled. Thus, it has been noted that the effects of technological innovation can alter the quantitative importance at the aggregate level of productivity gains that are derived from economies of scale; whereas the latter in turn may alter the sensitivity of macroeconomic performance to changes in demand conditions.

We should turn now to examine a third, and rather different development that underlays the acceleration recently observed in measured productivity, one that is more likely to persist, if only because it brought the cessation of increasingly serious measurement errors that had been contributing to the apparent "slowdown" of the productivity growth rate during the 1970s and 1980s. It will be seen that this, too, has a connection with developments in the sphere of information technologies and the manner of application. But on this point the argument is somewhat more intricate than it was in the first two cases, and to present it properly requires that I first provide a little background on the vexed subject of productivity measurement errors.

Ever since the emergence of the "computer productivity paradox", or "the productivity slowdown puzzle" as it should properly be called, economists recurrently have discussed the possibility that the

11) See, for example, the chronology developed for this purpose by Abramovitz and David (1999); Jorgenson and Stiroh (2000b) make essentially the same point in connection with their application of growth accounting at lower levels of aggregation.

12) This caveat may be taken to apply equally to the contributions of Gordon (2000a), Oliner and Sichel (2000), and the US Department of Labor (2000), to the interpretation of the sources of the post-1995 acceleration in productivity growth.

shrinkage of the TFP residual was in whole or part an artefact of biases in the indices of aggregate real product growth (13). Among the more popular suspects in this regard is the problem of obtaining unit prices for the products of service industries, and the consequent difficulty of measuring real product movements in a part of the US private business economy whose share in the current value of production has been expanding. Suspicion also has fallen on the likely failure of the price series used as deflators for the current value of production in a large number of commodity producing industries and services to take sufficient account of the improvements in product quality. As a result, the rate of price increases would tend to be overstated, leading to a downward bias in the measured growth of real output and productivity (14). The magnitude of the difference in measured real output growth that resulted when the Bureau of Economic Analysis (in the US Commerce Department) introduced quality adjusted (so-called "hedonic") price deflators for just one industrial branch - the manufacture of computer equipment, has served to underscore this more general worry (15).

The first of these two suspicions of serious measurement bias was emphasised by Griliches (1994), who drew attention to the existence of a substantial gap between average labour productivity growth rates in the better-measured, commodity-producing sector on the one hand, and a collection of "hard-to-measure" service industries, on the other. He suggested that the expanding share represented by the FIRE bloc (Construction, Trade, Finance, Insurance, and Real Estate), and miscellaneous other service industries, would have exerted an increasing drag on the economy's aggregate labour productivity growth rate. To the extent that the differentially slower productivity growth in services was the consequence of the understating the growth of services output, the magnitude of the overall downward bias would have increased during the 1970s and 1980s.

Now, it is not immediately apparent how these particular sources of measurement bias might bear upon our understanding of the subsequent *revival* of productivity growth. Taking them in reverse order, the hypothesized impact of the economy's structural drift towards "un-measurability" turns out to be quantitatively weak; at most it could have could have been responsible for only a tenth of the 1.3 percentage point slowdown in the average annual rate of measured aggregate productivity growth after the 1960s (16). Consequently, even if the relative expansion of "poorly measured"

13) Abramovitz and David (1999), Part 2, Section 3, provide a critical review of the literature on this issue.

14) It is important to make it clear that this problem is quite distinct from the main source of upward bias in the official "inflation rate" for the US, to which public attention was drawn by the 1997 report of the so-called "Boskin Commission", which criticized the BLS methodology formerly used in constructing the US Consumer Price Index (see Madrick, 1997). Of the approximate 1 percentage point per annum "overstatement" in the CPI's average growth, about 0.7 percentage points were ascribed to the effect of employing fixed quantity weights, i.e., calculating the (Laspeyres) price index for an invariant "basket of goods." The GDPdeflator, by contrast, is defined as a (Paasche) variable weight price index, to which this critique did not apply.

15) See, for example, Moulton (2000), pp. 36-38. This correction for quality improvements, however, being confined to one branch of manufacturing (and extended subsequently to cover digital telecommunications equipment and software, creates statistical distortions in the "real" (constant price) measures of the structure of the economy, and also has made the interpretation of comparative international indicator of output growth and productivity much more problematic than it had been formerly. For an excellent treatment of this little-recognized issue, see Wycoff (1995).

16) The effect on the weighted average rate of labor productivity of the shifting the output shares can be found in the following way. Gross product originating in Griliches' (1994), "hard-to-measure" bloc within GPDP averaged 49.6 percent of the total over the years 1947-1969, whereas its average share was 59.7 percent in the years 1969-1990. These averages were calculated from the underlying NIPA figures as geometric means of the terminal year values in each of the two intervals. The observed trend difference (over the whole period 1947-1990) between the labor productivity growth rates of the "hard-to-measure" and the "measurable" sectors identified by Griliches (1994), amounted to about 1.40 percentage points per annum. Thus, simple re-weighting of the trend growth rates lowers the aggregate labor productivity growth rate by 0.13 percentage points between 1947-1969 and 1969-1990, which amounts to rather less than 12 percent of the actual slowdown that Griliches was seeking to explain. See David (2000), Section 2.2, for further discussion of this issue.

service industries had halted completely after the early 1990s, which was not the case, the effect could not have contributed much to the apparent rebound in productivity (17).

A comparable difficulty is encountered by proponents of the other suggestion, namely the objection that quality improvements have been going largely unrecorded in the official figures for real product growth until lately. In other words, it was not so easy to come up with persuasive reasons for supposing that the downward bias on this account had become *more pronounced* after the 1960s, and so was responsible for the appearance of slower productivity growth. Indeed, according to Bresnahan and Gordon (1996), the rate of unmeasured quality improvements in durable goods was high during the early post WW II decades, and there were no *a priori* grounds for believing that the dimensions of the overall problem became more serious during the 1970s and 1980s - especially not in view of the introduction by the Bureau of Economic Analysis of GDP deflators that reflected "quality adjusted price indices" for computer and peripheral equipment (and, more recently for telephone switching equipment, semiconductors and some types of software) (18).

The point that deserves recognition here, however, directly contests the latter view, identifying both analytical and empirical reasons to support the hypothesis that the relative magnitude of the underestimation of quality improvements, and the consequent understatement of the real output growth rate, have not remained constant. Even though the argument is somewhat novel, the two-fold claim advanced in the following paragraphs can be summarised simply: firstly, the downward measurement bias in the US real output growth rate grew significantly after the early 1970s, but by the early 1990s its magnitude had stabilised; secondly, this temporal pattern arising from the underestimation of productivity quality improvements, was related causally to the course of the ICT revolution.

Through the mid-1970s to early 1990s, IT enabled firms to cut the costs of introducing new goods and services.

From the middle of the 1970s through to the early 1990s new information technologies increasingly were being applied in ways that enabled firms to cut the costs of introducing new goods and services, thereby encouraging firms to shorten their average product life-cycles, and to experiment with "mass customisation" (19). The proportion of sales revenues that were generated by newly introduced products was therefore increasing. As economists have long been aware, the official government price series tend to miss a good portion of the rapid fall that typically occurs in the relative prices of new products when they still are very young. Because those price series are used to deflate the total sales revenues of the industries introducing these novel goods, the resulting estimates of growth in the industry's real output, and in their productivity, tends to be understated.

Although this was not a "new" problem in the qualitative sense, it became a quantitatively more serious source of bias, precisely because the relative importance of new goods and services was

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17) A different and deeper set of unresolved measurement issues, nonetheless, deserves to be noticed. As Diewert and Fox (1999) have pointed out, these particularly affect the expanding provision of customised information services *- whether in free-standing form, or in bundled with tangible commodities. The core problems involve those of measuring the incremental utility that consumers derive from applications of information technologies that lower the costs of reducing risk, whether by increasing the availability of information to decision-agents, or by reducing marginal costs of providing highly specialized forms of insurance.*

18) See Cole et al.*, (1986), on the introduction of quality corrections using the "hedonic" price index methodology; Moulton (2000), pp. 37-39, for subsequent extensions of this initiative by the BEA.*

19) See David (2000, pp. 61-65) for further discussion and references on mass customization, and on the data supporting the particular hypothesis about measurement bias that is advanced here.

The growing importance of new products had a perverse effect. "Mass customisation" worked to depress measured productivity even further than had been the case historically.

increasing. During the rapid transition to mass customisation that was underway in the US during the 1980s, the average age of product lines was falling and the downward measurement bias in the output growth rate therefore became more and more pronounced. These developments reflected in good measure the application of new information technologies, and related organisational reconfigurations in R&D-intensive businesses. By enabling the integration of market research, new product design, production engineering, and marketing, ICT use contributed to reducing the fixed costs of new product innovation, and shortened the innovation cycle.

The phase in the evolution of digital technology that characterised the 1980s as the era of "the PC revolution" may not have done much to promote readily measurable gains in task productivity, for reasons that I have considered elsewhere. Yet, what is of importance here is that it unshackled innovative product design and marketing groups within many large organisations, in part by freeing them from dependence upon (and, hence, from the tighter constraints imposed by) hierarchically structured, mainframe-based information systems that served the control functions of central management.

Therefore, mass customisation, along with all that it entailed in the way of modern manufacturing and inventory control, justly can be regarded among the palpable consequences of the ICT revolution of the 1980s. This was not appreciated at the time by economic analysts who tended to regard the proliferation of PCs on office desks as little more than the miniaturisation of mainframe computing; a development which they saw as failing to deliver the sort of measurable productivity payoffs that had been realised in the late 1960s and 1970s, when mainframe systems released labour by taking over many back-room "number crunching" functions in banking and financial transactions, payroll and record processing, and the like.

The growing relative importance of new products in the economy, had a perverse effect upon measured productivity. This was the result of its interaction with the prevailing, official routines for tracking the prices of new products. Putting the matter most simply, the mass customisation movement in this phase of the computer revolution, paradoxically, worked to widen the gap between the actual and the measured productivity growth rate even further than had been the case historically. How big was this added downward bias? The preliminary estimates that I have made indicate that during the 1977-92 interval the increase in the magnitude of the underestimation bias may have been very substantial: perhaps big enough to push the measured annual growth rate in the private non-farm business economy downwards by 0.3 - 0.5 percentage points, in comparison to what would have been recorded had the effect of the bias in the price deflators remained unchanged (20).

This ballooning of the gap between the actual and the measured growth rate of productivity does not seem to have continued after the early 1990s, certainly not at anything approaching its former pace. Under the conditions envisaged for the calculations that I have just cited, the magnitude of the upward bias of the official price deflators was being enlarged simply due to the enlarged share

20) See David (2000, pp. 62-63), for discussion of underlying estimates of the movement in the share of newly introduced products in the total product flow through US retail distribution channels: this fraction was stable over the 1964-75 interval, rose dramatically between 1975 and 1992, and appears to have substantially stabilized thereafter. A memorandum is available on request from the author, setting out the assumptions and preliminary calculations used to derive the implications of those movements for the temporary expansion during 1975-1992 *in the magnitude of the understatement of the rate of growth in real GDP.*

that sales of newly introduced goods represented in the total value of commodities goods (other than computers and peripheral equipment). For that to have continued, the pace of new product innovation would have had to gone on *accelerating* sufficiently to continue the upward trend in the average rate at which product lines turned over. But, by the early 1990s the force of the wave of "mass customisation" appears to have been largely spent: the average age of product lines no longer was dropping as quickly as had been the norm in the 1980s, and the proliferation of variety within product lines began exerting stronger downward pressure on the mark-ups initially commanded by newly "customised" products.

The recent acceleration of measured TFP growth cannot be attributed to a reduced degree of underestimation – the rebound of TFP is a real phenomenon.

Consequently, this source of downward bias in the measured productivity growth rate was once again stabilised - albeit at a substantially higher level (namely by the added 0.3-0.5 percentage points) than that which characterised the era preceding the "slowdown" of 1974-1990. Had the drag exerted on the measured growth rate continued to increase through the 1990s, it would have masked some part of the revival in the rate of growth of measured TFP that has been observable in the years since 1992. At this point, perhaps, it should be emphasised that the burden of the preceding argument is that the magnitude of the slowdown in measured TFP growth from the rates maintained during the "golden age" (variously dated 1948-69, or 1950-72), was exaggerated by the worsening bias in the price deflators. Yet, the recent acceleration of measured TFP growth - compared to the pace of the latter during the late 1980s an early 1990s - cannot be attributed to a reduced degree or underestimation of the true rate of growth of output.

The implication to be drawn from this is that *the rebound* of the measured TFP growth rate is rightly viewed as a real phenomenon, calling for an explanation as such. But, a second implication is that if we want to make historical comparisons with the "golden age" of productivity growth, it would be necessary to adjust for the enlargement in the gap between the "true" and the measured rates of output growth that had contributed to the apparent productivity slowdown. One may then notice that adding an upward adjustment of as much as 0.3-0.5 percentage points to the growth rates presently found (in Table 2) for the entire period from the mid-1980s onwards, would bring the estimated pace of TFP growth during the most recent sub-period back up into the neighbourhood of the high average rates recorded for the 1950-72 "golden age" (21).

As has been previously remarked, a substantial component of this "historically comparable" adjusted TFP growth rate of 1.5 to 1.7 percent per annum in the years 1996-1999, is cyclically inflated above the sustainable trend. But, because the source of the upward adjustment is one that can be read as reflecting total factor productivity growth in sectors of the economy other than the vertically integrated computer sector, this correction carries the further implication that the direct impact of product quality improvements in the computer sector now appears less crucial a source

21) To make this rough calculation on the basis of the BLS estimates in Table 2, one can start simply by adding 0.3 to 0.5 percentage points to the 1.4 percent per annum figure shown for 1996-1998, obtaining a "corrected" range of 1.7-1.9 percent per annum for the latter period. But the Table 2 estimates are "semi-refined", whereas the 1.98 percent per annum average rate shown for 1950-72 by Table 1, is the BLS's "refined" estimate. Two further "adjustments" are thus in order. In place of the BLS figure for 1996-98, we may start from the fully refined TFPgrowth rate of 1.2 percent per annum that Oliner and Sichel (2000, Table 4), provide for 1996-1999. That yields an "corrected range" of 1.5 -1.7 percent per annum for this recent period. Secondly, in place of the rather high BLS estimate in Table 2 for the period 1950-72, we may substitute the more "refined" TFPgrowth rate estimate of 1.7-1.8 for these years. The latter accords with the underlying (input composition adjusted) estimates used by Gordon (2000a).

of the elevated rate of TFP growth. According to the estimates made by Oliner and Sichel (2000, Table 4), total factor productivity growth in "other non-farm business" contributed 0.5 percentage points to the total growth rate attained during 1996-1999. The adjustments for the under-estimated quality improvements (apart from semiconductors, computer and peripheral equipment) would thus push the other non-farm business sector's contribution up toward the 0.7 to 0.9 percentage point level (22).

This goes some way towards removing the puzzling concentration of total factor productivity growth in the "computer-producing" industries, and its corresponding absence from the "computer-using" sectors, which has been remarked upon by a number of recent studies. Stiroh (1998), and Jorgenson (2000), have taken the view that the low rates of total factor productivity growth outside the computer-producing sector are no "puzzle", but an entirely understandable consequence of the rapid fall in the relative (quality adjusted) price of computer capital services, which has induced substitution of the latter for the services of labour inputs. It is through that channel that they, along with Oliner and Sichel (2000), now see the information revolution as contributing indirectly to raising the growth rates of output and labour productivity in the economy at large; whereas it is the direct effects of multifactor productivity advances concentrated in the industries producing semiconductors and "computer investment-goods" that have been responsible for the spectacular fall of the price-performance ratios in those products.

One begins to form the view of the IT revolution as a source of efficiency improvements that have been gradual increasing in magnitude and permeating the economy.

By re-balancing that rather lop-sided picture in the way I have suggested here, one begins to form a view of the digital technology revolution as a source of efficiency improvements that gradually have been increasing in magnitude and permeating the economy. Such a view conforms more closely with our expectations of the way in which fundamental technological breakthroughs eventually precipitate cascades of technical and organisational innovation, which, in turn, are reflected in surge-like movements of the economy's total factor productivity growth rate. Whether or not the recent acceleration is to be seen as a harbinger of developments of this kind remains a matter of speculation. The study of historical experience, however, can afford us considerable guidance in understanding the mechanisms, and the conditions that may promote such far-reaching transformations of the economic regime.

4. General purpose technologies and productivity surges: an interpretive framework

Putting aside the issues of measurement, and the disentangling of transitory from the sustained components in measured productivity growth rates, we must now give closer consideration to the longer-term processes linking technological innovation, capital formation, structural change and sustained productivity growth. Consequently, it seems quite appropriate for me to draw upon some of the interpretive insights that historical research can offer, and to focus particularly upon the ways in which the advent of "general purpose engines" may precipitate a transition to a new techno-economic regime in which significantly higher levels of productivity become attainable.

The notion of a general-purpose engine, constitutes the primitive of the more extended concept of a GPT, or "general purpose technology" - a conceptualisation that has been gaining popularity

22) The proportionate contribution attributable to the "other non-farm business" sector after making these corrections also is raised somewhat: it lies in the range from 47 to 52 percent, whereas the fraction (0.5/1.2) suggested by the figures from Oliner and Sichel (2000, Table 4), implies a contribution of 42 percent.

recently in the literature of endogenous economic growth models. According to the formulation proposed originally by Bresnahan and Trajtenberg (1995, page 84):

> *"Most GPTs play the role of 'enabling technologies', opening up new opportunities rather than offering complete, final solutions. For example, the productivity gains associated with the introduction of electric motors in manufacturing were not limited to a reduction in energy costs. The new energy sources fostered the more efficient design of factories, taking advantage of the newfound flexibility of electric power. Similarly, the users of microelectronics benefit from the surging power of silicon by wrapping around the integrated circuits their own technical advances. This phenomenon involves what we call 'innovational complementarities' (IC), that is, the productivity of R&D in a downstream sector increases as a consequence of innovation in the GPT technology. These complementarities magnify the effects of innovation in the GPT, and help propagate them throughout the economy".*

"General purpose engines" may precipitate a transition to a new techno-economic regime in which significantly higher levels of productivity become attainable.

Economists working in the spirit of the new growth theory have sought to generalise these ideas, by identifying a range of GPTs that not only find applications in diverse sectors of the economy, but which act as catalysts, inducing complementary innovations in those other sectors. The interest in generalisation has in turn stimulated efforts to extend the list of historical examples, as well as to consolidate our understanding of the defining features of GPTs (23). According to the carefully developed criteria proposed by Lipsey, Bekar, and Carlaw (in Helpman, 1998), GPTs share the following characteristics: (1) wide scope for improvement and elaboration; (2) applicability across a broad range of uses; (3) potential for use in a wide variety of products and processes; (4) strong complementarities with existing or potential new technologies.

James Watt's (separate condenser) steam engine design springs to mind readily as an example of an innovation that meets these criteria, and, indeed, it is widely accepted as the GPT that is emblematic of the first industrial revolution. One might notice that while this seminal invention dates from the early 1780s, the elaboration of steam power technology extended over the next three quarters of a century: the automatic variable cut-off device, invented by the American, George Corliss, who patented the device in 1849, resulted in very significant gains in fuel economies; it also greatly enhanced the effectiveness of this power source in applications requiring both regular continuous rotary power, and adjustment to sudden variations of the load placed on the engine.

As Rosenberg and Trajtenberg (2000), recently observed, the widespread industrial utilisation of steam power in the US was a phenomenon that properly belongs to the second half of the nineteenth century, and in considerable part was the consequence of the diffusion of Corliss' engine design. Prior to 1850 much the greater part of the stock of steam power capacity was devoted to marine transportation (steam boats on the lakes and rivers), and to overland railway transportation, rather than large-scale manufacturing. Factory production of textiles in the US had begun by

23) Lipsey, Bekar and Carlaw (in Helpman, 1998, pp. 38-43), identify an extensive list of historical and contemporary GPTs, from power delivery systems (waterwheel, steam, electricity, internal combustion) and transport innovations (railways and motor vehicles) to lasers and the Internet. The concept has been extended to encompass "organizational techniques" (the factory system, mass production, flexible manufacturing, and even the unit system for continuous process production. David and Wright (1999b), on the other hand, argue against indefinitely lengthening the list, and recommend seeking in each historical context to understand the hierarchical structure of the technological elements that were formed into systems around a core GPT.

harnessing waterpower at sites along the Appalachian "fall-line" in New England, just as England's mechanised cotton-spinning factories of the later eighteenth century had arisen initially along the swift-flowing streams of the Derbyshire dales. The great urban-industrial agglomerations of the Lancashire cotton textile industry emerged only subsequently, when the falling costs of steam-power released the mills from those rural surroundings and the constraints of inelastic local supplies of labour.

Numerous additional observations concerning the technical and economic implications of steam power would deserve a separate treatment (24). But, the line of argument I wish to develop is better served by focusing on the parallels between the modern digital computer (microprocessor) and another general-purpose engine, one that figured prominently in what sometimes is referred to as the "Second Industrial Revolution". Of course, as on previous occasions (David 1990, 1991a), I refer here to the electric dynamo (25).

5. The electric dynamo as a GPT, and the dynamics of the 1920s productivity surge

The transformation of the American factory involved more than the simple diffusion of the electric motor. A new system of manufacturing, characterised by higher and more rapidly rising efficiency, emerged.

The electric dynamos of the late nineteenth century, like modern-day computers, formed nodal elements of physically distributed (transmission) networks. Both of them occupy key positions in webs of strongly complementary technical relationships that give rise to "network externality effects" of various kinds, and so make issues such as induced innovation and compatibility standardisation important for business strategy and public policy (26). In both instances we can recognise the emergence of a temporally 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. In each epoch, the successful exploitation of the new technology's evolving productivity potential has entailed the design 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.

The transformation of industrial processes by electric power technology was a long-delayed and far from an automatic business. It did not acquire real momentum until after 1914 to 1917, when the rates charged consumers by state-regulated regional utilities fell substantially in real terms, and central station generating capacity came to predominate over generating capacity in isolated industrial plants. Rapid efficiency gains in electricity generation during 1910 to 1920 derived from major direct investments in large central power plants, but also from the scale economies realised

24) For example, it may be pointed out that the greatly increased engine speeds that were attainable with Corliss-type steam engines in the closing decades of the nineteenth century, made these machines very attractive as the power source for generating electric current in the era before the emergence of the steam turbine power plant. This illustrates the general propositions (discussed below) that the process of deploying and exploiting a GPT is typically quite prolonged, and much of its economic impact derives from the confluence with, and enhancement of the benefits derived from other technological and organisational innovations.

25) See David (1991b), on the important economic respects in which information and electricity are not analogous; David (2000, pp. 77-82), for discussion of a number of other, mis-directed criticisms that have been leveled against drawing parallels between the computer and the dynamo revolutions.

26) With specific reference to the appearance of these issues in the context of network activities such as the electricity supply industry, see, for example, David (1987), David and Bunn (1988).

through integration and extension of power transmission over expanded territories. These developments were not simply matters of technology, but also reflected political and institutional changes that allowed utilities largely to escape regulation by municipal and town governments, facilitating the flow of investment capital into holding companies presiding over centrally managed regional networks. Together these supply-side changes propelled the final phase of the shift to electricity as a power source in US manufacturing, from just over 50 percent in 1919 to nearly 80 percent in 1929 (27).

But, the protracted delay in electrification was not exclusively due to problems on the supply side of the market for purchased electrical power. The slow pace of adoption prior to the 1920s was attributable largely to the unprofitability of replacing still serviceable manufacturing plants adapted to the old regime of mechanical power derived from water and steam. Coexistence of older and newer forms of capital often restricted the scope for exploiting electricity's potential. Prior to the 1920s, the "group drive" system of within-plant power transmission remained in vogue. With this system -- in which electric motors turned separate shafting sections, so that each motor drove related groups of machines -- primary electric motors often were merely added to the existing stock of equipment (28). When the favourable investment climate of the 1920s opened up the potential for new, fully electrified plants, firms had the opportunity to switch from group drive to "unit drive" transmission, where individual electric motors were used to run machines and tools of all sizes.

The advantages of the unit drive technology extended well beyond savings in fuel and in energy efficiency. They also made possible single-story, linear factory layouts, within which reconfiguration of machine placement permitted a flow of materials through the plant that was both more rapid and more reliable. According to the surveys of American manufacturing directed by Harry Jerome (1934: pp.190-91), rearrangement of the factory contributed to widespread cost savings in materials handling operations, serialising machines and thereby reducing or eliminating "back-tracking".

It is important to emphasise (especially for the benefit of economists engaged in modelling the dynamics of growth driven by GPTs) that the transformation of the American factory involved more than the simple "diffusion" of a particular general-purpose engine in the form of the electric motor. Rather, a new system of manufacturing emerged from the confluence, or convergence, of factory electrification with other trajectories of industrial innovation. The transformation of American manufacturing practices during the Interwar era, quite obviously finds a modern counterpart in the "information revolution's" converging advances in the technology of semiconductors and microprocessor fabrication, in fibre-optic cables, laser applications (for reading and recording digitised data in compressed formats, and in laser-pumped broadband optical networks), low-power cellular digital telecommunication systems, and myriad innovations in computer programming and data storage and retrieval technologies.

The transformation of manufacturing practices in the Interwar era finds a modern counterpart in the information revolution.

The package of electricity-based industrial process innovations that came into use during the 1920s could well serve as a textbook illustration of *capital-saving* technological change. Electrification saved fixed capital by eliminating heavy shafts and belting, a change that also allowed factory buildings themselves to be more lightly constructed, because they were more likely to be single-

27) See David and Wright (1999a), Figure E1, and text discussion.

28) For further technological details see Devine (1983), and Devine (1990).

storey structures whose walls no longer had to be braced to support the overhead transmission apparatus. The faster pace of material throughput amounted to an increase in the effective utilisation of the capital stock. Further, the frequency of downtime was reduced by the modularity of the unit drive system and the flexibility of wiring; the entire plant no longer had to be shut down in order to make changes in one department or section of the factory (29). Notice too that Henry Ford's transfer-line technique, and the speed-up of work that it permitted, was a contributory element of the high throughput manufacturing regime, as were the new continuous process technologies that grew in importance during this era.

The consequent effects of factory electrification upon industrial productivity are confirmed by the sharp fall recorded in the manufacturing sector's capital-output ratio during the 1920s, a development that contributed significantly in the early twentieth-century to reversing the nineteenth century trend towards economy-wide capital deepening. A pattern of capital-saving movements emerged quite pervasively throughout American manufacturing: all but two of seventeen major industry groups experienced a fall in the capital-output ratio during the 1919-1929 interval, whereas the ratio had been rising in every one of these groups during 1899 to 1909, and in twelve of the seventeen during 1909 to 1919. Furthermore, as David and Wright (1999b), recently have shown, this increase in the average productivity of fixed capital in industry was directly associated with the electrification of primary horsepower, and that correlation became stronger in the course of 1920s.

At the same time, there was an equally pervasive surge in the growth average labour productivity. The aggregate productivity growth rate for manufacturing in the 1920s was over 5 percentage points higher than the trend rate in the previous two decades, and, rather than being concentrated in a few lines of industry, the contributions to this acceleration were very evenly distributed among all the industrial groups. With both capital productivity and labour productivity rising concurrently throughout manufacturing, it is not surprising that even when total factor productivity growth is calculated for each of the major branches - thereby making allowance for the growth in purchased inputs of energy in the form of electricity supplied by central power stations - a widespread acceleration is observed to have occurred in the rates of growth of TFP between the "'teens" and the "'twenties".

Moreover, a significant statistical relationship is found between the magnitude of the acceleration in the rate of TFP growth and the increase in the fraction of mechanical power derived from secondary electric motors. The latter ratio in this era provides an indicator of the diffusion of the unit drive system of factory electrification. Its positive cross-section relationship with the measure of acceleration in the TFP growth rate implies that at least one-half of the temporal acceleration during the 1919-29 interval can be attributed to this phase of the electrification process (David 1991a).

A "yeast-like" like process is exactly what would be expected when productivity growth is surging due to a new general purpose technology.

In terms of the metaphors recently employed by Harberger (1998), to characterise two contrasting ways in which aggregate productivity growth occurs, the 1920s productivity surge was a "yeast-like" expansion that involved essentially the entire US manufacturing sector, rather than the result of rapid efficiency gains that had popped up in a small number of industries for idiosyncratic reasons, like "mushrooms" shooting up a random places in a field. David and Wright (1999a, 1999b), recently have suggested that a "yeast-like" process is exactly what would be expected where rapid productivity

29) Schurr et al.*, (1990), especially pp. 29-30 and 292-93.*

growth was surging under the coordinating influence of a new GPT, whereas the "mushroom-like" pattern that Harberger (1998), observed in US manufacturing during the 1970s and 1980s was more typical of interludes when the overall pace of productivity advance remained sluggish.

If we may reasonably characterise the pattern of total factor productivity advances in the US economy during the 1990s as moving from "mushrooms" toward "yeast", is there warrant for anticipating a future surge? Should we accept the view of the "new economy" as a restricted sector comprising a handful of industries that are achieving spectacular growth and productivity gains in the production of ICT-intensive goods and services? Or, discard that picture in favour of the more "yeasty", GPT conceptualisation of the entire economy being "digitally re-newed". In the following section I will conclude by venturing to tackle these intriguing questions.

6. Historical reflections on the future: from ICT productivity growth paradoxes to payoffs

We shall have to look to the further development of ICT to sustain the trend growth rate at recent levels. Fortunately, several promising technological trajectories still offer largely untapped potential.

We shall have to look to the further developments of digital information technologies, and their diffusion throughout the economy to sustain the future trend growth rate of TFP at the levels that have been achieved in the US economy at the very close of the 20th century. Certainly, any further acceleration in TFP growth would have to come from that direction. This is not meant as a discouraging view, either for the US or for the western European economies. Even in the immediately foreseeable future, several promising technological trajectories appear to offer still largely untapped potentials for productivity growth, especially productivity gains of the kind that our conventional statistical indicators will be able to register.

My vision of these has not been formed simply by extrapolating from previous historical experience with the diffusion and elaboration of general-purpose technologies. Nevertheless, from the following comments on three of these emerging areas of ICT application, it will be apparent that I do anticipate the recurrence of a pervasive alteration in the bias of factor efficiency growth - toward augmenting the efficiency of conventional tangible capital inputs, and of routine labour services. The effects of this upon measured TFP in many branches of the economy would then bear a resemblance to the productivity effects associated with the diffusion of the unit drive system of factory electrification during the 1930s.

One of the more rapidly emerging among these trajectories is the much-discussed expansion of inter-organisational computing via the Internet for the mass of transactions involving purchase ordering, invoicing, shipment tracking, and payments. All of those activities presently absorb much specialist white-collar labour time, and it is not clear that its displacement can be managed so easily by companies whose day-to-day operations depend in some degree upon the un-codified expertise of those employees. Nevertheless, recent estimates indicate that in many branches of economic activity 10-15% cost savings in procurement activities will be available through the diffusion of business-to-business e-commerce. Still higher percentage cost-savings in procurement and related inter-firm transactions are estimated, not only for manufacturing, but for service activities such as freight transport, and media and advertising. Service occupations such as these might be viewed as the modern day counterparts of the ubiquitous materials-handling tasks in the manufacturing sector, which became the target of innovative dynamo-based mechanisation during the 1920s (30).

30) See David and Wright (1999b), for fuller discussion of the interrelatedness of mechanization of materials handling and factory electrification in the U.S. during the 1920s and 1930s.

A second significant cost saving trajectory is likely to emerge with the development and increasingly widespread diffusion of new, specialised, robust, and comparatively inexpensive digital "information appliances". This new generation of appliances includes not only the enhanced PDAs (personal digital assistants) that already are coming into use among PC users, but a variety of function specific hand-held devices and other specialised tools that will be carried on belts, sown into garments, and worn as head-gear. They will embody advanced microprocessors and telecommunications components that enable them to be linked through sophisticated networks to other such appliances, as well as to mainframe computers and distributed databases, thereby creating complex and interactive intelligent systems (31).

The proliferation of interconnected special-purpose applicants of this sort also is likely to be reinforced by "network externality" effects upon demand, and so would expand new market niches for vendors of successive generations of "computer-related" hardware - the quality-adjusted prices of which are likely to fall far faster than the costs of the inputs used in their manufacture (32). But perhaps even more significantly, this emerging trajectory of convergent information and communications technology developments is one that is likely to directly impinge upon the performance of workers equipped with such devices, and hence boost conventional measures of productivity improvement in a widen array of industries.

The diffusion of tele-working represents a third trajectory with a potential to yield substantial long-term gains in measured total factor productivity, most notably from savings in infrastructure capital, as well as through the reduction of the costs of measures required to abate pollution and environmental degradation in congested urban areas. At present, "tele-working" remains still far from fully deployed in the US: only about a fifth of the workforce time in large service sector firms are providing data communications network links with employees' homes, and many of those are trying out "mixed systems" of central office and "outside" work. As was the case historically with the group drive system of factory electrification, substantial duplication of fixed facilities characterises this stage in the new GPT's diffusion. So, significant capital-savings through reductions of required commercial office space and transport infrastructures, are likely to result for the whole service sector only as "tele-working" becomes much more widely and completely deployed. Moreover, many of the workers who are participating in tele-working continue to travel on some days in the week to company offices where they share a "hot desk" with co-workers who are on a different schedule. In such situations, the promised productivity gains derived when workers are relieved of the wear and tear of extended "commutes" remain at best incompletely realised.

It remains a good bet that economists who continue proclaiming their scepticism about the information revolution's ability to deliver major long-term productivity pay-offs are going to be proved wrong.

For these and still other reasons, it remains a good bet that economists who continue proclaiming their scepticism about the information revolution's ability to deliver major long-term productivity payoffs are going to be proved wrong. Yet those payoffs will not come freely; they will entail much learning and further, costly organisational adaptations. Nor should they be expected to materialise overnight - even if a domestic macroeconomic environment conductive to long-term investment were to be maintained, and were we lucky enough to escape real and financial shocks in the international economy.

31) See Gibbs (1997), and especially Norman (1998), Chapter 11.

32) The implication, then, is that analysts who apply the "dual" approach to measuring the rate of multifactor productivity, such as Oliner and Sichel (2000), for example, are likely to find this growing branch of manufacturing "contributing" to the aggregate TFPgrowth rate as the "vertically integrated computer sector" presently does.

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