The Solow productivity paradox: what do computers do to productivity?

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"You can see the computer age everywhere but in the productivity statistics."
Robert Solow, New York Review of Books, July 12, 1987

Solow's aphorism, now more than ten years old, is often quoted. Is there a paradox? And if so, what can be said about it? This paper reviews and assesses the most common 'explanations' for the paradox. It contains separate sections evaluating each of the following positions:

(1) *You don't see computers 'everywhere,' in a meaningful economic sense.* Computers and information processing equipment are a relatively small share of GDP and of the capital stock.
(2) *You only think you see computers everywhere*. Government hedonic price indexes for computers fall 'too fast,' according to this position, and therefore measured real computer output growth is also 'too fast.'
(3) *You may not see computers everywhere, but in the industrial sectors where you most see them, output is poorly measured*. Examples are finance and insurance, which are heavy users of information technology and where even the concept of output is poorly specified.
(4) *Whether or not you see computers everywhere, some of what they do is not counted in economic statistics*. Examples are consumption on the job, convenience, better user-interface, and so forth.
(5) *You don't see computers in the productivity statistics* ***yet****, but wait a bit and you will*. This is the analogy with the diffusion of electricity; the idea that the productivity implications of a new technology are only visible with a long lag.
(6) *You see computers everywhere but in the productivity statistics because computers are not as productive as you think*. Here, there are many anecdotes, such as failed computer system design projects, but there are also assertions from computer science that computer and software design has taken a wrong turn.
(7) *There is no paradox: some economists are counting innovations and new products on an arithmetic scale when they should count on a logarithmic scale.*

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1. Background

On its face, the computer productivity paradox concerns the question: Why isn't U.S. output growing faster as we invest more in computers? But Solow's aphorism gains its resonance from a different, though related, question: Will the growing investment in computers and information technology reverse the post-1973 productivity slowdown? From 1948 to 1973, multi-factor productivity increased 1.9 percent per year in the U.S., and labour productivity grew at the rate of 2.9 percent; after 1973, these productivity growth rates were 0.2 percent and 1.1 percent.[1] Similar slowdowns have been observed in most of the industrialized economies of the OECD.

Another part of the context is the mechanism for diffusion of technical change. The view held by many economists is that productivity improvements are carried into the workplace through investment in new machinery. On this view, any technical change we are now experiencing must be embodied in the economy's investment in information technology, because that is the kind of machinery investment that is growing. Investment in information processing equipment accounted for about 34 percent of producer durable equipment investment in 1997, which is more than the share of industrial machinery (22 percent).[2]

There is substantial debate on this 'new machinery' view. It must obviously be true at some level that new technology implies new machines. But it is not obvious that new machines are the entire engine for improving productivity. In fact, if one correctly accounts for the enhanced productiveness of new machines (by making a quality adjustment to the data on capital inputs) then improved machinery will not, *by itself*, raise multi-factor productivity, though it should increase ordinary labour productivity.

The computer-productivity paradox also resonates because we have become, as it is often said (but not often quantified), an information economy. It is often said that quality change is a much larger proportion of final output today than it was in the past, and that quality change, more customized products, and the growth of services--as business inputs, as elements of consumer demand, and as contributors to U.S. exports--all mean that information is a much more important contributor to the production process than it used to be. If it is true that the use of information as a productive input is growing, or that information has become a more productive input, then this heightened role for information heightens as well the importance of information technology in a modern economy.

Thus, the context in which the Solow productivity paradox is interesting revolves around a number of unresolved economic issues and questions. There is the post-1973 productivity slowdown, a puzzle that has so far resisted all attempts at solution. There is the supposed recent shift from a goods economy to a services economy (actually, this is not all that recent; even in 1940, more than half of U.S. employment was outside the traditional goods-producing sectors[3]). There is the shift to an 'information economy' from whatever characterized the economy before (surely not absence of information, but perhaps information was less abundant because it was more costly). None of these economic shifts is very well understood. Understanding them is important for a wide range of economic policy issues, ranging from the role of education and training in the economy, to the role of investment (and therefore of incentives for and taxation on investment), to the determinants of economic growth, to forecasting the future trends of income distribution, and so forth. For each of the issues, it is thought that computers and the contribution of information technology are key. For example, Kreuger (1993) found that workers who use computers have higher earnings than workers who do not, suggesting that the adverse shifts in income and earnings distributions in the United States in recent years are connected with the growth of computers. Again, there is debate on this view: computers are sometimes substituted for human capital, reducing the demand for skill in jobs.

One should note a strong view against coupling the Solow paradox with some of these other issues. Griliches (1997), for example, has stated:

> "But then we're still stuck with the problem about the productivity slowdown, or paradox, which is a problem, but not a computer problem. Is the slowdown real or not? Or is it all a measurement issue? And more important, is it permanent, or is it transitory? Here the paradox is really not so much in terms of computers, but in terms of what is happening to science, what is happening to inventiveness, what is happening to other activities."

This paper reviews seven positions on the computer productivity paradox.

2. You *don't* see computers 'everywhere,' in a meaningful economic sense

In this view, what matters is the share of computers in the capital stock and in the input of capital services. These shares are small. An input with a very small share cannot make a large contribution to economic growth, and so we should not expect to see a major impact on growth from investment in computers. (In the remainder of this paper, I use the terms 'computers' and 'computer equipment' -- computers plus peripheral equipment -- interchangeably; 'information processing equipment' is a broader category that contains computer equipment as one of its components--see note 3.)

The most comprehensive explorations are Oliner and Sichel (1994) and Jorgenson and Stiroh (1995). Both papers evaluate the growth accounting equation:

$$d_tY = s_c d_t K_c + s_{nc} d_t K_{nc} + s_L d_t L + d_t ð \quad (1)$$

where $d_tY = dY/dt$ denotes the rate of growth of output; d_tK_c, d_tK_{nc} and d_tL are rates of growth of the inputs K_c which is computer capital (property, computer capital services), K_{nc} which is non-computer capital (services), and L which is labour; s_i which is the share of input I; and $d_tð$ is the growth of multifactor productivity. This equation says that the rate of growth of output (d_tY) equals the share-weighted growth in inputs (for example, $s_c d_t K_c$ is the rate of growth of computer capital, weighted by the share of computer capital in total cost), plus the rate of growth of multifactor productivity.

Jorgenson and Stiroh (1995) estimate the share of capital services provided by computer equipment capital using the capital accounting framework developed by Jorgenson (1980, 1989); Oliner and Sichel (1994) use computer equipment's income share. As table 1 shows, the results of both papers are compatible. Computer equipment made a relatively small contribution to economic growth, even during the period of the 1980's when computer technology became so widely diffused throughout the economy. In the growth accounting framework of equation (1), even rapid rates of input growth—and the growth of computing equipment has been rapid indeed—make relatively small contributions to growth when the share of this equipment is small. As table 2 shows, computer equipment still accounts for only around 2 percent or less of the physical capital stock[4], and under 2 percent of capital services.

TABLE 1
Contributions of computers, information equipment and software to economic growth

	Oliner and Sichel (1994)[a]		Jorgenson and Stiroh (1994)[d]		
	1970-79	1980-92	1979-85	1985-90	1990-96
Output growth rate average annual rate	3.42	2.27	2.35	3.09	2.36
Contributions of computing equipment	0.09	0.21	0.15	0.14	0.12
Information processing equipment	0.25[b]	0.35[b]	n.a.	n.a.	n.a.
Computing hardware, software and labour, combined (1987-93)	n.a.	0.40[c]	n.a.	n.a.	n.a.

[a] Oliner and Sichel (1994), Table 3, page 285, unless otherwise noted.
[b] Oliner and Sichel (1994), Table 10, page 305.
[c] Oliner and Sichel (1994), Table 9, page 303: note that the time period differs from the other two lines.
[d] Jorgenson and Stiroh (1994): Updated tables supplied by the authors.

Oliner and Sichel also enlarge the definition of computers to encompass all of information processing equipment (their table 10, page 305) and also computing software and computer-using labour (their table 9, page 303). The result remains unchanged. On any of these three definitions--computer equipment, information processing equipment, or the combination of computing hardware, software, and labour--the shares remain small (see table 2), and so does the growth contribution of information technology.

TABLE 2
Computer, information equipment, and software shares (data for 1993)

	Oliner and Sichel (1994)		Jorgenson and Stiroh (1994)	
	Capital Stock Shares	Income Shares	Capital Stock Share[e]	Capital Services Share
Computing equipment	2.0[a]	0.9[b]	0.5	1.8
Information processing equipment	11.7[a]	3.5[c]	n.a.	n.a.
Computing hardware, software and labour, combined	n.a.	2.7[d]	n.a.	n.a.

[a] Oliner and Sichel (1994), Table 2, page 279: share of the wealth capital stock (see text).
[b] Oliner and Sichel (1994), Table 10, page 305.
[c] Oliner and Sichel (1994), Table 10, page 305.
[d] Oliner and Sichel (1994), page 297.
[e] Updated tables provided by the authors: share of the productive capital stock (see text), which also includes land and consumer durables.

To check the reasonableness of their findings, Oliner and Sichel (1994) simulate results for the assumption that computers earn supernormal returns (use of equation (1) implies that computers earn the same rate of return as other capital equipment). Romer (1986), Brynjolfsson and Hitt (1996) and Lichtenberg (1993) all argued that computers yield higher returns than investment in other capital. These alternative simulations raise the contribution of computing equipment to growth (from around 0.2 in table 1 to 0.3 or 0.4). Still, the share of computing equipment is too small for any reasonable return to computer investment to result in a large contribution to economic growth.

Growth accounting exercises calculate the computer's contribution to *growth*; not to multifactor *productivity*. Growth accounting answers the question: "Why is growth not higher?" The paradox says: "Why is productivity not higher?" As equation 1 shows, multifactor productivity's contribution to economic growth is separate from the contribution of any input, including the input of computers. If one interprets the productivity paradox as applying to multifactor productivity, growth accounting exercises do not shed much light on it.[5]

In the growth accounting framework, then, computer growth is simply the response of input demand to the great fall in the price of computers . Indeed, Jorgenson, in conference presentations, has emphasized this exact point, as has Stiroh (1998). The enormous price decline in computing power has led to its substitution, in a standard production analysis framework, against all other inputs, including other kinds of investment. From this perspective, the economic impact of the computer is not a productivity story at all.

One reservation about this input substitution view arises because computer output (and therefore computer capital input) is estimated by deflation, using hedonic computer price indexes. Price and quantity are not independently estimated. Some have argued that the computer price declines are overstated (see the next section); if price declines are overstated, the growth of computer inputs is also overstated, and there is less substitution than the data suggest.

A second reservation arises because many economists seem to think that the amount of innovation they see in the economy—the number and pervasiveness of new products, embodying new methods of production, and new technological feats—are more than one could reasonably expect just from input substitution. On this view, there must also be a mismeasurement story, and therefore a missing productivity story, regardless of the validity of the input substitution story. This view is discussed in section 8, below.

A third reservation is that aggregate labour productivity is also low; not just multifactor productivity. If computers just substituted against other inputs, then labour productivity should grow (because of increased capital per worker), even though multifactor productivity does not. Stiroh (1998) shows just that at the industry level: more intensive computer usage raises industry labour productivity through input substitution, but it does not raise industry multifactor productivity. At the aggregate level, the share of computers is too small to make a major impact on either output growth or labour productivity.

Flamm (1997) has in effect (though not explicitly) reinterpreted the Solow productivity paradox as a semiconductor paradox: You see the *semiconductor age* everywhere (and not just in the computer industry). Price indexes for semiconductors have dropped even more rapidly than computer prices (see the discussion in section 3), and semiconductors go into other kinds of machinery (antilock brakes and 'intelligent' suspension systems on automobiles, for example). Flamm calculates the consumer surplus from declining semiconductor prices at around 8 percent of annual GDP growth, which cumulates to a huge number over the 50-year history of semiconductors. For the analysis of the productivity paradox, Flamm's results do not permit distinguishing the part of the demand for semiconductors that arises because of input substitution (the substitution of computers and other semiconductor-using equipment against inputs that do not use semiconductors), and the part of semiconductor demand that arises because they improve the productivity of using industries (if indeed they do affect productivity). However, Flamm estimates the output growth elasticity of demand for semiconductors at roughly eight times their price elasticity of demand, and his percentage point estimate of semiconductor contribution to GDP is around 0.2 for recent years: a number that is, perhaps fortuitously, similar to the growth accounting calculations for computers.

In summary, according to this view computers make a small contribution to growth because they account for only a small share of capital input. Does the same small share suggest that they likewise cannot have a large impact on productivity? Perhaps. But the paradox remains a popular topic for other reasons.

3. You only *think* you see computers everywhere

The contention that computer price indexes fall too fast (and therefore computer deflated output rises too rapidly) has several lines of logic, which are not particularly connected.

Denison (1989) raised two different arguments against the BEA hedonic computer price indexes. He contended, first, that the decline in the computer price indexes was unprecedented, and hence suspect. We can put this aside. The U.S. price indexes for computers have been replicated for other countries, with similar results (see, for example, Moreau 1996 for France and Harhoff and Moch 1997, for Germany). Hedonic price indexes for semiconductors fall even more rapidly.[6] Trajtenberg (1996) shows that hedonic price indexes for CAT scanners also have computer-like declines, and Raff and Trajtenberg (1997) show similar large declines in hedonic price indexes for automobiles in the early years of the century. Most of these price declines have been missed by conventional economic statistics (automobiles did not get into U.S. government price statistics until the third and fourth decades of the century, and one cannot even determine from government statistics how much high-tech scanning equipment hospitals buy). The computer price declines seemed to Denison unprecedented because similar price declines had not been published.

Denison's second argument (one he would levy against all of the above indexes) was that hedonic price indexes were conceptually inappropriate for national accounts. He thought hedonic price indexes measured willingness to pay for quality improvements (the demand side) and not the cost of producing improved quality (the supply side). However, in Triplett (1983, 1989) I showed this is incorrect, even when relevant. McCarthy notes: hedonic measures can be given both supply-side and demand-side interpretations. Denison also suggested that demand-side and supply-side measures would diverge in the case of computers, but there is no evidence of this (see Triplett 1989). There is little current support for Denison's position that hedonic indexes are inappropriate, so it is not necessary to consider these arguments further.

A second major line of reasoning on hedonic computer price indexes points to what is actually done with the personal computers that sit on so many of our desks. Many users have noted something like the following: "I used perhaps a quarter of the capacity of the old computer that sat on my desk. Now I have a new one for which I use perhaps a tenth of its capacity. Where is the gain?"

McCarthy (1997, paragraphs 4 and 15) expresses a similar view:

> "...The theoretical increase in [computers'] potential output, as measured by the increases in their input characteristics, is unlikely to ever be realized in practice.... Also, the increasing size and complexity of operating systems and software are likely to be resulting in increasing relative inefficiencies between the hardware and software.... The greater complexity means that some part of the increased computer speed is diverted from the task of processing to handling the software itself."

In other words, ever more powerful personal computers wind up being used to type letters, and the letters are not typed appreciably faster. Is that not evidence that the computer price indexes are falling too fast?

This is not evidence. Typing a letter uses computer hardware, computer software, and the input from the person (increasingly, not a secretary) who types it. The technical bottleneck is often the human input. But this hardly justifies revising upward the price index for the computer. The computer is purchased, the capacity is paid for, and any assertion that the purchaser could have made do with an earlier vintage is, even if proven, not relevant. And indeed, it is not proven. Increased computer capacity has been employed in an effort to make computing more efficient and user-friendly; not just faster (but see sections 5 and 7).

A third issue has emerged in the work of McCarthy (1997), a paper of interest to OECD countries considering following the U.S. lead on hedonic price indexes for computers. McCarthy observes that price indexes for software typically do not exist, and speculates that software prices decline less rapidly than computer prices. Actually, price indexes for word processing packages, spreadsheets, and database software have been estimated (Gandal 1994, Oliner and Sichel 1994, and Harhoff and Moch 1997). This research confirms that software prices have been declining steadily, but not at computer-like rates.

McCarthy then contends that because software is bundled with computers the slower price decline of software implies downward bias for the computer price index:

> "The overall quality of a computer package (hardware and all the associated software) has not been rising as rapidly as that of the hardware input characteristics on which the hedonic estimates of quality improvement are based. As a result, the quality adjustments being used in the estimation of the price deflators for computer investment are being overstated which leads to the price falls in computer investment also being overstated."
>
> McCarthy (1997, paragraph 18)

The issue can be addressed more cogently if McCarthy's argument is re-stated as follows. A computer price index can be thought of as a *price index for computer characteristics*. Suppose that hedonic functions are linear, and that the price index is also linear (a Laspeyres index).[7] Then if there are three characteristics bundled into a personal computer --computer speed (*s*), computer memory (*m*), and computer software (*z*)--we have:

$$I_c = aI_s + bI_m + cI_z \tag{2}$$

where *a*, *b*, and *c* are weights. The proper price index for computers (I_c) is a weighted average of price indexes for all three characteristics, or components, that are bundled into the computer transaction. However, the third characteristic, computer software that is bundled into the computer without a separate charge, is omitted from the computer price index. Because it has a price decline lower than the other two characteristics $(I_z < I_s, I_c)$, the computer price index based on the two characteristics will fall too fast. The same argument applies, in a modified form, if a price index for computer hardware is used in national accounts to deflate both computer hardware and software (perhaps because no separate software index is available).

If hedonic computer price indexes were constructed according to the 'price index for characteristics' method given by equation (2), I would agree they would be downward biased. The bias would be the same if we calculated real computer investment growth as the weighted average of growth rates of hardware characteristics (the form in which McCarthy cast his illustration).

But considering the actual calculations, omission of software biases the computer price indexes *upward*, which is the opposite direction from McCarthy's contention. Computer price indexes are actually calculated by quality adjusting observed computer prices for the value of changes in hardware characteristics. We observe prices of two different computers, P_{c1} and P_{c2}, where each computer consists of a different bundle of speed, memory, and software. The hedonic regression coefficients on computer hardware (speed and memory) are used to adjust the price difference between the two computers for changes in the computer's hardware (that is, its speed and its included memory). We have, then:

$$(P_{c1})^* = P_{c1}\,(h_s\,[s_2/s_1] + h_m\,[m_2/m_1]) \tag{3}$$

where the term on the left-hand side is the quality-adjusted price of computer 1; and on the right-hand side, h_i is the hedonic 'price' for characteristic *I*; and *s* and *m* are, respectively, speed and memory, subscripted for computer 1 and computer 2. The price index uses this quality-adjusted price in:

$$I_c = P_{c2}\,/\,(P_{c1})^*. \tag{4}$$

Equation (4) contains no adjustment for the *quantity* of bundled software (i.e., $h_z\,[z_2/z_1]$). If more or improved software is included, the quality adjustment in equation (3)-- $(h_s\,[s_2/s_1] + h_m\,[m_2/m_1])$--is too small, not too large, because the improvement in software receives *no adjustment*. The adjusted price, $(Pc1)^*$, is too low (not too high), so that the computer price index falls *too slowly*--it is biased *upward*, not downward, contrary to McCarthy's contention.[8]

Whether software prices are declining faster than hardware prices, or whether the quantity of software (bundled with the hardware) grows less rapidly than the rate of improvement in hardware characteristics like speed and memory, is not the issue. The price index for the computer-software bundle does not decline fast enough because no adjustment is made for the value of the increased quantity of software included in the bundle. Its quantity is treated as zero.

My own view on this matter agrees with Griliches (1994, p. 6), who in discussing BEA computer price indexes, wrote:

> " There was nothing wrong with the price index itself. It was, indeed, a major advance...but...it was a unique adjustment. No other high-tech product had received parallel treatment...."[9]

4. You may not see computers 'everywhere,' but in the industrial sectors where you most see them, output is poorly measured

Griliches (1994) noted that more than 70% of private sector U.S. computer investment was concentrated in wholesale and retail trade; finance, insurance and real estate; and services (divisions F, G, H, and I of the 1987 Standard Industrial Classification System).[10] These are exactly the sectors of the economy where output is least well measured, and where in some cases even the concept of output is not well defined. Thus Griliches writes:

> "Why has this [computer investment] not translated itself into visible productivity gains? The major answer to this puzzle is very simple: ...This investment has gone into our 'unmeasurable sectors,' and thus its productivity effects, which are likely to be quite real, are largely invisible in the data."
>
> Griliches (1994, 11)

That there are serious measurement problems in all of these areas is well established. Griliches (1992) is an example of a long history of attempts to sharpen measurement methods and concepts for services. Triplett (1992) presents an additional review of the conceptual issues in measuring banking output, and Sherwood (1999) discusses the insurance measurement problem.

It is also the case that services account for a large part of output. Services that directly affect the calculation of GDP are those in personal consumption expenditures (PCE) and in net exports (and of course the output of the entire government sector is notoriously mismeasured).[11] Consumption of non-housing services accounts for about 43 % of personal consumption expenditures, or 29 % of GDP, and net export of services is about 1.3% of GDP.

The productivity numbers are not calculated for total GDP. One widely-used BLS productivity calculation refers to the private business economy. It is difficult to break out an explicit services component for that aggregate. However, government and housing are excluded from private business, and one can remove these components from GDP to approximate the private business (farm and non-farm) economy (see table 3). PCE non-housing services plus net export of services amounts to about 43 % of final private sector non-housing demand.

TABLE 3
Final-demand services as a proportion of private non-housing purchases (1996, in billions)

		Percent
1. Gross domestic product, less government and housing	5,442.1	100.0
2. PCE non-housing services	2,251.2	41.4
3. Net exports of services	96.6	1.8
4. Final demand services (line 3 plus line 4)	2,347.8	43.1

SOURCE: *Survey of Current Business*, December 1997, NIPA Tables 1.1 and 2.2.

Thus, services make up a large proportion of the aggregate productivity ratio. These include many--such as bus transportation--that have probably not benefitted appreciably from output-enhancing productivity improvements caused by computers. Nevertheless, a small proportion of mismeasurement in some of the larger services categories would impact the productivity statistics substantially. If the sign of the measurement error is in the right direction, this could help resolve the computer productivity paradox.

What of the sign of the measurement error in services output? Even though some sector is measured badly, we cannot know the sign of the error for sure. 'Mismeasurement' does not *always* mean upward bias in the price indexes and downward bias in the output and productivity measures.

Banking, for example, is measured badly. A considerable amount of research has accumulated on measuring banking output in alternative ways (see Triplett 1992, Berger and Mester 1997, and Fixler and Zieschang 1997). Some of the proposed alternative measures make more sense to me than either of the measures that are used in U.S. government statistics.[12] But they do not seem to imply a higher rate of growth of banking output and productivity. For example, Berger and Mester (1997) report that multi-factor productivity in banking fell during a period when the BLS banking labour productivity measure was rising sharply.

The alternative banking measures, like the government ones, can be criticized because they omit things such as the increased convenience that automatic teller machines have provided. For this and other reasons, Bresnahan (1986) shows that the downstream influence of information technology on banking is substantial. Bresnahan (in private discussions) has pointed out that the innovation that made the ATM practical was devising methods to curtail fraud. But Berger and Humphrey (1996) show that the effect of the ATM on banking cost has been perverse: the ATM costs about half as much per transaction as a human teller, but ATM transactions are smaller, and about twice as many occur for the same volume of transactions. If the ATM has had little significant impact on banking cost, then all of the ATM's improvement in banking productivity must come from consumer valuation, at the margin, for increased convenience. But since the ATM service has typically not been charged for until recently, one must estimate consumer surplus and add it into the banking output measure, to get an estimate of the contribution of technology to banking output and productivity.

Would adding an allowance to banking output for the convenience of ATM's yield a large upward adjustment? Frei and Harker (1997) reported that one large bank which aggressively tried to reduce customer access to human tellers very quickly lost a substantial amount of its customer base. Beyond some point of utilization, the value of the ATM falls below the value of the human teller.

Adding a valuation for ATMs would probably increase the measured rate of growth of banking output and therefore increase banking productivity. Improved measurement of banking and financial output might therefore help to resolve the paradox. But, as the foregoing suggests, the magnitudes are not clear.

Some economists have approached the measurement problem in services by examining circumstantial, as it were, evidence of anomalous behaviour of the statistics in some of these badly measured areas. For example, Stiroh (1998) extends Jorgenson and Stiroh's (1995) methodology to analyze the contribution to growth of computers at the sectoral level. He identifies, from among 35 industrial sectors, the most computer intensive sectors. His computer-using services sectors are Griliches' poorly measured ones--wholesale and retail trade, finance, insurance and real estate, and services (SIC division I).

Stiroh finds that noncomputer input growth decreased as the use of computer capital services increased in these computer intensive sectors. Cheaper computers substituted for other inputs, including labour. But measured output growth rates increased less rapidly as well: "For all computer-using sectors ... the average growth rate of multifactor productivity fell while [computer] capital grew" (Stiroh 1998). An inverse correlation between computer investment and multifactor productivity growth does seem anomalous. See also Morrison and Berndt (1991) for a compatible result. Either computers are not productive, or output growth is undercounted. This anomaly is consistent with the 'badly measured services' hypothesis. However, it also emerges in Stiroh's results for computer-intensive manufacturing industries, such as stone, clay and glass, where output measurement problems are, if not absent, not well publicized.

Prescott (1997) noted that prices of consumption services that he regards as 'badly defined' (personal business, which includes finance and insurance from Griliches' list, plus owner-occupied housing, medical care, and education) rose 64 percent between 1985 and 1995, while 'reasonably-well defined services' (the others) rose only 40 percent. He felt this implied measurement error in the former prices.[13] The evidence of price divergence is not compelling in itself (no economic principle suggests that prices should always move together--it is commonplace in price index theory that relative prices do diverge). But if the price indexes are overstated, then deflated output growth and multifactor productivity growth are both understated.

The Boskin Commission estimated that the CPI (which provides deflators for many components of PCE) was overstated in recent years by 1.1 percent, of which approximately 0.4 percentage points was mismeasurement of prices for consumer services. Most of that would translate into error in deflated output of services in the productivity measures.[14] For measurement error to explain the slowdown in economic growth, real consumption, or productivity requires either that measurement error increased after 1973, or that the shares of the badly measured sectors increased. There is little evidence for the former, and although services have increased, their shares have not grown by as much as productivity declined. Moreover, any increasing measurement error must have occurred gradually; yet the productivity slowdown was abrupt. I doubt this can explain the post-1973 slowdown of real per capita consumption and productivity.

Overall, mismeasurement of services probably has the right sign to resolve the paradox. But does the mismeasurement hypothesis (as typically stated) have enough strength to resolve the paradox? My own guess is that it does not.

5. Whether or not you see computers everywhere, some of what they do is not counted in economic statistics

An enormous amount of recent computer and software development has been directed toward making computers easier to use. For example, when the Brookings Institution converted to Windows 95, they gave us as a manual "Windows For Dummies." On page 12 of this manual I read:

> "Windows fills the screen with lots of fun little boxes and pictures. DOS is for people who never put bumper stickers on their cars."

But then the manual points out, correctly, that pictures require much more computing power, so using Windows 95 requires a relatively powerful computer.

Where do we count the value of increased convenience and better user interface in economic statistics? If they are productive, then the improvement will show up in the productivity figures, or at least in the labour productivity data. On the other hand, if the pictures are just more 'fun,' then these have created more consumption on the job. Consumption on the job is not counted in economic statistics. If more advanced computer software contributes partly to output and partly to making workers more content, some of that gain will be lost in economic statistics.

Whether the newest developments in software and computers have in fact made computers that much more user-friendly is also an unresolved issue. Whether the benefits are worth the changeover cost is another unsettled issue (see section 6).

The computer facilitates the reorganization of economic activity, and the gains from reorganization also may not show up in economic statistics. The following example (but not the analysis) comes from Steiner (1995).

Consider a not so hypothetical toy company that once manufactured toys in the United States. The computer, and faster and cheaper telecommunications through the Internet, has made it possible to operate a toy business in a globally integrated way. Today, the company's head office (in the U.S.) determines what toys are likely to sell in the United States, designs the toys, and plans the marketing campaign and the distribution of the toys. But it contracts all toy manufacturing to companies in Asia, which might not be affiliated with the U.S. company in any ownership way. When the toys are completed, they are shipped from the Asian manufacturer to U.S. toy retailers; thus, this U.S. toy company has no direct U.S. wholesale arm either. The billing and financial transactions are handled in an offshore financial center in the Bahamas. The computer and advanced information technology have made it possible for this company to locate the activities of manufacturing, distribution, financial record-keeping and so forth around the world where costs are lowest.

From the standpoint of the stockholders and company management, the computer has permitted vast increases in the profitability of this company. But where do these gains show up in *U.S.* productivity statistics?

In this case, the computer may have increased the productivity of Asian toy manufacturers, of Liberian shipping companies, and of Caribbean banking and payments establishments, by giving them better access to American markets and American distribution. The only activity left in the United States is the toy company's head office. What is the measure of 'output' of a head office?

If the impact of computers on the toy company's profitability *does* enhance U.S. productivity, calculating the computer's productivity effect requires determining ways to account for the design, marketing, distribution, and coordinating activities of the U.S. head office. Those are service activities where the outputs are presently imperfectly measured.[15]

6. You don't see computers in the productivity statistics *yet*, but wait a bit and you will[16]

David (1990) has drawn an analogy between the diffusion of electricity and computers. David links electricity and computers because both "form the nodal elements" of networks and "occupy key positions in a web of strongly complementary technical relationships." Because of their network parallels, David predicts that computer diffusion and the effects of computers on productivity will follow the same protracted course as electricity:

> "Factory electrification did not...have an impact on productivity growth in manufacturing before the early 1920's. At that time only slightly more than half of factory mechanical drive capacity had been electrified.... This was four decades after the first central power station opened for business."
>
> David (1990, 357)

This idea has received very widespread diffusion in the popular press.

Whether or not the computer's productive potential has yet to be realized fully (see section 7), I doubt that electricity provides an instructive analogy. Mokyr (1997) warns us that: "Historical analogies often mislead as much as they instruct and in technological progress, where change is unpredictable, cumulative, and irreversible, the analogies [are] more dangerous than anywhere." The networking properties of computers and electricity may or may not be analogous, but the computer differs fundamentally from electricity in its price behaviour, and therefore in its diffusion pattern.

More than four decades have passed since the introduction of the commercial computer. The price of computing power is now less than *one-half of one-tenth* of 1 percent (0.0005) of what it was at its introduction (see table 2). In about 45 years, the price of computing power has declined more than *two thousand fold*. No remotely comparable price decreases accompanied the dawning of the electrical age. David reports that electricity prices only began to fall in the fourth decade of electric power; and although Nordhaus (1997) estimates that the per lumen price of lighting dropped by more than 85 percent between 1883 and 1920, two-thirds of that is attributable to improved efficiency of the light bulb. Sichel (1997) presents an alternative estimate. Gordon's (1990) price indexes for electricity generation equipment only extend to 1947, but there is little to suggest price declines even remotely in the league with those for computers.

Because their price histories are so different, the diffusions of electric power and computing power have fundamentally different--not similar--patterns. In the diffusion of any innovation, one can distinguish two sources of demand for it. The innovation may supplant an earlier technology for achieving existing outcomes—new ways of doing what had been done before. An innovation may also facilitate doing new things.

The introduction of electricity did not initially affect what had been done before by water power or steam power.[17] Electricity made it possible to locate manufacturing plants away from the stream side. That is, the diffusion process for electricity was initially the diffusion to new ways of doing things. Only after a long lag did electricity generation affect the things that had been done before.

In the computer diffusion process, the *initial* applications supplanted older technologies.[18] Water and steam power long survived the introduction of electricity; but old, pre-computer age devices for doing calculations disappeared long ago. In electricity, extensions to new applications preceded the displacement of old methods because the price of electricity did not make the old methods immediately obsolescent. In the computer diffusion process, the displacement of old methods came first, because old calculating machines were made obsolescent by the rapidly falling price of computing power.

TABLE 4
Computer equipment price indexes

	Mainframes	PCs	Computer Equipment
1958	142,773.6		
1972	3,750.4		
1982	382.5	578.7	404.9
1987	144.9	217.6	170.4
1992	100.0	100.0	100.0
1996	49.1	37.9	45.5
1997	42.1	25.2	34.6

Although some new applications of computing power are quantum improvements in capabilities, price effects matter here as well. In adopting computerized methods, the high-valued ones are implemented first. As computing power has become ever cheaper, the incremental computerizations are expected to have been lower valued; new applications are low-value applications at the margin, not high-value ones. This principle is suggested by utilization rates. When I was a graduate student, I took my cards to the computer center and waited for the computer; the computer was expensive, and I was cheap. Now, the computer on my desk waits for me. The computer has become so very cheap that it can be used for activities that are themselves of not particularly high value.[19]

7. You see computers everywhere but in the productivity statistics because they're not as productive as you think

Dilbert (cartoon of 5/5/97) claimed that the "total time that humans have waited for Web pages to load...cancels out all the productivity gains of the information age." Dilbert is certainly not the only curmudgeon who has questioned whether the spread of information technology has brought with it benefits that are consistent with either the amount of computer investment or the vast increase in computer speed.

It is commonplace that the history of the computer is the constant replacement of one technology with a newer one. The down side of rapid technological advance is the breathtaking rate of obsolescence that has caused the scrapping of earlier waves of investment well before the machines are worn out. Had these machines not been discarded, the flow of computer machine services today would be larger--but probably not that much larger. A personal computer with an 8086 chip attained 0.33 MIPS in 1978; a Pentium-based computer had 150 MIPS in 1994, and more than 200 today. Had we saved all of the 8086 machines ever built, they would not add that much to today's total stock of installed MIPS.

Nevertheless, no matter how little they are worth today, real resources went into the production of those 8086 machines in 1978-82 when they were state of the art. There is no return today for the substantial resources given up to investment in computers in the relatively recent past.

It is not only the hardware. Stories of very expensive 'computer systems redesign' projects are legion. The Wall Street Journal (April 30, 1998, page 1) reported that "42% of corporate information-technology projects were abandoned before completion" and "roughly 50% of all technology projects fail to meet chief executives' expectations." The 'year 2000 problem' could be added to the list. At the personal computing level, there is the constant churning of standardized personal computer operating systems, spreadsheet and word processing packages. Even if every new upgrade were a substantial improvement, there is still the cost of the conversion: many persons within the computer industry and without have asked whether conversion costs are adequately considered in the upgrade cycle. But the upgrading process goes on.

Raff and Trajtenberg (1997) show that the quality-adjusted price decline for automobiles early in their history was comparable to computers. But for a large number of car buyers, the Model T proved good enough and they did not need to be on the technological frontier. The failure of the 'Model T' to emerge in the computer market may reflect fundamental differences in the computer and the car markets. If you bought a used Model T you could still drive it on the same highway that the new one used (you can't 'drive' the old computer on the new highway). And you could always find someone to fix it. The computer repair industry has shown nowhere near the growth of the computer industry.

Is all of this upgrading productive or is it wasteful? Informed opinion is divided. One may do the same word processing tasks with new technology and with old. What is the value of the marginal improvements in, say, convenience and speed? They may not, as some users assert, be worth all that much--but their cost is also not high, in the newest technology. Graphics and icons, for example, take a lot of computer capacity; but because machine capacity is cheap in the newest technology, the incremental cost of providing those is low, so they are provided in the newest software. From the technologists' view, they *can* at small cost give users a little animated icon to show when a page is printed, instead of a mundane 'job printed' signal. And they can also give software users a tremendous range of menu choices at small cost, so why not do it?

The curmudgeon points to the end result of adding all these features: A far faster computer, with far greater memory capacity, that executes many of its jobs more slowly than the older, slower machine. More menu choices, too, have costs.

Then too, the user is conscious if the software designer is not, that changeover itself is costly.[20] The time cost of users is undoubtedly a far greater component of the cost of upgrading systems than any of the direct costs associated with the changes. Typically, only the direct costs are recorded in organizations' ledgers, but the 'down time' associated with changes affects productivity (see Blinder and Quandt 1997).

Computer industry spokespersons are fond of the analogy that says computer industry technology has given consumers something like a Rolls-Royce that goes

200 miles per hour, gives 500 miles per gallon, and costs $100. The curmudgeon on computer and software progress hears a different story:

> "We have the software equivalent of a new toll road for you to drive, but you must buy our new Rolls-Royce equivalent computer to use it. And you can't drive on the old highway, which was already paid for, because we don't maintain it anymore."

Moreover, if past decisions on computers have been incorrect or inappropriate, that may also suggest that we have already invested too much in computers. Computers are less productive than they were thought to be when decisions were made to 'computerize.' That bodes less well for the future.

One final point should be made. One of the computer's accomplishments may have been to cut the cost of various kinds of rent-seeking behaviour, and to facilitate rivalrous oligopoly behaviour, market sharing strategies, and so forth. The computer has made it possible to execute far more stock market transactions, for example. Bresnahan, Milgrom and Paul (1992) explored the value of enhanced information in the stock market. They concluded that improved information did not contribute to productivity because information really just affected who received the gains; it did not increase the social gain from stock market activity. That suggests the importance of distinguishing the computer's effects on individuals or on firms from effects on the economy--some gains to individuals or to firms at the expense of other individuals or firms, so that there is no net effect at the economy-wide level.

8. There is no paradox: Some economists are counting innovations and new products on an arithmetic scale when they should use a logarithmic scale

For many economists, and especially business economists, the preceding discussion will not be satisfactory. We are a 'new economy,' in this view, inundated with an unprecedented flow of innovations and new products, and none of this flow of the new is reflected in the productivity numbers. This new economy view is repeated in the newspapers, in business publications and places such as Federal Reserve Bank reviews, and we hear it at conferences.

In a way, this new economy view of the paradox is not a computer paradox at all. Rather, people are stacking up and cumulating anecdotes. Those anecdotes about new products, new services, new methods of distribution and new technologies are no doubt often valid observations. Although no one knows how to count the number of these 'new' things, I would not seriously dispute the proposition that there is more that is new today than there was at some time in the past. Yet, these anecdotes lack historical perspective.

To have an impact on productivity, the *rate* of new product and new technology introductions must be greater than in the past. A simple numerical example makes the point. Suppose all productivity improvements come from the development of new products. Suppose, further, that in some initial period 100 products existed and that ten percent of the products were new. In the following period, there must be 11 new products to keep the rate of productivity growth constant, and in the period after that 12 new products are required. At the end of 10 years, a constant productivity rate requires 26 new products per year, and after 20 years, 62 new products and so on.

Most of the anecdotes that have been advanced as evidence for the 'new economy' amount to assertions that there are a greater *number* of 'new' things. Diewert and Fox (1997, table 5) comment on estimates of the number of products in the average grocery store. In 1994 there were more than twice as many products in the average grocery store as in 1972 (19,000, compared with 9,000).[21] But the 1948-72 rate of increase (from 2,200 in 1948 to 9,000) is over four times as great as the 1972-94 increase (the intervals 1948-72 and 1972-94 are roughly equal). Thus it is true that in 1994 there were many more products in grocery stores than there were two decades before, but the *rate* of increase in new products had fallen.

Diewert (1993) cites an example, taken from Alfred Marshall, of a new product in the 19th century: Decreased transportation costs, owing to railroads, made fresh fish from the sea available in the interior of England for the first time in the second half of the 19th century. In developing a related point, Mokyr (1997) refers to "the huge improvements in communications in the 19th century due to the telegraph, which for the first time allowed information to travel at a rate faster than people.... The penny post, invented ... in the 1840s, did an enormous amount for communications -- compared to what was before. Its marginal contribution was certainly not less than Netscape's."

The numerical example above implied that each new product had the same significance as before. In fact, new products of the 1990's must equal the significance of automobiles and appliances in the 1920's and 1930's (home air conditioning first became available in the early 1930's, for example), and of television and other communications improvements in the 1940's and 1950's (mobile telephones, for example, were introduced in the 1940's). If the average significance of new products in the 1990's is not as great as for individual new products from the past, then the number of them must be greater still to justify the new economy view of the paradox.

The same proposition holds for quality change. It is amazing to see quality improvements to automobiles in the 1990's, great as they have been, held up as part of the unprecedented improvement story, or--as in a press account I read recently--quality change in automobiles given as an example of the new economy, contrasted with a ton of steel in the old. Actually, the first thing wrong with that contrast is that quality change in a ton of steel has been formidable. Second, quality change in autos is a very old problem in economic statistics; it did not emerge in the 1990's as a characteristic of the new economy. Hedonic price index methodology was developed in the 1930's to deal with quality change in automobiles (Court, 1939). The study by Raff and Trajtenberg (1997) suggests that the rate of quality improvement in automobiles was greater in the first decade of the twentieth century than in its last decade.

I believe that the number of new products and ‘new things’ is greater than before. But that is not the question. The proper question is: Is the rate of improvement, the rate of introduction of new things, unprecedented historically? I do not believe we know the answer to that question.

Thus, the paradox has gained acceptability partly because some economists have mistakenly been counting new innovations on an arithmetic scale, and--finding more of them--have thought they have evidence confirming the paradox. They ought to be looking at a logarithmic scale, a scale that says you must turn out ever greater numbers of ‘new things’ to keep the current rate of ‘new things’ up to the rates of the past.

We look at the new products and new technical changes at the end of the 20th century, and we are impressed. We should be. But are they increasing at an increasing rate? Is the number of new products increasing more rapidly on a logarithmic scale? I think it safe to assert that the empirical work in economic history that would confirm the increasing rate hypothesis has not been carried out.

Notes

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1 U.S. Department of Labor (1998, and website).

2 In 1977, the shares were 22 percent for information equipment and 26 percent for industrial equipment (data provided by Nicole Spugnardi at the BEA). “Information processing and related equipment” in the BEA data includes the categories office, computing and accounting machinery (which in turn includes computers and peripheral equipment), communication equipment, instruments, and photocopy and related equipment. Computer equipment in 1997 amounted to about 40 percent of information processing equipment, and about 14 percent of producer durable equipment investment.

3 The goods-producing industries, agriculture, forestry and fishing, mining, manufacturing, and construction accounted for 49 percent of employed persons, and 49 percent of the “experienced labour force,” in the 1940 Census (Statistical Abstract of the United States, 1944, table no. 128, pp. 116-118).

4 Oliner and Sichel (1994) figure for computing equipment’s share of the *wealth* capital stock (2.0 percent) is higher than Jorgenson and Stiroh’s share of the *productive* capital stock (0.5 percent) partly because Jorgenson and Stiroh’s capital stock includes land and consumer durables.

5 Alternatively, if one thought the Solow paradox referred to *labour* productivity, then growth in computer input will affect labour productivity even if it does not affect multifactor productivity. It seems to me, as it has seemed to others (see David 1990), that Solow must have been talking about multifactor and not labour productivity. In any case, labour productivity also slowed after 1973 and has not revived.

6 The major empirical work on semiconductor price indexes is Flamm (1993, 1997), Dulberger (1993), and Grimm (1998). Triplett (1996) compares computer, semiconductor, and semiconductor manufacturing equipment price indexes.

7 Without these two simplifying expositional assumptions, the price index becomes a very complicated construction, as I indicated in Triplett (1989), and it unduly complicates the exposition for no gain for present purposes. Empirically, however, the measurement is sensitive to both assumptions.

8 The exclusion of software from the hedonic regression does not necessarily bias the coefficients of the included variables. The bias to the price index from omitted variables might go either way, depending on the unknown correlation between included and excluded variables, and on the unobserved movement of the excluded variable(s).

9 In the interval following BEA's introduction of the hedonic computer equipment price indexes in 1985, they were not extended owing to a combination of factors: (a) Shortage of resources within BEA. Though there was something to this, the "Boskin Initiative" to improve economic statistics came along soon after (1989), and there were no hedonic projects in the Boskin initiative (and very few resources for price index improvements) (U.S. Department of Commerce 1990). (b) Lack of appreciation, perhaps, by decision-makers of the significance of what was done, and overreaction to somewhat mild outside criticism and more forceful, though indirect, criticism from within the U.S. statistical system. Though it made sense to let the dust settle a bit after the introduction of the computer indexes, this was undoubtedly the most far-reaching innovation, internationally, in national accounting in the decade of the 1980's (for some of its international implications, see Wyckoff 1995).

10 In the revised BEA capital stock data (supplied by Shelby Herman of BEA), these sectors account for 72.3 percent of computer capital stock in the benchmark year of 1992.

11 Most services in SIC division I are intermediate products (such as the services of consulting economists) that do not enter final GDP.

12 The BLS output measure used in the banking industry productivity measure is a substantially different definition from the BEA banking measure used in calculating components of GDP. See Triplett (1992).

13 Prescott (1997) includes owner-occupied housing services in his 'badly defined' category, on the grounds that a user cost measure would be theoretically preferable to owners' equivalent rent, which is the measure now used in the national accounts and the CPI. Because the Jorgenson (1989) expression for the user cost of capital has the rental value on the left side of the equation, Prescott's point cannot be a theoretical one because rental and user-cost measures should in theory be the same. He must, rather, implicitly be asserting that user cost estimates work better in the case of owner-occupied housing than the use of rental foregone. The evidence goes against Prescott's assertion. See Gillingham (1983) for the case of owner-occupied housing and Harper, Berndt, and Wood (1989) for analysis of comparable problems in the estimation of user cost for other capital goods. I do not mean to suggest that there are no problems with measuring the cost of owner-occupied housing; just that Prescott's reasoning is not consistent with the empirical evidence.

14 I reviewed the Boskin Commission bias estimates for the measurement of real PCE (and therefore productivity) in Triplett (1997).

15 And in any case, there is no present convention for imputing them to head offices. In

the 1987 SIC, a company head office or management office is designated an 'auxiliary.' The employment and expenses of auxiliary offices are lumped into the data for the industry that the head office manages. So, if this toy company still manufactured toys in the U.S., the *costs* of the head office would be put into the toy manufacturing industry, on the assumption that whatever the head office does, it contributes its services to the manufacturing establishments of the company. No imputation for the services of the head office would have been made.

In a globalized world, putting the costs of head offices into manufacturing industries no longer makes economic sense. In the new North American Industry Classification System (NAICS), head offices are put in a separate industry and grouped in a sector with other economic units (like holding companies) that have no natural output units. (*Federal Register* 1997).

16 Parts of this section are adapted from my "comment" on Oliner and Sichel (1994).

17 David (1990, 357) notes the "unprofitability of replacing still serviceable manufacturing plants embodying production technologies that used mechanical power derived from water and steam." He remarks that "applications of electric power awaited the further physical depreciation of durable factory structures...." That manufacturers waited for water-powered equipment to wear out before replacing it with electric is eloquent testimony to the powerful impact of prices and obsolescence on computer diffusion: the evidence suggests that computers do not deteriorate appreciably in use (Oliner, 1993), but how many older generation computers are still in service?

18 As an illustration, Longley (1967) showed that matrix inversion algorithms for early computer regression programs were patterned on short-cut methods used on mechanical calculators and contained inversion errors that affected regression coefficients at the first or second significant digits. The designers of faster and cheaper methods to displace old ones did not initially take advantage of the computer's speed to improve the accuracy of the calculations.

19 It is not inefficient to let utilization of the lower cost input adjust to economize on the use of the higher cost one.

20 It is hard to avoid wondering if much of this cost could not have been avoided, had the retention of old icons and symbols been made an objective of the upgrade design. The analogy to the typewriter's QWERTY keyboard (retained on the computer) is apt: Why is there no similar inertia in changing software commands and icons?

21 Reservations might be expressed about this interpretation of the number of products.

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