May 7, 1998
corrected: May 20

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 (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*

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[1] This paper is based on remarks originally presented at the Conference on Service Sector Productivity and the Productivity Paradox, Ottawa, April 11-12, 1997. The draft was written while the author was Chief Economist, Bureau of Economic Analysis, and was presented in preliminary form at the January, 1998 Chicago meetings of the American Economic Association, in a session titled "Is Technological Change Speeding Up or Slowing Down?" I am greatly indebted to Claudia Goldin for conversations on some relevant points of economic history. Copies of the paper can be obtained from the author at: Brookings Institution, 1775 Massachusetts Ave., NW, Washington, D.C. 20036, phone 202-797-6134 or e-mail: JTRIPLETT@BROOK.EDU.

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.*

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 labor productivity grew at the rate of 2.9 percent; after 1973, these productivity growth rates were 0.2 percent and 1.1 percent.[2] 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 in the economy. In a view held by many economists, 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 in 1997, which is more

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[2] U.S. Department of Labor (1998a, 1998b).

than the share of industrial machinery (22 percent).[3]

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 labor productivity.

The computer-productivity paradox also resonates because we have become, 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 than it was in the past, 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[4]).

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[3] In 1977, the shares were 22 percent for information equipment, 26 percent for industrial equipment (unpublished detailed data found at the BEA Stat-USA websites, http://www.stat-usa.gov/BEN/ebb2/bea/aatitlot.prn and http://www.stat-usa.gov/BEN/ebb2/bea/uadata.exe). “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.

[4] 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 labor force,” in the 1940 Census (Statistical Abstract of the United States, 1944, table no. 128, pp. 116-118).

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 to 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 is 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 sometimes substitute against human capital, as they do against other inputs, reducing the demand for skill in jobs such as, say, bank tellers.

One should note a strong dissenting 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."

The following numbered sections review seven positions on the computer productivity paradox.

I. 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; the term "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 sets of authors calculate the growth accounting equation:

$$(1)\quad d_tY = s_cd_tK_c + s_{nc}d_tK_{nc} + s_Ld_tL + d_t\pi$$

where $d_tY = dY/dt$, the rate of growth of output, d_tK_c, d_tK_{nc} and d_tL are rates of growth of the inputs—$K_{c,}$ computer capital (properly, computer capital services), $K_{nc,}$ non-computer capital (services), and L, labor—s_i is the share of input i, and $d_t\pi$ 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, $s_cd_tK_c$ 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 very rapid rates of input growth—and the growth of computing equipment has been rapid indeed—make only 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[5], and under 2 percent of capital services.

Oliner and Sichel enlarge the definition of computers to encompass all of information processing equipment (their table 10, page 305) and also computing software and computer-using labor (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 labor—the shares remain small (see table 2), and so does the growth contribution of information technology.

To check the reasonableness of their results, Oliner and Sichel (1994) simulate results for

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[5] Oliner and Sichel (1994) compute computing equipment's share of the *wealth* capital stock (2.0 percent), which 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. Note that the capital stock share of computers is much smaller than their investment share; computers are very short-lived investments.

the assumption that computers earn supernormal returns (use of equation (1) implies that computers earn the same rate of return as earned on other capital equipment). Romer (1986), Brynjolfsson and Hitt (1996) and Lichtenberg (1993) all argued or implied 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), but all of them confront the same problem: The share of computing equipment is simply 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 its contribution 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 very much light on it.[6]

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. On this view, 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 in government statistics 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

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

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 VII, below.

A third reservation is that aggregate labor productivity is also low, not just multifactor productivity. If computers just substituted against other inputs, then labor 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 labor 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 labor 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 II), 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, 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 an impact on productivity? Perhaps. But the paradox remains a popular topic for other reasons, which are discussed in the following sections.

II. 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 for this reason suspect. We can now put this aside. The U.S. price indexes for computers have been replicated for other countries, with similar rapidly-falling results (see, for example, Moreau, 1996 for France). Hedonic price indexes for semiconductors fall even more rapidly than for computers.[7] 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 are conceptually inappropriate for national accounts. Denison thought that hedonic price indexes measure uniquely willingness to pay for quality improvements (the demand side of the market) and not the cost of producing improved quality (the supply side). However, in Triplett (1983, 1989) I showed this is incorrect, even when it is relevant, because 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 for such divergence (I discuss this in Triplett, 1989). So far as I know, there is little current support for Denison’s position that hedonic indexes are conceptually inappropriate, so it is not necessary to consider these arguments more fully here.

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

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[7] 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.

noted something like the following: "I used perhaps a quarter of the capacity of my old computer. 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 faster and more powerful personal computers, with ever larger memory sizes, 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?

I do not think it is 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 just as well with an earlier vintage is, even if proven, not relevant. And indeed, it is also 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 IV and VI).

A third issue has emerged in the work of McCarthy (1997), a paper which has excited quite a bit of comment within other OECD countries who are 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 McCarthy's speculation: Software prices have been declining steadily, but not at computer-like rates.

McCarthy then contends that because software is often bundled with computers the slower price decline of software must mean that computer price indexes are biased downward. “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, for the sake of the exposition, that hedonic functions are linear, and that the price index is also linear (a Laspeyres index).[8] Then if there are three characteristics bundled into a personal computer--computer speed (s), computer memory (m), and computer software (z)--we have:

$$(2)\ I_c = aI_s + bI_m + cI_z$$

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 its price index declines less 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 actually constructed according to the "price index for characteristics" method given by equation (2), I would agree with McCarthy that 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 (which is 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},

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[8] 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.

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:

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

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:

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

Equation (4) contains no adjustment for the *quantity* of bundled software (i.e., $h_z\ [z_2/z_1]$). If more software, or improved software, is included in the bundle, 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, $(P_{c1})^*$, is too low (not too high), which means that the computer price index falls *too slowly*—it is biased *upward*, not downward, contrary to McCarthy's contention.[9]

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, are neither one 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 implicitly treated as zero.

In conclusion, neither evidence nor reasoning indicates a serious downward bias to the computer price indexes. My own view on this matter agrees with Griliches (1994, page 6), who in discussing BEA computer price indexes, wrote:

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[9] Assuming that the exclusion of software from the hedonic regression does not 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 in the excluded variable.

> “ 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....”[10]

III. 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).[11] 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 (finance, for example, or insurance, or consulting economists, as an example from the services division of the SIC).

> 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, page 11).

That there are serious measurement problems in all of these areas is well established. The volume edited by Griliches (1992) is a fairly recent 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 (forthcoming)

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[10] 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).

[11] 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 1992.

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).[12] 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 clearly excluded from private business, and one can readily 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.

Thus, services make up a large proportion of the aggregate productivity ratio and they are poorly measured. Of course, services include many—such as household utilities, bus transportation, barber and beauty shops and so forth—that have probably not benefitted appreciably from output-enhancing productivity improvements caused by computers. Nevertheless, a relatively small amount of mismeasurement in some of the larger services categories would impact the productivity statistics substantially. If the sign of the measurement error goes in the right direction, mismeasured services could go a long way to 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* means upward bias in the price indexes and downward bias in the output and productivity measures.

Banking, for example, is measured badly: The output measure in national accounts makes questionable economic sense. A considerable amount of research has accumulated on measuring banking output in alternative ways (I reviewed much of it in Triplett, 1992, but Berger and

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

Mester, 1997, and Fixler and Zieschang, 1997, are more recent contributions). These alternative measures of banking output make more sense to me than either of the measures that are used in U.S. government statistics.[13] 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 labor 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 banking customers. 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 cut down 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 (and freedom from fear about fraud). But since the ATM service is typically not charged for, 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 (to save cost), very quickly lost a substantial amount of its customer base. Bank customers want human tellers, too. Although the availability of ATM's is certainly an advantage for banking customers, 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, estimation is complicated, and the magnitudes are certainly not at all clear.

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[13] 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).

Some economists have approached the measurement problem in services by examining circumstantial, as it were, evidence of anomalous behavior 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 labor. 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.[14] The evidence of price divergence is not compelling in

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[14] Prescott (1997) includes owner-occupied housing services in his "badly defined" category, on the grounds that a user cost measure of housing services is theoretically preferable to owners' equivalent rent, which is the measure now used in the national accounts and the CPI. Because the standard 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 empirically in the case of owner-occupied housing than the use of rental foregone. This empirical issue has been explored extensively in the literature, and 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 does not seem

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.[15] For measurement error to explain the slowdown in economic growth, productivity, or real consumption, 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, increasing measurement error, if it did increase over time, must have occurred gradually; the productivity slowdown, on the other hand, was abrupt.

I doubt that *increasing* mismeasurement of services consumption can explain the post-1973 slowdown of real per capita consumption, and therefore of productivity. Mismeasurement might, however, account for loss of some of the computer's contribution to growth in the past two decades or so.

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

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

> "Windows fills the screen with lots of fun little boxes and pictures. DOS is for people who never put bumper stickers on their cars." (*Windows for Dummies*, page 12)

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consistent with the empirical work that has been done on this topic.

[15] I reviewed the Boskin Commission bias estimates, and their implications for the measurement of real PCE (and therefore productivity), in Triplett (1997).

Following the passage quoted, the Windows for Dummies manual points out, correctly, that pictures require much more computing power, so using Windows 95 requires a relatively powerful computer. An enormous amount of recent computer and software development has been directed toward making computers easier to use.

Where do we count the value of increased convenience and better user interface in economic statistics? If they are productive, if pictures and icons result in more work being done, then the improvement will show up in the productivity figures, or at least in the labor productivity data.

On the other hand, if the pictures are just more "fun," then I suppose that new software incorporating screen graphics, "point and click" controls, and so forth has created more consumption on the job, compared with earlier software. Consumption on the job is not counted anywhere in economic statistics. If more advanced computer software contributes partly to output and partly to making the workers more content when they are working, some of that gain will be lost in economic statistics.

Even conceding that a little fun has value, I suspect the technologists have oversold these "fun little boxes and pictures." Whether the newest developments in software and computers have in fact made computers that much more user-friendly is an unresolved issue. Whether the benefits are worth the all changeover cost is another unsettled issue (see section VI).

But *if* the software designers have met their goal, *if* modern computers and software are more user-friendly and more flexible, and *if* the computer power on your desk has been directed toward that end, we would not capture much of the improved interface in economic statistics.

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).

Suppose 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 directly from the Asian manufacturer to large U.S. toy retailers; thus, this U.S. toy company has no direct substantial U.S. wholesale arm, either. The billing and financial transactions are handled in some offshore financial center, perhaps 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 in different parts of 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 impact of the computer on the toy company's profitability does contribute to 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 services activities where the outputs are presently imperfectly measured.[16]

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[16] 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, and indeed in a world in which the head office may manage establishments belonging to many different industries, 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). Where those units provide services to U.S. manufacturing establishments, one could impute the head office's management services to the costs of the manufacturing units. But in the global toy manufacturing world, it is not clear that the head office is providing services to the Asian manufacturing plants, or to anyone else.

V. You don’t see computers in the productivity statistics *yet*, but wait a bit and you will.[17]

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, page 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 VI), 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 behavior, 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 4). 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, rather than to electric power generation. Sichel (1997) presents an alternative

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[17] Parts of this section are adapted from my “comment” on Oliner and Sichel (1994).

estimate. Gordon's (1990) price indexes for electricity generation equipment only extend to 1947, but there is little in that history to suggest price declines even remotely in the same league as 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. The manufacturing plant that had been located by the stream and that transformed water power to mechanical energy directly did not convert to electricity. It did not convert because water power remained cheaper (electricity transformed water power twice, first into electrical energy and then into mechanical energy).[18] 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 with water or steam power.

In the computer diffusion process, the *initial* applications supplanted older technologies for computing.[19] Water and steam power long survived the introduction of electricity; but old, pre-computer age devices for doing calculations disappeared long ago. Do our research assistants still use Marchant calculators? (Or even know what they are?) The vast and

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[18] David (1990, p. 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 computers from the first decade or two of the computer age are still in service? Computing power and electric power have different, not similar, histories.

[19] 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 therefore 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, they just "computerized" exactly what had been done before.

continuous decline in computing prices has long since been factored into the decision to replace the computational analogy to the old mill by the stream—electric calculators, punched-card sorters, and the like—with modern computers.

In electricity, extensions to new applications preceded the displacement of old methods because the price of electricity did not make the old methods immediately obsolete. In the computer diffusion process, the displacement of old methods came first, because old calculating machines were rapidly made obsolete by the rapidly-falling price of computing power.

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 became ever cheaper, the incremental computerizations are 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. And it is not so much that I have gotten more expensive, it is instead that the computer has become so very cheap that it can be used for activities that are themselves of not particularly high value.[20]

The price histories of electric power and computing power during their respective first four decades differ by at least a thousandfold. What is known about the differences in the diffusion processes for electric power and computing power is consistent with that thousandfold price difference. Indeed, it is inconceivable that it would be otherwise. Accordingly, I do not believe that the diffusion story for electric power, as outlined by David, matches very well the diffusion history—and prospects—of computing power.

VI. 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

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[20] That computers are less than fully utilized is sometimes cited as an inefficiency that is somehow related to the paradox. It is not inefficient to let utilization of the lower cost input adjust to economize on the use of the higher cost one. That modern computers stand idle much of the time is just another indication that they are cheap—or, to put it another way, it is another piece of information that confirms the rapidly falling price index for computers (see section II, above).

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. They usually emerge as newspaper anecdotes when there is a very expensive project, or some abject failure of a redesign project, usually after a massive cost overrun. Examples are a $3+ billion Internal Revenue Service failure several years ago, and a Medicare record system project that was criticized more recently. In some organizations, it almost appears that the completion of a computer systems redesign project brings with it the realization (or claim) that it is outdated and needs to be replaced with a new system. 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, though that seems more a managerial problem, or the result of software lasting far longer than its designers intended, than an inherent computer/software problem.

At the personal computing level, there is the constant churning of standardized personal computer operating systems, spreadsheet and word processing packages, and so forth. Even if every new upgrade were a substantial improvement for all the users, 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. Do most users really need to be on the frontier? But the upgrading process goes on.

Raff and Trajtenberg (1997) show that the quality-adjusted price decline for automobiles in the early part of their history was comparable to computers. But for a large number of car buyers, the Model T proved good enough, they did not need to be on the technological frontier, even if some other buyers wanted the best that could be obtained. The failure of the Model T to emerge in the computer market may be evidence of technicians run amok, but it also may reflect fundamental differences in the computer market and in the car market. If you bought a used Model T you could still drive it on the same highway that the new one used (in the case of the computer you can't drive the old machine 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 making 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 graphics and icons 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, so why not do it? 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. A 386 machine, with an earlier operating system and earlier version of a word processing package, may be faster for some operations than a Pentium with the latest operating system and word processing upgrade. To get the gains offered by the newest word processing upgrade requires a considerable cost in upgraded operating system and upgraded machine, plus giving up something that the old system provided, which is the opposite way of looking at it, compared with the technologist view of the software designers.

Menu choices, too, have costs. My newest e-mail upgrade has far more choices than the old, but some of the things I did before now require more key-strokes, and the system is much slower in executing the commands that the earlier version performed with alacrity. That is just a computer application of the general economic principle that, while increased opportunities for choice are desirable, making choices is costly, so I do not want to be forced continually to choose from a wider menu.

Some computer professionals also question the direction recent software design has been taking. Michael Dertouzos was quoted (*New York Times*, June 24, 1997, section C, page 1): "Calling today's machine 'user friendly' because of its endless choice of fonts and screen patterns is tantamount to dressing a chimpanzee in a green hospital gown and earnestly parading it as a surgeon."

Then too, the user is conscious, if the software designer is not, that changeover itself is costly. It is not just the acquisition cost of a new package, nor the cost of mounting and debugging it, it is also the substantial cost to the users in unlearning old commands and learning new ones.[21] 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 takes its substantial toll on productivity (Blinder and Quandt, 1997, also emphasize the costs of learning and obsolescence as a drag on realizing the productiveness potential of computers).

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."

Nevertheless, people do not, by and large, forego the newest improvements and retain the old technology, or do not do it very long. It is troubling to appeal to some sort of market failure

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[21] 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?

(the well-publicized Microsoft antitrust case to the contrary) as the reason. If there is something to this "wastefulness" explanation for the computer paradox, it is a managerial and decision-making failure on the part of users of computer equipment and software.

If past decisions on computers have an elements of inefficiency, what of the future? One way of looking at it is to say that when we finally learn to use our computers, the future promises to fulfill the hopes so often disappointed in the past. Computers *are* productive, it is only that we humans have not used them productively, and they *will* improve productivity in the future, even if they haven't in the past. That says that the true, potential return to computers is much greater than the return that has been measured so far. If the true or potential return is much greater, then the economy ought to invest far more in computers than it has.

But 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. As with most of the debate on this topic, research knowledge at present does not go much beyond the insights of Dilbert.

One final point should be made. One of the computers' accomplishments may be to cut the cost of various kinds of rent-seeking behavior, and to facilitate rivalrous oligopoly behavior, 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 its effects on the economy—some gains to individuals or to firms are at the expense of other individuals or firms, so there is no net effect at the economy-wide level.

VII. 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. They believe there is a paradox because they believe they see more technical changes, more new products, more changes in consumer service, in methods of delivery, and in other innovative areas than is consistent with government productivity numbers. 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. It once was true, the story goes, that products were standardized and therefore easy to measure. Today, we are told there is an *unprecedented* stream of new products and quality improvements and customized products to meet market niches, product cycles are shortening to an *unprecedented* degree, new services from industries such as banking and finance are being introduced with a rapidity that is *unprecedented* historically, the Chairman of the Federal Reserve Board has been quoted to the effect that the *unprecedented* current level of technological innovations is a once in a century phenomenon that will yield an enormous upward kick to productivity.

In the new economy view, the productivity paradox is not really a computer paradox. Rather, people are stacking up and cumulating anecdotes, whether from within their own companies or from what they read in the newspapers or hear other people saying. Those cumulated anecdotes do not seem consistent with the modest rise in the aggregate productivity numbers. From this point of view, it is not so much a belief that the computer has increased productivity, but rather a belief that productivity has improved, based on other evidence. Indeed, the sentence in Solow (1987) immediately preceding the widely-quoted aphorism makes the same point: "[The authors] are somewhat embarrassed by the fact that *what everyone feels to have been* a technological revolution, a drastic change in our productive lives, has been accompanied everywhere...by a slowing-down of productivity growth, not by a step up" (emphasis supplied).

Thus, the computer was a signal or perhaps a symbol for all this innovation-new product productivity that people thought was happening. The computer provided a rationale that explained why this perception that the rate of technical change was accelerating in the economy was correct, and why the productivity statistics were wrong. For that reason, economists took the paradox seriously. It wasn't so much whether computers were seen everywhere, or not seen everywhere, or whether they were themselves productive, or whether some of their uses were wasteful, or the other considerations discussed in sections I-VI of this paper. It was, rather, that the computer gave plausibility to all the new things economists thought they saw in an anecdotal way but which did not show up in the aggregate productivity numbers.

Those anecdotes about new products, new services, new methods of distribution and new technologies are no doubt 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 wholly lack historical perspective, and for that reason are misleading as evidence on productivity.

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 just 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, as the arithmetic of compound increases shows. As the economy grows, an ever larger number of new products is required just to keep the productivity growth rate constant.

Most of the anecdotes that have been advanced as evidence for the "new economy" amount to an assertions that there are a greater *number* of "new" things, which is not necessarily a greater rate. As an example, many economists have cited the number of products carried in a modern grocery store as evidence of increased consumer choice, of marketing innovations, and so forth.[22]   Diewert and Fox (1997, Table 5) report that in 1994 there are more than twice as many products in the average grocery store than in 1972 (19,000, compared with 9,000). But the 1948-72 rate of increase (from 2,200 in 1948 to 9,000) was 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 are many more products in grocery stores than there were two decades before; but the rate of increase has fallen.

Some other illustrations enhance the point. The Boskin Commission cited welfare gains from the increased availability of imported fine wines, and so forth. Because of the great reduction in transportation costs, we now get Australian wine in the United States at low prices (as low, in my experience, as in Australia). That is certainly an increase in the number of commodities available, and an increase in welfare. But is the increase in tradeable commodities a larger proportionate increment to choice and to consumption opportunities than the increments that occurred in the past?

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[22] Reservations might be expressed about this interpretation of the number of products in supermarkets.

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. Mokyr (1997) observed that: "Nothing like the [present] unprecedented increase in the quality and variety of consumer goods can be observed in Britain during the Industrial Revolution. The working class still spent most of its income on food, drink, and housing." Considering the very small number of consumption goods then available to the average worker, and even allowing for the fact that the fresh fish were undoubtedly initially consumed mostly by the middle class, was the introduction of fresh fish a smaller proportionate increase in the number of new commodities than is the availability of Australian wine and similar goods a century later? I suspect the best answer to this question is: we do not know. But we also have looked at the decade of the 1990's with far too short a historical perspective.

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."

One could go on. My 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. Again, much of what has been said about the new economy is true; what has been lacking is a proper historical appreciation for the magnitudes and significance of new product introductions and quality change in the past.

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. If the number of "new things" is a measure of productivity improvement, then we have to have an increase in the rate of introduction of new things, not just an increase in the number. Most of the anecdotes that have been cited for the "new economy" suggest that many economists have been looking at the wrong question, they have been looking at the number of new things rather than the rate.

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 tremendously impressed by them. We should be. It is clear those new products are increasing welfare, and the technical innovations are contributing to output. But are they increasing at an increasing rate? Is the number of new products increasing more rapidly on a logarithmic scale? That is not clear at all. For the "new things" to improve productivity, they must be increasing at an increasing rate. 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.

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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 labor, combined (1987-93)	n.a.	0.40[c]	n.a.	n.a.	n.a.

Notes:

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.

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	Capital Services Share
Computing equipment	2.0[a]	0.9[b]	0.5[e]	1.8[e]
Information processing equipment	11.7[a]	3.5[c]	n.a.	n.a.
Computing hardware, software and labor, combined	n.a.	2.7[d]	n.a.	n.a.

Notes:

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.

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.

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