STEPHEN D. OLINER
Board of Governors of the Federal Reserve System

DANIEL E. SICHEL
Brookings Institution

Computers and Output Growth Revisited: How Big Is the Puzzle?

DURING THE PAST 15 years, U.S. companies have poured billions of dollars into information technology. Yet, through the 1980s, many observers argued that these companies were not getting their money's worth. As hard as analysts scoured the numbers, they could not show that computing equipment contributed much to productivity growth, leading to Robert Solow's famous quip that "you can see the computer age everywhere but in the productivity statistics."[1]

More recently, the tables have turned. Much academic and popular opinion has moved toward the position that, at long last, businesses have learned how to use their computing equipment effectively. For example, Erik Brynjolfsson and Lorin Hitt provide firm-level evidence that computing equipment earned hefty returns in the late 1980s.[2] And—based in part on this evidence—*Business Week* proclaimed that "the productivity surge of the last two years . . . may reflect the efforts of U.S.

The views expressed here are our own and should not be attributed to the institutions with which we are affiliated. We would like to thank William Gale, Claudia Goldin, Robert Gordon, and Jack Triplett for helpful comments and suggestions. We also thank Derek Douglas and Kirsten Wallenstein for outstanding research assistance, David Tremblay of the Software Publishers Association for help with software sales data, David Prince for help with software prices, and Lisa Guillory for administrative support.

1. Robert M. Solow, "We'd Better Watch Out," *New York Times Book Review*, July 12, 1987, p. 36. Many studies have suggested that computing equipment earned a subpar return. For example, see Osterman (1986), Loveman (1988), and Morrison and Berndt (1991).
2. Brynjolfsson and Hitt (1993).

companies to finally take full advantage of the huge sums they've spent purchasing information technology."[3]

Both the puzzle of the 1980s and the recent suggestion that information technology might be driving aggregate productivity stem from a basic premise: namely, that computing equipment should have had a visible effect on aggregate economic growth. We examine this basic premise by asking, how much could computing equipment plausibly have contributed to economic growth over the past two decades? And what are reasonable expectations for the 1990s?

To answer these questions, we begin with Denison-style growth accounting—which identifies the underlying sources of growth—to develop baseline estimates of the contribution of computers to output growth.[4] Because so much past research has focused on computer hardware, that is our starting point. The remainder of the paper then examines whether the assumptions underlying the baseline might lead to an understatement of computers' contribution to growth. The assumptions we examine are that computers earn the same return as other capital, that the output of computers is correctly measured by official procedures, and that focusing on computer hardware alone is appropriate.

Three main results emerge from this analysis. First, under the standard neoclassical assumptions used for our baseline growth accounting, the contribution of computer hardware to the growth of gross output between 1970 and 1992 was small—only 0.16 percentage point annually. Furthermore, computers contributed even less to the growth of net output—which is a better measure of economic welfare than gross output—because so much of the gross return to computers was eaten up by depreciation. In large part, the contributions were small because computing equipment was a very minor share of the total capital stock.[5]

Importantly, these qualitative results hold up even when computers are assumed to earn supernormal returns of the size suggested by several recent studies.[6] The qualitative results also hold up when computers are assumed to generate a substantial amount of output that is not mea-

3. Michael J. Mandel, "The Digital Juggernaut," *Business Week*, The Information Revolution, Special 1994 Bonus Issue, pp. 22–31.

4. Denison (1985).

5. David Romer hinted at this explanation in his comment on Baily and Gordon (1988), as did Brynjolfsson (1993).

6. See Brynjolfsson and Hitt (1993), De Long and Summers (1991, 1992), Krueger (1993), and Romer (1987).

sured by official procedures. Together with the baseline contributions, these results suggest that the computer puzzle of the 1980s was more apparent than real. Put simply, computer hardware should not have been expected to make a large contribution to output growth in this period.

The second main result is that the traditional focus on computer hardware alone misses other important factors. In particular, computer hardware must be combined with software and labor inputs to produce computing services. Although admittedly crude, our estimates suggest that adding in software and computer-services labor could roughly double the contribution that hardware makes to output growth. To make these calculations, we develop new quality-adjusted price indexes of applications software for personal computers (PCs); the indexes are described briefly later in the paper. Moreover, because the information revolution has not been driven by computers alone, an exclusive focus on computer hardware misses the role played by other information processing equipment, such as communications gear. This other equipment further boosts the overall contribution to output growth.

The third main result is that computers probably have not caused much of whatever pickup in aggregate productivity growth has occurred in recent years.[7] And, looking forward, rapid growth of real computer hardware and software purchases, by itself, will probably not generate a big pickup in output growth. This latter result obtains because, even with robust growth, the share of computer hardware and software in the capital stock will likely remain small. As we show, a substantial pickup in their contribution would require dramatic assumptions about the rate of return earned by computers.

Basic Facts

Table 1 reports the growth rates of real investment, real net capital stock, and price deflators for computers and other information processing equipment since 1970.[8] The figures in the table cover three successively broader categories of equipment. The first is computer and pe-

7. In fact, Gordon (1993) argues that there has not been anything unusual about the pattern of labor productivity growth in recent years; that is, the recent improvement in productivity likely reflects cyclical dynamics rather than a shift in the underlying trend.

8. The growth rates reported throughout this paper are annual log differences.

Table 1. Growth in Investment, Capital Stocks, and Deflators of Computers and Other Information Processing Equipment, 1970–93[a]

Percent per year[b]

Equipment category and measure[c]	*1970–75*	*1975–80*	*1980–85*	*1985–90*	*1990–93*
Computer and peripheral equipment					
Real investment	24.1	40.1	33.9	13.3	26.4
Real net capital stock	24.5	34.8	36.7	19.4	18.3
Deflator	−18.6	−15.0	−14.7	−11.0	−18.3
Office, computing, and accounting equipment					
Real investment	10.7	24.0	22.5	9.1	25.8
Real net capital stock	16.2	18.9	26.0	16.7	14.8
Deflator	−2.5	−1.7	−6.4	−8.5	−15.8
Information processing equipment					
Real investment	5.8	14.3	9.0	5.6	13.7
Real net capital stock	8.5	8.9	10.1	9.5	7.1
Deflator	4.0	4.1	2.3	−1.8	−7.5

Source: Authors' calculations using data from Bureau of Economic Analysis.
a. All real series and deflators are calculated on a 1987 dollar basis.
b. Average annual log difference multiplied by 100.
c. For a full description of the types of equipment included in each of these aggregates, see U.S. Office of Management and Budget (1987).

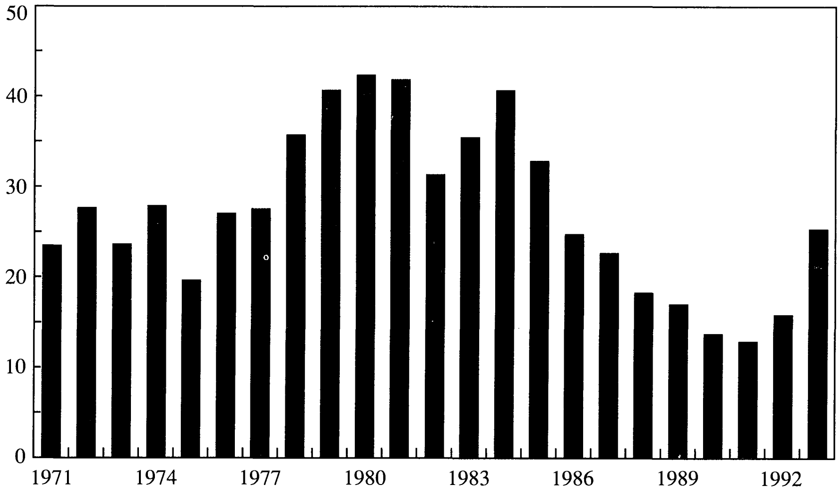
ripheral equipment (CPE), the category on which we focus throughout most of the paper. The second is office, computing, and accounting equipment (OCA), a frequently used aggregate that adds in typewriters and other noncomputer office equipment. The third encompasses all information processing equipment—the sum of OCA, communications equipment, scientific instruments, and photocopy machines. All the figures in table 1 are based on data published by the Bureau of Economic Analysis (BEA).[9]

As can be seen, real investment in CPE grew rapidly in each five-year period from 1970 to 1990 and again from 1990 to 1993. The growth rates ranged from an annual average of 13.3 percent over the 1985–90 period to 40.1 percent over the 1975–80 period. The real net stock of CPE has

9. Published BEA data used in this paper are primarily from U.S. Bureau of Economic Analysis (1992, 1993). Where needed, these data are updated from selected issues of the *Survey of Current Business* or with data provided directly by BEA. We also use some unpublished BEA data as described in the appendix. For computer and peripheral equipment, BEA publishes data for investment but not for the capital stock. As described in the appendix, we construct capital stock series using procedures that are identical to those used by BEA to construct capital stocks for OCA.

Figure 1. Growth in Net Stock of Computer and Peripheral Equipment, 1971–93

Annual log differences ($\times$ 100)[a]



Source: Authors' calculations based on BEA investment data and weights.
a. Log difference of the real net capital stock (1987 dollars).

also increased at an extremely fast pace since 1970.[10] Across the subperiods, the fastest growth of CPE investment and capital stock appears to have been before 1985. (This pattern can also be seen in figure 1.) One important factor behind the robust growth of real investment and real capital stock has been the steep drop in computer prices. Over the periods shown in the table, BEA's quality-adjusted price deflator for CPE investment fell at annual rates ranging from 11 percent to 18.6 percent.

The middle and lower parts of table 1 show less extraordinary, though still robust, rates of growth in real investment and real capital stock for the two broader aggregates. In addition, the rate of price decline for OCA has been less rapid than that for CPE, and prices actually rose for

10. BEA also publishes two other measures of the capital stock: the gross stock and a lesser-known measure called the "capital-input" stock. As described earlier, BEA does not publish stocks for CPE, so we construct all three stock measures using procedures analogous to those used by BEA. Although the levels of these three measures differ substantially, their growth rates over the full period from 1970 to 1993 are nearly identical. Moreover, the differences over subperiods are modest. Substituting the gross stock or the capital-input stock for the net stock in table 1 would change the CPE growth rate by less than 3 percentage points in any period. The next section briefly describes the conceptual differences between these measures of the capital stock and motivates the particular measures used in our growth accounting.

information processing equipment through the 1970–85 period. These comparisons suggest, not surprisingly, that computers have been the most technologically dynamic component of information processing equipment.

However, the data for the broader aggregates suffer from serious index number problems. Consider, for example, the deflator for OCA. Table 1 shows that this deflator's rate of decline has become more rapid over time, from which one might infer that the pace of technical improvement in these assets has accelerated. In fact, this pattern merely reflects the shift in the mix of real investment spending toward computers, whose prices are falling faster than those of other items in OCA. Such relative price changes create distortions in a fixed-weight measurement system. The CPE aggregate is much less affected by these distortions, since the amount of relative price change within this grouping is small compared to that within the aggregates that pool computers and other equipment.[11]

Table 2 characterizes the share of CPE in all nonresidential equipment and structures. As shown on the first line of the table, CPE has accounted for a rapidly growing share of real investment within this aggregate; after having been 1 percent or less until 1980, the share skyrocketed to 17.8 percent in 1993. The CPE share of the real net capital stock also has grown substantially over time. However, these real shares—although often cited—are not meaningful concepts. They suffer from the same index number problems described above. For example, if real investment were measured in terms of constant 1992 dollars rather than constant 1987 dollars, the real CPE shares would decline dramatically, as CPE spending would be valued at the much lower 1992 prices for computers. Indeed, a base year can be chosen to yield almost any real CPE share.

Nominal shares, by contrast, are unaffected by this choice and, as we show in a later section, such shares play a critical role in standard growth

11. BEA is well aware of this problem. The agency has begun to publish alternative estimates of the growth of real GDP and GDP prices that alleviate the distortions in its standard measures; see Allan H. Young, "Alternative Measures of Change in Real Output and Prices," *Survey of Current Business*, April 1992, pp. 32–48, for a discussion of these so-called superlative indexes. Unfortunately, BEA does not publish superlative indexes for OCA or information processing equipment. Later in the paper, when our analysis focuses on information processing equipment, we construct a superlative index for the capital stock of this broader category.

Table 2. Computers and Other Information Processing Equipment as a Share of Total Nonresidential Equipment and Structures, 1970–93[a]
Percent

Equipment category and share measure	*1970*	*1975*	*1980*	*1985*	*1990*	*1993*
Computer and peripheral equipment						
Real share						
Investment	0.1	0.2	1.0	4.7	8.7	17.8
Net capital stock	0.0	0.1	0.2	1.3	3.1	5.1
Nominal share						
Investment	2.6	2.1	3.5	6.4	6.3	7.6
Net capital stock	0.8	0.6	0.9	1.8	2.1	2.0
Memo:						
Nominal share, net capital stock						
Office, computing, and accounting equipment	1.6	1.3	1.5	2.0	2.2	2.0
Information processing equipment	7.1	7.1	7.6	10.1	11.1	11.7

Source: Authors' calculations using data from Bureau of Economic Analysis.
a. All real series are calculated on a 1987 dollar basis.

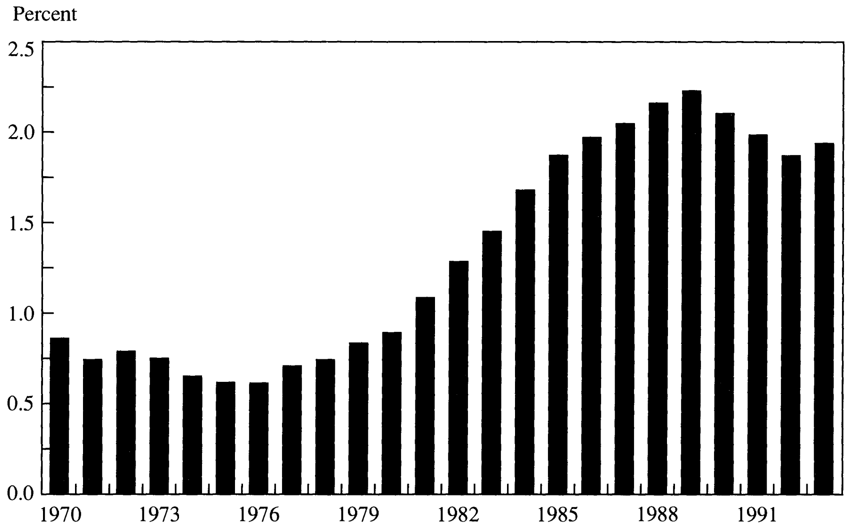
accounting. When measured in nominal terms, CPE accounted for only 7.6 percent of total investment in nonresidential equipment and structures in 1993 and for only 2 percent of the net stock of these assets.[12] Thus, as can be seen in figure 2, computers remain a relatively minor input to production. The small share of the capital stock goes a long way toward explaining why we find such a modest growth contribution from computers later in the paper.

Some authors—notably Stephen Roach as well as Lawrence Lau and Ichiro Tokutsu—have analyzed the growth contributions of broader categories of high-technology assets.[13] A broader focus is appropriate for assessing the impact of the microelectronics revolution as a whole. This paper does not undertake such an ambitious task, although we do measure the growth contribution of all information processing equipment. The memo item in table 2 shows why this wider purview could be important: information processing equipment accounted for 11.7 percent

12. Measuring the CPE share in terms of the gross capital stock or the capital-input stock would yield about the same result. In 1993, CPE represented 1.7 percent of the nominal gross stock of nonresidential equipment and structures and 1.8 percent of the corresponding capital-input stock.

13. Roach (1991) and Lau and Tokutsu (1992).

Figure 2. Nominal Share of Computer and Peripheral Equipment in the Total Net Stock of Nonresidential Fixed Capital, 1970–93



Source: Nominal net stock of computer and peripheral equipment based on authors' calculations using BEA investment data and weights. Total nominal net stock from BEA.

of the nominal net capital stock in 1993, more than five times the nominal CPE share. This step-up in the share mainly reflects the large stock of communications equipment, which—like computers—has a considerable amount of embedded microelectronics.

Baseline Growth-Accounting Results

This section uses a standard growth-accounting framework to assess the contribution of computing equipment to the growth of gross and net business output in the United States from 1970 to 1992. The growth contributions derived here are based on the usual set of neoclassical assumptions: (i) constant returns to scale in production; (ii) the existence of competitive equilibrium, which forces the private marginal product of each factor to equal its real user cost; and (iii) the absence of externalities, which eliminates any potential wedge between private and social marginal products. Later, we relax these assumptions to examine the robustness of the baseline results.

Methodology

Consider the aggregate production function

$$(1) \qquad Y = F(\mathbf{X}, t),$$

where Y is real output, $\mathbf{X} = (X_1, X_2, \ldots, X_n)$ is a vector of capital and labor inputs, and t represents shifts in the production technology over time. Let P denote the price of output. Then, assumptions (ii) and (iii) above imply that the social marginal product of each input $(\partial F/\partial X_j)$ equals its real rental price (r_j/P). By differentiating equation 1 with respect to time and then setting $\partial F/\partial X_j$ equal to r_j/P, we obtain the standard growth-accounting equation:

$$(2) \qquad \dot{Y} = \Sigma s_j \dot{X}_j + M\dot{F}P,$$

where dots above the variables indicate rates of change, where s_j equals $r_j X_j/PY$ and represents the share of nominal income accruing to input j, and where $M\dot{F}P$ equals $(\partial F/\partial t)/Y$ and represents the rate of growth in multifactor productivity. Under neoclassical assumptions, the nominal income share for each input equals its output elasticity. With constant returns to scale, the income shares sum to one.

The growth-accounting exercise that we undertake in equation 2 relies heavily on the methodology and data employed by the Bureau of Labor Statistics (BLS) to measure multifactor productivity.[14] BLS uses equation 2 to compute the contributions of aggregate labor input, aggregate capital input, and *MFP* to the growth of real value-added in private nonfarm business and other broad sectors of the economy. Also, BLS calculates the contribution of each input to growth on a year-by-year basis and then averages these annual figures to measure contributions over longer time spans. Thus, even over long time spans, BLS's procedure measures each year's marginal growth contributions.

Our only departure from BLS's methodology is to separate computing equipment (K_C) from all other capital. With this split, the growth-accounting equation becomes

$$(3) \qquad \dot{Y} = s_C \dot{K}_C + (s_K \dot{K} - s_C \dot{K}_C) + s_L \dot{L} + M\dot{F}P,$$

14. See Bureau of Labor Statistics (1983) for an overview of their basic methodology and Bureau of Labor Statistics (1994) for a discussion of recent improvements.

where $s_C\dot{K}_C$ is the growth contribution of computers, $s_K\dot{K} - s_C\dot{K}_C$ is the contribution of all capital other than computers, and $s_L\dot{L}$ is the contribution of aggregate labor input.

The contribution of computers depends on the income share, s_C, which is unobservable. To impute s_C, we follow the method used by BLS to impute income shares for other types of capital, although we omit tax terms for simplicity. BLS employs Dale Jorgenson's well-known user cost of capital as a proxy for the unobserved rental price (r_C). With this procedure, the income share for computing equipment is

$$s_C = r_C K_C / PY = (i + \delta_C - \dot{p}_C) p_C K_C / PY, \tag{4}$$

where PY is nominal output, i is a measure of the nominal rate of return common to all capital, δ_C is the depreciation rate on computing equipment, p_C is the price index for computing equipment, and its rate of change, $\dot{p}_C$, is the rate of nominal capital gain (actually loss) on this equipment.

The nominal (pretax) rate of return, i, is a key parameter in equation 4. Again following BLS procedures, we impute i on a year-by-year basis as the average ex post return earned by the net stock of all nonresidential equipment and structures, forcing computers to earn the same return as other fixed capital.[15] With this estimate of i, the income share s_C can be calculated using BEA and BLS data for the other variables that appear in equation 4.

The gross return in equation 4 ($i + \delta_C - \dot{p}_C$) covers not only the opportunity cost of holding a computer for one period (i) but also the loss in asset value over the period ($\delta_C - \dot{p}_C$). Hence, equation 4 defines the income share needed to assess the contribution of computers to the growth of *gross* output. We also measure the contribution of computers to the growth of *net* output—that is, gross output minus depreciation. To obtain this net contribution, we calculate a net income share that strips out the change in asset value ($\delta_C - \dot{p}_C$). Accordingly, we employ the net income share

$$s_{C,NET} = i p_C K_C / PY_{NET}, \tag{4'}$$

where Y_{NET} denotes real net output. Note that we remove $\delta_C - \dot{p}_C$, not merely the depreciation term, δ_C, to calculate the net income share. We do this because the rate of depreciation for computers, as measured by

15. See the appendix for details.

BEA, actually corresponds more closely to $\delta_C - \dot{p}_C$ than to δ_C alone, a point discussed in the next subsection.

Data

We rely on BLS data for every variable in the growth-accounting formula in equation 3 except the income share for computing equipment, s_C, and the real stock of this equipment, K_C.[16] These annual BLS data cover the private nonfarm business sector in the United States and measure the growth of real output ($\dot{Y}$), real capital input ($\dot{K}$), and labor input ($\dot{L}$) with superlative indexes.[17] These indexes capture shifts in relative prices over time by changing their aggregation weights. Thus, these BLS series are free from the index number problems that arise in fixed-weight measurement systems.

BLS's measure of capital input covers producers' durable equipment, nonresidential structures, residential rental structures, inventories, and land. Effectively, this measure aggregates growth rates of asset-specific capital stocks, with imputed nominal income shares serving as the weights. Similarly, BLS's labor input aggregates the growth in hours worked by various demographic groups, using hourly compensation to determine the weights.

The asset-specific capital stocks used by BLS are not the well-known gross or net stocks produced by the BEA, but an alternative BEA measure known as the "capital-input" stock. Although all three stocks—gross, net, and capital input—are computed as a weighted sum of past investment outlays, they employ different weights. For the capital-input stock, the weights are intended to approximate the decline in an asset's service flow as it ages.[18] Thus, the resulting stocks provide a measure of

16. See Bureau of Labor Statistics (1983, 1994) for details on the construction of their data.

17. Specifically, BLS employs a Fisher Ideal index of real output and Tornquist indexes of capital and labor input. For a discussion of superlative indexes, see Diewert (1987).

18. The capital-input weights decline slowly during the early years of an asset's lifetime and then more rapidly as it approaches retirement, on the assumption that most decay occurs late in an asset's lifetime. In contrast, the gross stock, with its weights set at unity until retirement, can be viewed as measuring the service flow from assets that suffer no physical decay until retirement. The net stock is not a measure of capital services, but rather measures the market value of existing capital under the assumption of straight-line depreciation.

the services yielded by each asset, as is appropriate for growth accounting.

To be consistent with BLS's methodology, we measure $\dot{K}_C$ as the log difference of the real capital-input stock of CPE. Our procedure for constructing this CPE stock mimics that employed by BEA for other types of equipment and structures and is described in the appendix.

The other data series we construct are the gross and net income shares of computer capital. As shown in equations 4 and 4′, the variables required to construct these shares include nominal gross and net output (PY and PY_{NET}), the nominal stock of computing equipment ($p_C K_C$), the rate at which this equipment loses value ($\delta_C - \dot{p}_C$), and the nominal rate of return (i). For PY, we use BLS's estimate of current-dollar output in the private nonfarm business sector; PY_{NET} equals BEA's estimate of nominal net domestic product in the same sector. We construct $p_C K_C$ as the nominal *net* stock of CPE, with the details again provided in the appendix. The net stock is appropriate here because $\delta_C - \dot{p}_C$ represents the rate of decline in the asset's market value. Based on BEA data, we estimate $\delta_C - \dot{p}_C$ to have averaged 24.3 percent a year over the 1970–92 period.[19] This hefty loss of value reflects the rapid obsolescence of computing equipment. Using the procedure described in the appendix, we estimate i to have ranged from a minimum value of 10.5 percent in 1982 to a maximum of 13.5 percent in 1989, with an average value of 12.3 percent a year over 1970–92. Because equation 4 omits all taxes, i represents a nominal pretax return and is within a plausible range.

With these estimates of i, we can calculate the annual rental income earned per dollar of computing equipment ($i + \delta_C - \dot{p}_C$). Over 1970–92, the estimates above imply that $i + \delta_C - \dot{p}_C$ averaged 36.6 percent. By contrast, for other nonresidential equipment and structures, we estimate that the gross return, $i + \delta_{OES} - \dot{p}_{OES}$, averaged only 15.4 percent, reflecting the much slower loss of value implied by BEA data. The high

19. This figure is the annual depreciation rate for our net stock of CPE, which—as noted above—was estimated in accord with BEA procedures. It may seem surprising that we use this number as an estimate of $\delta_C - \dot{p}_C$, rather than of δ_C alone. However, BEA's measure of depreciation captures losses of value from all sources, including the obsolescence caused by rapid declines in quality-adjusted prices. To associate the BEA depreciation rate with δ_C and then to add on $-\dot{p}_C$ would double count the decline in these prices. In any case, our results for the growth contribution of CPE are quite robust to the assumed value for $\delta_C - \dot{p}_C$. For a detailed discussion of the issues surrounding BEA's measure of depreciation, see Oliner (1994).

Table 3. Sources of Growth in Real Gross Output of Private Nonfarm Business, 1970–92

Units as indicated

Measure	*1970–92*	*1970–79*	*1980–92*
Growth rate of output[a]	2.77	3.42	2.27
Contributions from[b]			
Computing equipment	0.16	0.09	0.21
Other capital	1.00	1.18	0.88
Labor hours	0.95	1.17	0.79
Multifactor productivity	0.67	0.99	0.42
Income shares[c]			
Computing equipment	0.6	0.3	0.9
Other capital	29.1	28.8	29.3
Labor hours	70.3	70.9	69.9
Growth rate of inputs[a]			
Computing equipment	27.6	27.8	27.4
Other capital	3.4	4.1	3.0
Labor hours	1.4	1.7	1.1

Source: Authors' calculations using BEA and BLS data.
a. Average annual log difference multiplied by 100.
b. Percentage points per year.
c. Percent.

rental rate for computing equipment is required to cover the cost imposed by rapid obsolescence, leaving the owners of this equipment with a net rate of return equal to that of other assets.

Contribution of Computers to Gross and Net Business Output

Table 3 shows the contribution of computing equipment to the growth of real gross output in the baseline case over three time periods, 1970–92, 1970–79, and 1980–92. The central result is that computing equipment has made a small contribution to growth. Over 1970–92, we estimate that this equipment contributed only 0.16 percentage point annually to the growth of gross business output, as shown on the second line of the table. Focusing on the more recent period from 1980 to 1992, we find that the contribution is more than double that in the preceding decade but still only 0.21 percentage point a year. Although growth contributions of this size are nothing to sneeze at, they remain quite small compared with the productivity slowdown of about one-and-a-half percentage points in the early 1970s.[20]

20. Denison (1985, p. 35).

Furthermore, the contribution of computer hardware is swamped by that of noncomputer capital. As table 3 also shows, the contribution from capital other than computers averaged 1.0 percentage point a year over 1970–92, about six times the contribution from computers. Interestingly, the growth contribution of noncomputer capital diminished somewhat in the 1980s, more than offsetting the increase in the contribution of computers. This pattern suggests that computers may have displaced other types of capital as firms altered the mix of their investment outlays to take advantage of the declining quality-adjusted prices of computers.[21]

The lower part of the table explains why computing equipment has had so little effect on growth. Recall that the growth contribution of any input equals the product of its nominal income share and the growth rate of the input's stock. For computing equipment, the real capital-input stock has grown extremely rapidly—at an average annual rate of 27.6 percent over 1970–92. However, the share of nominal income accruing to computing equipment remains negligible. This share, s_C, averaged only 0.6 percent over 1970–92, and, although s_C generally rose over the period, its maximum value was only 1.1 percent (attained in 1989). This share remained small because the stock of computing equipment continued to represent a tiny fraction of the nominal capital stock in the United States, as described earlier. Recall that, as shown in table 2, computing equipment in 1993 accounted for just 2 percent of the net current-dollar stock of private nonresidential equipment and structures.

Thus, our response to Solow's quip is that computers are not "everywhere" when judged by the metric that matters for growth accounting—the share of current-dollar income. This observation is the key to resolving the computer paradox: computing equipment can be productive at the firm level and yet make little contribution to aggregate growth, precisely because computers remain a relatively minor factor of production.

Thus far, our results have characterized the contribution of computers to the growth of *gross* business output. However, the contribu-

21. If so, the true contribution of computers to output growth could be less than 0.16 percentage point annually over 1970–92. That is, if computers had never been invented, firms presumably would have spent more on other capital than they actually did. Thus, in a world without computers, the annual growth rate would not necessarily have been a full 0.16 percentage point lower than what is actually observed.

tion to *net* business output is also needed to fully assess the role of computing equipment in the economy. As is well known, Edward Denison and Dale Jorgenson engaged in a long-standing debate about whether growth accounting should be done on a gross or net basis.[22] In a very useful paper, Charles Hulten argued that Denison and Jorgenson were both right.

> [The two methods of growth accounting] are not substitutes, but complements which reveal different aspects of the growth process: gross product is the correct output concept for estimating the structure of production, while net product is the correct concept for measuring the welfare consequences of economic growth.[23]

To make this point concrete, consider an extreme example. Suppose a machine were invented that could produce $6 trillion of output each year, doubling the size of the U.S. economy. Suppose further that this machine depreciated fully in a year and cost $6 trillion to replace. On a gross basis, the machine would make a massive contribution to growth and would have a large impact on the structure of production. However, from a welfare point of view, the machine would be useless. All the income generated by the machine would be needed for its replacement, leaving none to support consumption spending. Thus, the machine's contribution to welfare would be zero.

Table 4 shows that the contribution of computers to growth in net business output over 1970–92 is estimated to have been just 0.06 percentage point a year. The net contribution over 1980–92, while more than double that estimated for 1970–79, is still only 0.07 percentage point annually. These figures are much smaller than the analogous gross contributions because depreciation eats up such a large share of the gross return to computing equipment. Thus, from a welfare point of view, computers made a very small contribution over this period, even on the

22. See the collection of articles by Denison, Griliches, and Jorgenson in the May 1972 *Survey of Current Business*, part 2. This debate has continued to simmer, as evidenced by Jorgenson's comments on Baily and Schultze (1990).

23. Hulten (1992, p. 9). To measure the welfare consequences of growth, Hulten develops a "wealth-accounting" framework that decomposes the growth of national wealth into the contributions from physical capital, human capital, and a productivity residual. Although this framework is conceptually appealing, it is difficult to implement because the accumulated level of human capital must be valued. Therefore, we account for the net contribution of computers in the more usual way, by modifying equation 3 to be a decomposition of net business output.

Table 4. Baseline Contribution of Computing Equipment to the Growth in Real Net Output of Private Nonfarm Business, 1970–92
Units as indicated

Measure	*1970–92*	*1970–79*	*1980–92*
Contribution to output[a]	0.06	0.03	0.07
Growth rate of computer capital[b]	27.6	27.8	27.4
Net income share of computing equipment[c]	0.2	0.1	0.3

Source: Authors' calculations using BEA and BLS data.
a. Percentage point per year.
b. Average annual log difference multiplied by 100.
c. Percent.

assumption that computers were as productive at the firm level as any other type of capital.

What If Computers Earn Supernormal Returns?

The previous section showed that the contribution of computers to the growth of gross and net output has been small under standard neoclassical assumptions. However, the continuing debate about the contribution of capital to growth—along with the recent literature on the computer paradox—raises the possibility that standard growth accounting might understate the true contribution of computers. In particular, computers might generate positive externalities or might produce supernormal private returns, both of which would be misallocated to the multifactor productivity residual under standard growth accounting.[24] This section recalculates the contribution of computers to growth allowing for externalities and supernormal returns of a magnitude implied by several recent studies.

What If Capital Investment Generates Positive Externalities?

Paul Romer as well as Bradford De Long and Lawrence Summers, together with other researchers, have suggested that capital investment generates substantial positive externalities.[25] Pinning down the exact

24. The possibility that standard capital measures might miss embodied technical change is another reason to suspect that the role of capital might be understated. For computers, however, this issue is unimportant; measures of real investment and capital stock already include most, if not all, embodied technical change because of the use of quality-adjusted prices for computers.

nature of these externalities has always seemed problematic. However, the general types of externalities that they discuss—building the knowledge base and learning-by-doing—could be especially important for new capital goods like computers. Therefore, these studies are a good starting point for an investigation of externalities associated with computers.

In an early paper on endogenous growth, Romer presents a simple model with positive externalities from knowledge spillovers.[26] In his model, increases in physical capital not only boost the productive resources of the firm making the investment but also raise the level of technology available to other firms—hence the knowledge spillovers. Based on theoretical and empirical arguments, Romer suggests that the coefficient on capital in a growth-accounting equation should range from 0.7 to 1.0, well above capital's income share of about 0.3. We explore the most extreme case by setting the output elasticity of capital equal to unity.

To estimate a nominal social return, i_{soc}, consistent with Romer's externalities, we allow the output elasticity to exceed the income share. Specifically, we solve for i_{soc} based on an output elasticity for nonresidential equipment and structures that is three-and-one-third (1.0/0.3) times larger than assumed in our baseline case. From 1970 to 1992, the resulting average annual value of i_{soc} is 49.4 percent, as shown by the "Romer" estimates in table 5. This value, which reflects both the private return to capital and the output generated via the assumed externality, is about four times greater than the nominal net return implicit in the standard growth-accounting exercise. When we add on the value for $\delta_C - \dot{p}_C$ described previously, the resulting gross return averages about 74 percent a year over 1970–92.

Using this estimate of i_{soc}, the contribution of computers to aggregate growth is easily calculated by the procedure outlined earlier in the paper. As shown in table 5, the implied Romer contribution to gross output is 0.32 percentage point a year from 1970 to 1992, while the contribution to net output is 0.24 percentage point annually. These numbers do not change the general conclusion reached previously in the paper—that computers have been a relatively modest source of growth. Moreover, it is worth stressing that a very large externality has been assumed to

25. Romer (1986, 1987) and De Long and Summers (1991, 1992).

26. Romer (1987). Also, see Romer (1994) and the other articles in the same symposium for a sampling of the current direction of research.

Table 5. Alternative Estimates of Computers' Contribution to Growth, Various Time Periods
Units as indicated

Case	Net output: Nominal return[a]	Net output: Contribution to growth[b]	Gross output: Nominal return[c]	Gross output: Contribution to growth[b]
1970–92				
Base case	12.3	0.06	36.6	0.16
Romer	49.4	0.24	73.7	0.32
De Long and Summers	33.5	0.16	57.8	0.25
1987–91				
Base case	12.3	0.06	36.6	0.16
Brynjolfsson and Hitt	56.7	0.27	81.0	0.35
1984–89				
Base case	12.3	0.08	36.6	0.21
Krueger	36.2	0.23	60.5	0.38

Source: Authors' calculations using BEA and BLS data, Romer (1987), De Long and Summers (1992), Krueger (1993), and Brynjolfsson and Hitt (1993).
a. The nominal return associated with net output equals i, measured as percent per year.
b. Percentage point per year.
c. The nominal return associated with gross output equals $i + \delta_C - \dot{p}_C$, measured as percent per year.

generate these "Romer" contributions. By increasing the output elasticity of capital from about 0.3 to 1.0, this contribution assumes that the gross private return to capital represents only 30 percent of the total social return, with the remainder owing to positive externalities.

De Long and Summers also suggest that externalities are important. In particular, they argue that workers and managers learn new skills and more efficient methods of production by using newly installed equipment. Because firms cannot easily keep such knowledge to themselves, equipment investment generates positive externalities for the economy as a whole. An external benefit might also arise if equipment manufacturers could improve the design of existing models by drawing on the experience of equipment users. Employing data for a broad cross-section of nations, De Long and Summers find a strong link between equipment investment and economic growth, which they take as evidence of high social returns to equipment investment. Although Alan Auerbach, Kevin Hassett, and Oliner have raised serious questions about their results, we suppress these concerns for now in order to calculate the growth contribution of computers implied by De Long and Summers' estimates.[27]

27. Auerbach, Hassett, and Oliner (1994).

Among their many sets of results, those reported for the member countries of the Organization for Economic Cooperation and Development (OECD)—which tend to have economies similar to that of the United States—are most relevant for our purpose. We use De Long and Summers' OECD results from their main sample period, 1960–85.[28] For that sample period, the estimated coefficient on equipment investment in their growth regression implies a nominal net social return (i_{soc}) of 33.5 percent.[29] This return, while not as high as the value of i_{soc} implied by Romer's paper, is still more than two-and-one-half times larger than the baseline estimate of the nominal net return. As shown in table 5, this value of i_{soc} implies a contribution to gross output of 0.25 percentage point a year from 1970 to 1992, while the contribution to net output is 0.16 percentage point annually. These contributions are only about one-tenth of a percentage point higher than our baseline contributions.

Thus, even if one believes that capital goods generate large positive externalities, the growth contribution of computers remains relatively modest. Moreover, we regard the growth contributions derived in this section as generous upper bounds, owing to some skepticism about the externalities yielded by equipment investment. Auerbach, Hassett, and Oliner show that De Long and Summers actually provide no statistically significant evidence of external benefits to equipment investment in the OECD countries. In addition, Romer's recent work emphasizes the external benefits generated by research activity rather than by investment in physical capital.[30] Nonetheless, the results here give a flavor of how large the growth contribution from computers would be if externalities were important.

What If Computers Generate Large Private Returns to Workers and Firms?

Even if computing equipment does not yield substantial external benefits, the private returns from their use could be higher than is implicit in the baseline growth accounting. In other words, computers could yield a private rate of return that exceeds the return earned by other types of

28. De Long and Summers (1992, table 6).

29. The appendix explains how we derive this figure from De Long and Summers' results.

30. See Romer (1994, p. 20), where he states: "My greatest regret is the shift I made while working on these external effects models, a shift that took me away from the emphasis on research and knowledge . . . toward the emphasis on physical capital."

capital. Two recent studies by Brynjolfsson and Hitt and by Frank Lichtenberg provide evidence that computers generate large private returns at the firm level.[31] In addition, Alan Krueger has found that workers who use computers earn a sizable wage premium, presumably because of their enhanced productivity.[32] This section explores the implications of these studies for the effect of computers on aggregate growth. We should note, however, that the studies discussed here represent some of the most favorable views of the growth contribution of computers. As noted in the introduction, much other research has found subpar returns to computer investment.

Brynjolfsson and Hitt estimate standard Cobb-Douglas production functions in which computer capital appears as an input separate from other capital. To estimate the parameters of the production function, Brynjolfsson and Hitt use firm-level data from an annual survey conducted by the International Data Corporation (IDC), covering 1987–91. The 367 firms included in the survey accounted for a sizable share of the U.S. business sector, generating sales of nearly $2 trillion in 1991.[33]

Based on the estimated coefficient on computer capital in the Cobb-Douglas regression, Brynjolfsson and Hitt report a gross return ($i + \delta_C - \dot{p}_C$) of 81 percent for the full sample. Subtracting our estimate of $\delta_C - \dot{p}_C$ from this figure yields a nominal return (i) of nearly 57 percent, several times higher than the baseline return of 12.3 percent. This point estimate raises the possibility of substantial underinvestment in computers during the 1987–91 period, unless firms faced large adjustment or learning costs.[34]

In any case, table 5 reports the growth contributions implied by Brynjolfsson and Hitt's figure. As can be seen, the contributions to the growth of gross and net output over the 1987–91 period are, respectively, 0.35 and 0.27 percentage point annually. Thus, the contributions are still not huge even when we allow for hefty private returns to the use of computers.

31. Brynjolfsson and Hitt (1993) and Lichtenberg (1993).

32. Krueger (1993).

33. Lichtenberg (1993) also analyzes firm-level returns to computers and obtains similar results.

34. Although Brynjolfsson and Hitt's point estimate of the gross return ($i + \delta_C - \dot{p}_C$) differs greatly from our baseline value, their estimate has large standard errors. A 95 percent confidence interval around their gross return estimate of 81 percent ranges from about 40 percent to about 120 percent, which nearly encompasses our baseline estimate of 36.6 percent.

In a very interesting paper, Krueger investigates whether individuals who use computers at work receive a wage premium relative to other workers. Employing data from the Current Population Survey, he found a nominal wage premium of 10 to 15 percent during the latter half of the 1980s. This wage premium can be converted into an estimate of the growth contribution of computers as follows.

Assume a real wage premium of 15 percent, the top of the range estimated by Krueger.[35] In addition, Krueger reports that the proportion of workers using computers at work rose from 24.6 percent in 1984 to 37.4 percent in 1989, an increase of 12.8 percentage points. Thus, we estimate the growing use of computers to have contributed 1.92 percentage points to the change in the average real wage over this period (15 percent multiplied by 0.128), or about 0.38 percentage point a year. Now, suppose that this contribution to the change in the average real wage reflects an equivalent change in labor productivity. And assume that the productivity change "contributed" fully to output growth rather than partly to reductions in employment. Then, the greater use of computers in the workplace contributed 0.38 percentage point a year to the growth of (gross) output between 1984 and 1989.

This contribution is shown in the Krueger estimates of table 5, along with the large 60.5 percent gross rate of return implied by such an annual output contribution. The return net of depreciation, *i*, equals 36.2 percent and generates an annual contribution of 0.23 percentage point to the growth of net output. As was true for the results based on the work of Romer and De Long and Summers, these annual contributions are still relatively small.

Moreover, this simple calculation skews the results toward showing the largest possible contribution from computers. Specifically, we attributed the entire wage premium to the computer itself but ignored the training required by workers to use computers effectively. More realistically, the wage premium reflects both the additional physical capital at the worker's disposal and investments in human capital. Thus, the Krueger estimates shown in table 5 probably overstate the growth contribution from computer capital.

35. Because Krueger estimates the wage premium from a cross-sectional regression, the premium can be interpreted as a real wage premium. In the conclusion of his paper, Krueger also makes a calculation of the growth contribution of computers similar to the one in this paragraph.

What If Computers Generate Unmeasured Output?

As many commentators have pointed out, much of the output of information technology is intangible and difficult to measure. This observation has led some analysts to suggest that, at least in part, the resolution of the computer paradox lies in measurement issues; that is, if one only had better tools for measuring the economy, a more substantial effect of computers on output growth would be evident.[36] In this section, we explore the plausibility of this conjecture.[37]

Suppose that computers generate a substantial amount of unmeasured output. For example, suppose that computing equipment generates enough unmeasured output to boost its net return to 50 percent, or four times larger than the return earned by other assets.[38] This net return is consistent with the Romer estimates in table 5, and, as shown there, implies a gross return to computer capital that is double the baseline gross return. Thus, for every dollar of gross output generated by computers and measured by official procedures, a full dollar of output is assumed to be unmeasured. However, as the Romer estimates show, even adjusting for this amount of undermeasurement will not generate a huge contribution to the growth of gross output. On the input side, computers alone are just too small to account for much of the action.

There is another sense in which the "smallness" of computers limits their impact on the measurement of total GDP. Namely, the *final demand* share of the difficult-to-measure services produced by computers

36. For example, see National Research Council (1994), Griliches (1994), and Brynjolfsson (1993). For an opposing view, see Sichel (1994).

37. The advent and spread of computers likely has generated substantial consumer surplus. For example, many of the convenience benefits of sophisticated airline reservation systems have likely flowed to consumers, as airlines compete with one another. Although consumer surplus might play an important role in welfare analysis, it is difficult to measure and has never been included in official output measures. We do not consider it here.

38. This example focuses on the net return (i) because the other pieces of the growth contribution of computers are unlikely to be affected by undermeasurement of real output growth. In particular, real computer capital is measured independently of real output. Further, the pieces of the income share (depreciation, nominal computer capital, and nominal output) probably would not be affected if real output were undermeasured. Although undermeasurement of real output could reflect missing nominal output, most research has highlighted problems with the price indexes used to translate nominal output to real output.

is also small. Although this point seems to contradict the apparent pervasiveness of computers, Martin Baily and Robert Gordon note that other companies purchase as inputs many of the services produced by computers.[39] These purchased inputs are not directly counted as part of GDP because, to avoid double counting, GDP only includes the value of products at the final stage of production. For example, financial services—excluding insurance—accounted for just 3.3 percent of GDP in 1992, after eliminating double counting.[40] Thus, even if computers have generated a difficult-to-measure explosion in the quality and variety of financial services, this undermeasurement probably does not lead to much understatement of total economic growth.

Moreover, mismeasurement of output growth is not a new phenomenon resulting just from the widespread use of computers. In 1961, the Stigler Committee report, which studied price statistics for the Bureau of the Budget, identified several problems contributing to a worrisome measurement gap at that time, including slow introduction of new products into price index samples and inadequate adjustment for quality change.[41] Of course, back in 1961 the committee was not concerned with computers but rather with relatively new products that were undergoing rapid quality change at that time, including televisions, synthetic fabrics, and drugs. Thus, whatever undermeasurement of output growth is associated with computers, growth of total output may not be any more undermeasured now than in the past.[42]

What about Software and Computer-Services Labor?

So far we have followed the literature by considering only computer hardware. However, we believe that this focus on hardware alone misses important aspects of how computing equipment is actually used. Hardware is never used in isolation. Rather, it must be combined with software and labor inputs to produce computing services. Therefore, to assess computers' contribution to growth, as they are actually used, it is necessary to consider computing services, not just hardware.

39. Baily and Gordon (1988).
40. *Survey of Current Business*, July 1994, p. 64.
41. National Bureau of Economic Research (1961, pp. 23–49).
42. See Nordhaus (1994) for an argument that conventional measures might have substantially understated real output growth over long time spans.

To do this, we extend the basic growth-accounting framework to include software and computer-services labor as inputs. To implement the extended equation, we gather data on software sales and prices, employment in computer-services industries, and budget shares of information systems departments in U.S. companies. As we point out, this extended growth accounting faces many difficult measurement issues; nonetheless, our results provide a rough estimate of the growth contributions of software and computer-services labor. To foreshadow the results, we find that the growth contribution of computing services (defined to include hardware, software, and computer-services labor) averaged 0.4 percentage point annually over 1987–93, about double that of hardware alone.

The basic growth-accounting relationship in equation 3 can be extended in an obvious way to include software and computer-services labor. The term for total labor input, $s_L\dot{L}$, can be split into two parts: a term for computer-services labor, $s_{CL}\dot{L}_{CL}$, and a term for all other labor, $s_L\dot{L} - s_{CL}\dot{L}_{CL}$. In addition, the contribution of software, $s_{CS}\dot{K}_{CS}$, can be added to equation 3.[43] We now proceed to approximate the income shares of software and computer-services labor and the growth rates of these inputs.

Income Shares for Software and Computer-Services Labor

We estimate the income shares from survey data on the budgets of information systems departments of large U.S. companies, reported by Vijay Gurbaxani.[44] He reports data collected by IDC from 1976 to 1984. Over this period, budget shares were fairly stable; the average budget share for hardware was 38 percent, and the average share for software was 28 percent. We attribute the remaining 34 percent to computer-

43. Adding the software term affects the growth-accounting relationship in two ways. First, when the stock of software is counted as a capital asset, investment in software should be counted in output. This would boost the level of nominal output—which would slightly reduce the income shares of all other inputs—and could have a minor impact on the growth rate of real output. Second, the estimated return to all other types of capital would be slightly affected because there is one more capital asset. Because these adjustments would have very small effects, we ignore them for the sake of expository clarity.

44. Gurbaxani (1990, pp. 63–66). Implicitly, we are assuming that budget shares equal income shares.

services labor.[45] These shares suggest that hardware accounts for only a bit more than one-third of total computing expenses at large companies.

A shred of more recent evidence provides a check on the software budget share. The Gartner Group estimates that total software sales were $31.0 billion in 1992.[46] In the same year, nominal investment in CPE was $36.5 billion. These figures imply that software purchases were 85 percent of hardware expenditures, while Gurbaxani's budget shares imply a figure of 74 percent (=0.28/0.38). These two estimates are reasonably close to each other and confirm the importance of nonhardware inputs.

Income shares for software and computer-services labor are computed by scaling the 1 percent income share of hardware estimated previously in this paper with these budget shares. (We round the 0.9 percent income share for computing equipment for 1980–92 from table 3.) This calculation implies an income share for software of about 0.74 percent and an income share for computer-services labor of about 0.89 percent.[47] As a check on the income share for computer-services labor, we compare it with Brynjolfsson and Hitt's estimate of this share for 1991. Using data from a more recent IDC survey of large U.S. firms, these authors report that labor costs in information systems departments accounted for 0.7 percent of gross output, similar to the share implied by Gurbaxani's data.

Growth of Nominal Software Purchases

We obtained nominal sales data for the software used on personal computers from the Software Publishers Association (SPA).[48] These data extend from 1987 to 1993, covering word processing software, spreadsheets, data base programs, and all other applications sold at retail.[49] Table 6 summarizes the data. As can be seen in the lower panel,

45. This estimate for computer-services labor is an overestimate because some other small budget items (for which we do not have detail) are lumped into the labor share.

46. Unpublished data from the Gartner Group in Stamford, Connecticut.

47. The software budget share is calculated as (0.28/0.38) times 1 percent and the share of computer-services labor is calculated as (0.34/0.38) times 1 percent.

48. Figures are published quarterly by the SPA in a press release.

49. In addition to sales at retail outlets, these figures include purchases of software directly from the publisher. Also, these figures include software sold through licensing agreements with hardware manufacturers. The figures exclude operating systems like DOS and Windows.

Table 6. Nominal Sales of PC Applications Software, 1987–93

Measure and year	*Total*	*Word processors*	*Spreadsheets*	*Data bases*
Millions of dollars				
1987	2,313.0	339.3	344.7	207.2
1988	3,247.5	499.5	442.9	337.7
1989	3,633.9	686.3	571.4	318.0
1990	4,585.8	917.9	703.1	345.0
1991[a] (old basis)	5,713.2	1,136.0	946.7	396.8
1991[a] (new basis)	5,063.6	812.4	739.1	309.7
1992	5,745.4	829.5	795.3	348.5
1993	6,809.6	1,021.6	801.2	475.5
Annual log differences (×100)				
1987–88	33.9	38.7	25.1	48.8
1988–89	11.2	31.8	25.5	−6.0
1989–90	23.3	29.1	20.5	8.2
1990–91	22.0	21.3	30.0	14.0
1991–92	13.2	2.1	7.3	11.8
1992–93	17.0	20.8	0.7	31.1
Average growth, 1987–93	20.1	24.0	18.2	18.0

Source: Software Publishers Association (SPA).
a. In 1991, the SPA revamped their data procedures, yielding two sets of figures for that year. The figures labeled "new basis" are comparable to the later figures, while the "old basis" figures are comparable to the earlier data. Total includes miscellaneous PC applications software not shown in the table.

sales of these software applications have grown rapidly since the late 1980s. Aggregating over all PC applications software, the growth of nominal sales averaged 20.1 percent annually from 1987 through 1993.[50]

We use this figure as an estimate of nominal growth in total software purchases because it is difficult to obtain solid data over time for the rest of the software market. This market also includes PC operating systems, all software for mainframes and workstations, along with software developed by users in-house. Thus, we implicitly assume that the growth rate of the excluded categories equals that of PC applications software. In fact, purchases of mainframe software probably grew more slowly than purchases of PC software over this period, as PCs continued to displace larger computing platforms. Accordingly, our estimate of the growth in total software sales likely is biased upward.

50. Data from the Software Publishers Association for earlier years, which are not directly comparable to the later data, imply an average annual growth rate of consumer software sales of 29.0 percent between 1984 and 1988.

Growth of Real Software Purchases

To convert the growth of software purchases from nominal to real terms, price indexes for software are required. Although there is an extensive literature on quality-adjusted prices for computer hardware, little work has been done on software prices. We know of three studies that estimate price indexes for PC software.[51] Brynjolfsson and Chris Kemerer as well as Neil Gandal derive hedonic price indexes for spreadsheets, while in a previous paper we developed matched-model indexes for spreadsheets, word processors, and data base programs. Also, some earlier studies estimated the cost per line of software code written for larger computing platforms.[52]

For this paper, we use our matched-model indexes to convert the nominal software sales to real terms. These indexes control for quality indirectly, by estimating price changes from only those software models, or versions, whose quality did not change. The adequacy of the quality adjustment depends on the degree to which the market for quality is in equilibrium. If equilibrium prevails, the introduction of a new model or version with a better price-quality trade-off will push down the prices of existing models to equalize quality-adjusted prices. In this situation, a matched-model index will correctly capture the change in quality-adjusted prices. Because the required market equilibrium may not prevail, matched-model indexes have been criticized for failing to fully adjust for changes in quality.[53] Nevertheless, we choose the matched-model indexes because they provide the widest coverage across different software applications. Hedonic indexes—which require the identification of quantifiable characteristics for each product—are difficult to implement for complex and hard-to-describe products like software.

To develop matched-model indexes, we assembled new data on the prices of PC applications software for IBM-compatible machines, covering word processing, spreadsheet, and data base programs. Our quarterly sample ran from 1985:1 through 1993:4, with prices pulled from advertisements in computing magazines, including *PC Magazine*, *Personal Computing*, and *PC World*.[54]

51. Brynjolfsson and Kemerer (1993), Gandal (1994), and Oliner and Sichel (1994).

52. See Gurbaxani (1990, chap. 2) for a discussion of many of the earlier studies.

53. For example, see Dulberger (1989).

54. The panel for word processors included 487 price quotes, while the panels for spreadsheets and data base programs included 352 and 514 quotes, respectively. For each application, we had observations for many distinct models and versions.

Table 7. Matched-Model Price Changes for PC Applications Software, 1985–93[a]
Annual log differences (×100)

Year	*Total*	*Word processors*	*Spreadsheets*	*Data bases*
1985–86	...	−11.4	−9.9	−11.3
1986–87	−2.0	−2.7	−1.9	−1.0
1987–88	−1.5	−0.4	−1.5	−3.0
1988–89	−2.1	3.4	−7.5	−4.2
1989–90	−3.7	−1.3	−4.4	−8.8
1990–91	−1.6	−1.9	2.5	−10.5
1991–92	−6.5	−6.4	−9.1	−1.0
1992–93	−0.8	0.1	−4.0	2.6
Average, 1985–93	...	−2.6	−4.5	−4.7
Average, 1987–93	−2.7	−1.1	−4.0	−4.2

Source: Oliner and Sichel (1994).
a. The index for the total is a weighted average of the last three columns using the weights implicit in the nominal sales figures shown in table 6. Weights are not available for 1985–86.

Table 7 displays the annual rate of change in the resulting matched-model index for each type of software. As shown, quality-adjusted prices of word processing programs are estimated to have fallen at an average annual rate of 2.6 percent between 1985 and 1993. For spreadsheet and data base programs, the estimated average annual decline in quality-adjusted prices was somewhat more rapid—4.5 percent and 4.7 percent, respectively.[55] These declines in software prices are much slower than those implicit in BEA's deflators for computer hardware.

These results are similar to those obtained in some earlier studies of software prices. For example, Gurbaxani—after surveying the literature—adopted an estimate of 5 percent for the annual drop in the cost of software development.[56] Also, our matched-model results for spreadsheets are similar to those obtained by Brynjolfsson and Kemerer using hedonic techniques.[57] Their study estimates that quality-adjusted prices

55. Our results may understate the pace of decline in the most recent years. We have not included prices of upgrades, products purchased in software "suites," or products bundled with hardware. These alternative sales channels—which have recently become more widespread—likely represent an effective price decline for particular applications. However, such a bias would only appear during the transition from a period when most sales were for new stand-alone products to a period when most purchases were through these other channels.

56. Gurbaxani (1990).

57. Brynjolfsson and Kemerer (1993).

Table 8. Growth of Real Sales of PC Applications Software, 1987–93
Annual log differences ($\times 100$)

Year	*Total*	*Word processors*	*Spreadsheets*	*Data bases*
1987–88	35.4	39.1	26.6	51.8
1988–89	13.3	28.4	33.0	−1.8
1989–90	27.0	30.3	24.9	17.0
1990–91	23.6	23.2	27.5	24.5
1991–92	19.7	8.5	16.4	12.8
1992–93	17.8	20.7	4.7	28.5
Average growth, 1987–93	22.8	25.0	22.2	22.1

Source: Real growth equals nominal growth from table 6 minus the change in the deflator from table 7.

of spreadsheets fell at an average annual rate of 2.8 percent between 1987 and 1992.[58] By contrast, Gandal estimates that quality-adjusted prices for spreadsheets fell considerably faster—about 15 percent a year between 1986 and 1991.[59] The large discrepancy between these two studies for spreadsheets indicates that the application of hedonic techniques to software may be problematic.

With the matched-model price indexes and the nominal sales figures, we compute rates of change in the real sales of PC software, as reported in table 8. As the first column shows, we estimate that total real sales grew at an average annual pace of 22.8 percent a year from 1987 to 1993.[60]

Growth of the Real Capital Stock of Software

The growth rates calculated above from the SPA figures are for new purchases of software, not for the stock of software in service. Using a steady-state assumption, however, we can obtain an estimate of the growth of this real stock. Under the perpetual inventory method with

58. These authors report an annual decline of 6.7 percent in real terms (page 17). To convert this figure to nominal terms, the average annual increase in the GDP deflator—which was 3.9 percent over that period—must be added. Thus, the nominal price decline was 2.8 percent annually over that period.

59. Gandal (1994). He has kindly provided us with his data, and we hope to uncover the source of the rapid price declines that he reports.

60. The deflator for the total is obtained by weighting the price changes for each application by its share in the nominal sales of all three applications.

geometric depreciation at rate δ, the stock of an asset equals a weighted average of past purchases, where the weights equal unity on current-period purchases, $1 - \delta$ on the previous period, $(1 - \delta)^2$ on purchases two periods previous, and so on. If purchases grow at a constant rate, the growth of this capital stock equals the growth rate of purchases. Table 8 shows that the growth of total software purchases has not been literally constant over time. However, for our purposes, little is lost by assuming that real software purchases have grown at a constant annual rate of 22.8 percent. Therefore, we use this growth rate as an estimate of the growth in the real stock of software.

Measuring the Growth of Computer-Services Labor

Calculating the growth rate of computer-services labor is simple, in principle, but can entail serious measurement problems. Quantifying the growth of total labor input used to create computer services is difficult because much of this labor represents work done by end users rather than by computer specialists. Also, adjusting for changes in the quality of computer-services labor is difficult. Despite these problems, we estimate the growth of computer-services labor from data on employment in computer and data-processing services, as reported by the BLS.[61] From 1987 to 1993, employment in these industries grew at a hefty 6 percent annual rate, well above the 1¼ percent growth for private employment as a whole. Although this series misses important pieces of computer-services employment, we rely only on its growth rate, implicitly assuming that the excluded pieces grew at the same rate.[62]

Growth Contributions of Software and Computer-Services Labor

Using the pieces estimated above, we now calculate the contribution of computing services, including software and computer-services labor,

61. Bureau of Labor Statistics, *Employment and Earnings*, establishment survey data from various issues.

62. Employment growth in these industries from 1987 to 1993 could be a biased estimate of growth in actual computer-services labor. As outsourcing spreads and more companies purchase computer services from outside vendors, employment counted in the computer-services industry will be boosted by the shift of employees from other industries, even if the employees did the same job in both industries.

Table 9. Contributions of Computing Services to Growth in Real Gross Output of Private Nonfarm Business, 1987–93

Units as indicated

Measure and category	*1987–93*
Contributions from[a]	
Computing services	0.40
Hardware	0.19
Software	0.16
Labor	0.05
Income shares[b]	
Hardware	1.0
Software	0.7
Labor	0.9
Growth of inputs[c]	
Hardware	18.8
Software	22.8
Labor	6.0

Source: Authors' calculations as described in the text.
a. Percentage point per year.
b. Percent.
c. Average annual log difference multiplied by 100.

to gross output. In terms of the notation described earlier, we need estimates of the income shares for hardware, software, and computer-services labor (s_C, s_{CS}, and s_{CL}) and the growth rates for each input ($\dot{K}_C$, $\dot{K}_{CS}$, and $\dot{L}_{CL}$). Estimates for these pieces—averaged from 1987 to 1993—are collected in table 9.[63] This table also shows the contribution to gross output of each of these inputs and the total contribution of computing services. As the table shows, the total contribution is 0.40 percentage point a year over the period.[64] This figure is about double the contribution of hardware alone, with software making up the bulk of the difference. Thus, broadening the focus to computing services by including software and computer-services labor helps to resolve the computer paradox.

63. The BLS data for multifactor productivity, which we used to calculate the nominal rate of return to capital (i), extend only to 1992. We assume that the value of i in 1993 equaled its value in 1992, 13.4 percent.

64. The contribution of computing services to net output would be notably smaller. We do not calculate this figure because we have no independent information on depreciation rates for software.

What about Other Information Processing Equipment?

In the preceding section, we expanded the scope of our growth accounting to include software and computer-services labor, rather than simply computer hardware. This section widens our inquiry in another direction by examining the growth contribution of all information processing equipment. Although most of the literature has focused on computers, the information revolution has affected a broad range of other equipment, especially communications equipment.

As indicated in table 2, BEA's category of information processing equipment accounted for nearly 12 percent of the nominal net stock of nonresidential equipment and structures in 1993; this share is about six times larger than that of computers and peripherals alone. Put another way, computers accounted for about 17 percent of the nominal net stock of information processing equipment. In 1992, according to BEA data, communications gear represented about 58 percent, scientific instruments 17 percent, and photocopying and assorted other office equipment the remaining 8 percent.

We calculate the growth contribution of each type of information processing equipment in the same way that we calculated the baseline contributions of computers in table 3. In particular, we assume that information processing equipment earns the same nominal return, i, as all other nonresidential fixed capital.[65] This return could have been set higher, as with the supernormal returns to computers discussed earlier. However, the argument for supernormal returns appears weaker here than for computers. For an aggregate as broad as information processing equipment, it becomes increasingly difficult to believe that various frictions prevent firms from investing sufficiently to drive down the returns to those earned by other assets.

Under the baseline assumptions, the top panel of table 10 shows that information processing equipment contributed 0.31 percentage point annually to output growth over the period from 1970 to 1992, about double that of computers. Thus, even though computers represent only one-sixth of the stock of information processing equipment, they account for

65. In addition, the depreciation rate and capital gain (loss) for each asset are calculated from BEA data.

Table 10. Contributions of Information Processing Equipment to Growth in Real Gross Output of Private Nonfarm Business, 1970–92

Units as indicated

	1970–92	*1970–79*	*1980–92*
Contributions from[a]			
Information processing equipment	0.31	0.25	0.35
Computer and peripheral equipment	0.16	0.09	0.21
Communications equipment	0.09	0.07	0.10
Other information processing equipment[b]	0.06	0.09	0.04
Income shares[c]			
Information processing equipment	2.7	2.1	3.5
Computer and peripheral equipment	0.6	0.3	0.9
Communications equipment	1.3	1.0	1.6
Other information processing equipment[b]	0.8	0.8	1.0
Growth rate of inputs[d]			
Information processing equipment	11.6	11.5	11.4
Computer and peripheral equipment	27.6	27.8	27.4
Communications equipment	7.1	7.3	6.9
Other information processing equipment[b]	6.8	10.5	4.3
Memo:[a]			
Contribution of information processing equipment plus computer software and labor, 1987–92	...	...	0.50
Information processing equipment other than computers	...	...	0.10
Computer hardware	...	...	0.19
Computer software[e]	...	...	0.16
Computer-services labor[e]	...	...	0.05

Source: Authors' calculations as described in the text.

a. Percentage point per year.

b. Includes photocopy equipment, scientific instruments, and office, computing, and accounting equipment other than computers and peripherals.

c. Percent.

d. Average annual log difference multiplied by 100.

e. Contributions for software and labor are for period 1987–93, as shown in table 9.

about half of its growth contribution. This pattern occurs because, as shown in the lower part of the table, BEA estimates that the real capital-input stock of computers has grown far more rapidly than that of other information processing equipment. Therefore, expanding the universe to information processing equipment, by itself, does not greatly increase growth contributions if official BEA data are used.

The BEA data, however, may be problematic for some categories of equipment. Although the hedonic price index for computers captures quality change reasonably well, the deflators for other assets, especially that for communications equipment, likely miss a substantial portion of quality change. Quality-adjusted prices for communications equipment may well have declined substantially between 1970 and 1992, rather than increasing at an annual rate of more than 3½ percent, as reported by BEA.[66] Suppose prices of communications equipment fell enough to double the growth rate of the real capital-input stock of this equipment. Although this adjustment would double the growth contribution of communications gear, it would boost the contribution of information processing equipment by only about 0.1 percentage point.

Thus, including all information processing equipment could add a few tenths to the annual growth contribution of computer and peripheral equipment alone. Previously, we showed that bringing in software and computer-services labor also boosts the contribution by a couple of tenths. The memo item in table 10 shows the combined effect of adding these items. As shown, the contribution to output growth is now up to 0.5 percentage point a year during 1987–92, a sizable figure. To get the contribution up to this level, however, we had to move well beyond the typical focus on computer hardware.

Have Computers Caused a Surge in Growth? Will They?

Thus far, we have examined the computer paradox from a variety of perspectives, including an assessment of the contributions that software and computer-services labor make to economic growth. We now assess the recent contribution of computers to growth as well as their likely future contribution.

66. Flamm (1989) argues that, at least through the mid-1980s, prices for communications equipment did not decline nearly as fast as those for computers. In fact, using data from Flamm's study, Gordon (1990, pp. 401–403) reports average annual price declines for communications equipment of only 1 percent from 1965 to 1984. Although more rapid declines were reported for periods before 1965, all of Gordon's figures show a much slower decline than for computer prices. Flamm raises the possibility that the breakup of AT&T may have led to faster price declines. Anecdotal evidence, cited in the July 25, 1994, issue of *Business Week*, provides support for a more rapid drop in prices in recent years (pp. 68–70).

How Large Was the Contribution in 1992 and 1993?

The argument is often made—as summarized in the *Business Week* story quoted at the start of this paper—that computers could be behind the stronger productivity growth noted in recent years. However, a close look at the growth contributions of computing services in 1992 and 1993 casts doubt on this argument. Assume, as before, that hardware and software earn the same nominal return as other capital. Then, following the baseline procedures developed in this paper, we estimate that in 1992 and 1993 computing services contributed an average of 0.35 percentage point a year to growth in gross output, a contribution that is actually a touch smaller than the average contribution from 1987 to 1993 shown in table 9. These results undermine the argument that the country is in the midst of a computer-generated pickup in productivity growth.

Moreover, as noted earlier, Robert Gordon has argued that recent improvements in productivity growth likely reflect cyclical dynamics rather than a shift in the underlying trend.[67] According to his view, there has been no surge in trend productivity to be explained by computers or any other special factor.

Baseline Projections

With the framework developed in this paper, we project the effect of computing services on growth through 2003 under a variety of scenarios. We start with projections for three scenarios—pessimistic, midrange, and optimistic—that parallel the baseline results for computing services, in which hardware and software earn the same net return as other capital. Later, we consider the possibility that returns to computer hardware and software rise rapidly in coming years, as revolutionary applications are developed and widely adopted. Although we focus on contributions to the growth of gross output, remember that contributions to net output would be substantially smaller because so much of the gross return to hardware and software would be eroded up by depreciation.

To keep things simple, we begin by describing how contributions of computer hardware are projected for each scenario and then explain the

67. Gordon (1993).

Table 11. Forecast Assumptions for the Growth Contribution of Computing Services, 1994–2003

Average annual log differences ($\times 100$)

	Pessimistic (average growth rate for 1988–93)	*Midrange (average growth rate for 1984–93)*	*Optimistic (1993 growth rate)*
Nominal net CPE stock	2.2	6.5	7.5
Nominal output in private nonfarm business	4.8	5.6	5.4
Real CPE capital-input stock	17.2	20.9	24.4
Real software input	20.3	24.7	28.8
Computer-services labor input	5.8	7.1	7.7

Source: Authors' calculations as described in the text.

extensions required to include software and computer-services labor. As the growth-accounting relationship in equation 3 makes clear, forecasting the contribution of hardware requires projections of the growth rate of the real stock of computer hardware ($\dot{K}_C$) and its income share (s_C). Projecting the income share requires assumptions about the future paths of nominal income (PY), the nominal stock of computer capital ($p_C K_C$), and the elements of the gross rate of return ($i + \delta_C - \dot{p}_C$).

For the baseline projections, the pieces of the gross rate of return are fixed across scenarios at their 1992 values: i equals 0.134, and $\delta_C - \dot{p}_C$ equals 0.243. Forecast assumptions for the other key variables—the real capital-input stock of CPE, the nominal net stock of CPE, and nominal output—are shown in table 11. For a pessimistic scenario, we assume that each of these three variables grows at its average rate over the five years 1988–93, which includes the 1990–91 recession. In this scenario, the real capital-input stock of CPE grows at slightly more than 17 percent a year. The midrange scenario, based on average growth rates over the nine years from 1984 to 1993, assumes that the real CPE stock rises at nearly 21 percent a year. Finally, the optimistic scenario—based on the robust growth rates of 1993—posits that this stock increases at an annual rate exceeding 24 percent.

In order to add in software and computer-services labor, projections are needed for the growth of these inputs ($\dot{K}_{CS}$ and $\dot{L}_{CL}$) and their income shares (s_{CS} and s_{CL}). Income shares for software and computer-services labor are obtained by scaling the projected income share for hardware in

Table 12. Projected Contributions of Computing Services to Growth and Projected Income Shares[a]
Units as indicated

	1993 actual	*2003*			
		Pessimistic	*Midrange*	*Optimistic*	*Takeoff*
Contributions from[b]					
Computing services	0.39	0.27	0.44	0.56	0.99
Hardware	0.21	0.13	0.20	0.26	0.49
Software	0.11	0.11	0.18	0.23	0.42
Labor	0.06	0.04	0.06	0.07	0.07
Income shares[c]					
Computing services	2.3	1.9	2.6	2.8	4.6
Hardware	0.9	0.7	1.0	1.1	2.1
Software	0.6	0.5	0.7	0.8	1.5
Labor	0.8	0.6	0.9	0.9	0.9

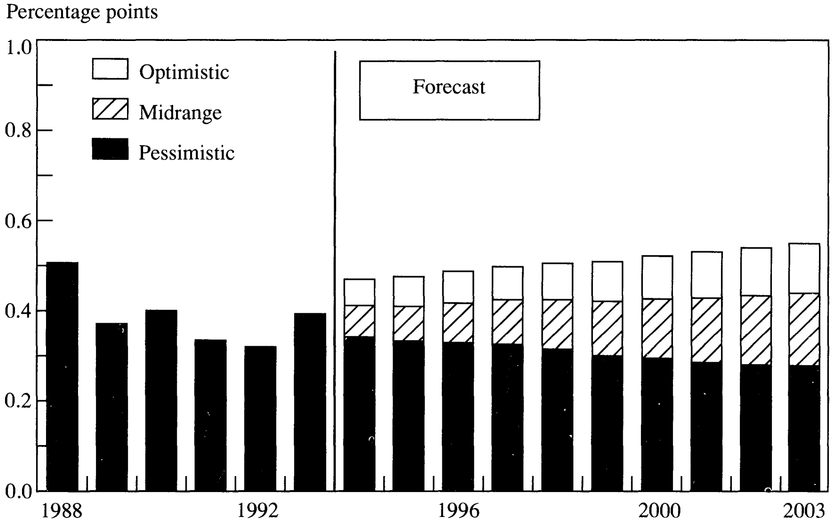
Source: Authors' calculations as described in the text.
a. Computing services include computer hardware (CPE), software, and computer-services labor.
b. Percentage point per year.
c. Percent.

each of the three scenarios by 0.7 and 0.9, respectively, the same scaling factors used to compute these income shares above. As for input growth rates, the labor input for each scenario is projected to increase by its average rate over the respective period. For growth of the real software input, a slightly different procedure is used to ensure the correct ranking of scenarios.[68]

Projections of the gross contribution under each scenario are shown in table 12 and summarized in figure 3. As can be seen in figure 3, the midrange scenario—based on average growth rates over 1984–93—yields a contribution of computing services to growth in 2003 of 0.44 percentage point. This figure is barely higher than the contribution in 1993. Under the optimistic scenario, the contribution of computing services rises, but not very fast, moving up to 0.56 percentage point by 2003. Under the pessimistic scenario, the gross contribution to growth falls to just 0.27 percentage point.

68. For the pessimistic scenario, the growth of real software input is set equal to its average over the past five years, analogous to the procedure for hardware. For the midrange scenario, the growth of real software input is set so that the ratio of midrange to pessimistic growth rates for software equals that ratio for hardware. A parallel procedure was used to set the growth of real software input for the optimistic scenario.

Figure 3. Contributions of Computing Services to Growth in Real Gross Output, 1988–2003



Source: Authors' calculations as described in the text.

The main message of these baseline projections is that—even with very rapid growth of hardware, software, and labor inputs—the contribution of computing services to growth is unlikely to increase appreciably over the next ten years. This reason is simple. As long as computer hardware and software earn the same net return as other capital, the nominal income share of computing services remains modest, reaching only 2.8 percent by 2003 even in the optimistic scenario.

What If the Best Is Yet to Come?

These projections are based on the assumption that computer hardware and software continue to earn the same net rate of return as other assets. What if these neoclassical assumptions are wrong in a fundamental way?

Paul David, among others, has suggested that the big productivity gains from information technology are still to come.[69] He argues that radically new technologies diffuse gradually, in part because it may not

69. David (1989, 1990).

be profitable or possible to scrap the old technology immediately. Moreover, truly revolutionary applications often require major reorganizations of production, which take a long time to discover. David loosely suggests that the largest productivity gains from a new technology—and hence its most sizable rates of return—occur after the technology has diffused substantially throughout the economy.

David makes this argument vivid by looking back at the spread of electric motors. He notes that the main discoveries making commercial application of electricity feasible occurred between 1856 and 1880. Yet, early applications—such as replacement of a large steam-power unit—generated only modest savings through reduced power costs. Gradually, electric power spread, so that by 1919 electricity accounted for 50 percent of the mechanical-drive power in manufacturing. And it was in the following decade that productivity growth picked up sharply, as firms learned to reorganize production and material handling to fully exploit the new paradigm.[70] Thus, only after the 50 percent diffusion mark were the largest productivity gains seen.

In a casual sense, this story seems readily applicable to computers. For computers, the externalities and learning-by-doing described by Romer and by De Long and Summers might not generate visible payoffs for the aggregate economy for a long time. For example, telecommuting, mobile offices, and "virtual" work places only now appear to be catching on. Some observers have suggested that these developments could radically reduce the need for office buildings, highways, and other physical infrastructure. Further, the explosion of computer networks, linking more and more employees within and across businesses, could generate substantial benefits through the low cost of acquiring and sharing large amounts of information. Other revolutionary applications of information technology may remain to be discovered. The key question, of course, is what rate of return will these activities earn?

Whatever the answer to this question, David's story raises the possibility that we as a society are on the cusp of an upsurge in productivity. While the timing of such an upturn would be difficult to predict, one piece of evidence suggests that computers may be near the 50 percent diffusion point highlighted by David. Krueger estimates that about 37 percent of workers used computers on the job in 1989.[71] Lawrence Katz

70. David (1989, tables 2 and 3).

71. Krueger (1993).

and Krueger report that by 1993 this share had risen to 47 percent, implying that computer use had spread to nearly half of all workers.[72]

To capture these ideas in a projection, we assume that the nominal net return earned by computer hardware and software rises rapidly over the next decade. This assumption fits with David's suggestion that supernormal returns are earned only after diffusion approaches the 50 percent mark, which Katz and Krueger's figures imply the United States has roughly hit. We assume that this return rises linearly from 13.4 percent in 1993 (the net return assumed for all other nonresidential equipment and structures) to 49 percent by 2003, which corresponds to the Romer estimate in table 5.[73] For all the other variables needed to calculate contributions to growth, we retain the values in the optimistic scenario described above.

As shown in figure 4 and table 12, in the scenario labeled "takeoff," the contribution of computing services to gross output growth rises from 0.39 percentage point in 1993 to nearly 1 percentage point in 2003.[74] This is a very notable pickup. But we doubt that the takeoff scenario has begun to unfold. Specifically, if the returns to computing equipment really have jumped, we should have observed a speedup in the trend growth of the computer capital stock. As figure 1 shows, however, the growth rate of the computer stock has not been especially rapid in recent years. This simple observation suggests that David's scenario remains theoretical.

Whatever its plausibility, this projection does point to developments in micro and macro data that should emerge in coming years if a computer-generated pickup in productivity gets under way. First, in case studies and micro data, one should see evidence of more truly revolutionary applications adopted on a wide scale. Additional investments in computers for routine applications are unlikely to yield sufficient returns to generate a large contribution to growth. Second, on the macro side,

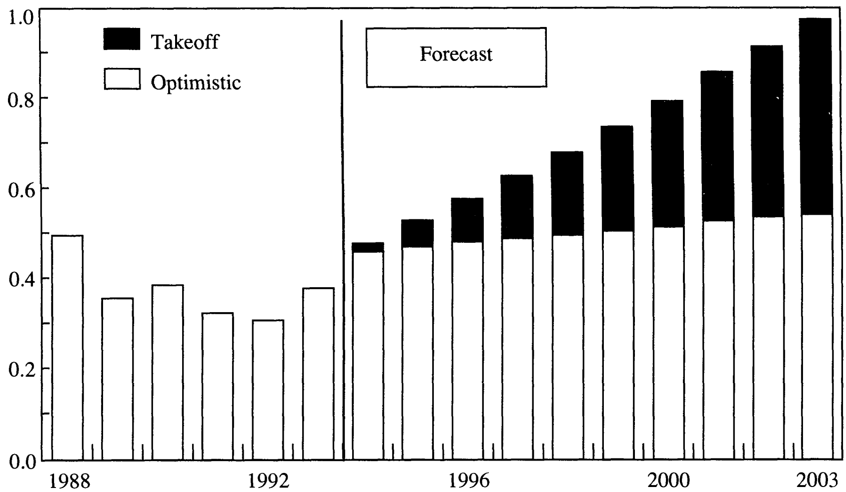
72. Katz and Krueger (1994).

73. This assumption implies that the income share of hardware and software rises rapidly through 2003. The share of computer-services labor, however, is not changed from the optimistic scenario. Implicitly, we assume that real wages and average labor productivity for these workers grow at roughly the same rate, preventing any dramatic movement in this income share.

74. We should note, however, that any supernormal returns to computers likely would be transitory. After some time, continued investment in hardware and software by profit-maximizing firms would be expected to drive the net return back down to that earned on other assets and to reduce the growth contribution.

Figure 4. Contributions of Computing Services to Growth in Real Gross Output, 1988–2003

Percentage points



Source: Authors' calculations as described in the text.

one should see much faster growth in the stock of computing equipment, as firms respond to profit opportunities opened up by these new applications.

Conclusion

This paper revisits the question, how much could computing equipment plausibly have contributed to economic growth since 1970, and what are the prospects looking ahead? To answer these questions, we used Denison-style growth accounting to estimate baseline contributions of computer hardware to output growth. The remainder of the paper then examined reasons why this baseline might understate the growth contribution of computer hardware.

This analysis generated three main results. First, under the assumptions used for the baseline growth accounting, the contribution of computer hardware to growth in gross output was small between 1970 and 1992. And computers contributed very little to the growth of net output because depreciation erodes much of the gross return to computers. These qualitative results stand even when computers earn supernormal returns of the magnitude suggested by several recent studies. Also, the qualitative results hold up even if computers were to generate substantial amounts of unmeasured output.

This evidence suggests that the puzzle about computer hardware in the 1980s was more apparent than real. To restate Solow's quip, computers were not in the productivity statistics because, it turns out, computers were not everywhere. Recall that in 1993 computer and peripheral equipment accounted for just 2 percent of the nominal net stock of business capital in the United States. By way of historical comparison, in 1890 railroads accounted for about 18 percent of this stock.[75] Clearly, computers have a long way to go before they become as widespread as railroads in the nineteenth century.

The second main result is that other important inputs, apart from computer hardware, should be taken into account, including computer software and labor inputs. Although somewhat rough, our estimates suggest that adding in software and computer-services labor approximately doubles the contribution of hardware. Moreover, because the information revolution encompasses more than just computers, a primary emphasis on computer hardware skips over the important role played by communications and other information processing equipment.

The third main result is that computers probably have not been behind whatever pickup in aggregate productivity may have occurred in recent years. And in the future, continued rapid growth in the stock of computer hardware and software probably will not generate a substantial upturn in computing services' contribution to output growth, unless there is a dramatic surge in the rate of return earned by computers. Accordingly, some observers may have unrealistic expectations for computers in the 1990s.

As a final point, our results suggest that earlier explanations of the computer paradox are not needed to explain this puzzle in aggregate data. Basically, three alternative explanations have been advanced.[76]

75. This share can be computed from data in Gallman (1986) and Fishlow (1966). Personal correspondence with Robert Gallman suggests a somewhat lower capital stock share.

76. For detailed discussions of alternative explanations, see Baily and Gordon (1988), Brynjolfsson (1993), and National Research Council (1994).

The first is that computing equipment was not used effectively, implying a subpar return. However, we demonstrate that the contribution of computing equipment to aggregate growth would still be modest even if this equipment earned a normal or supernormal return. The second explanation is that the new technology was used effectively but that an outdated system of national accounts failed to measure much of the additional output produced.[77] This explanation may well be important for certain products or industries. Nonetheless, our results imply that, even if computers generate a substantial amount of output that is not measured, accounting for this output does not greatly increase the growth contribution. The third explanation for the 1980s experience—put forward by David—is that the gains from new technologies just take a long time to be realized. In this view, the 1980s were an early phase of the computer revolution, with the most productive uses of computers still to come. While this story probably contains some truth, it still remains to be seen how large an effect will develop. Furthermore, there is little evidence to date of a computer-related surge in aggregate productivity.

APPENDIX

Calculating Capital Stocks and Rates of Return

THIS APPENDIX provides details concerning the calculation of selected capital stocks and rates of return mentioned in the text.

Capital Stocks

The Bureau of Economic Analysis has published real and nominal investment data for CPE back to 1982.[78] Earlier data are unpublished but available back to 1959. We construct the capital-input stock, the net capital stock, and the gross stock for CPE—both real and nominal figures—in exactly the manner used by BEA to construct stocks for OCA. For example, to get real OCA capital input, BEA takes a weighted average of current and past real gross investment, with the weights reflecting the

77. See Griliches (1992, 1994).
78. U.S. Bureau of Economic Analysis (1992, 1993).

decay path of OCA over time. For real OCA net and gross stocks, BEA uses the same procedure with different weights. To construct stocks for CPE, we use the weights used by BEA for OCA. These weights can be obtained from BEA or from the authors. Analogous to BEA procedures, nominal CPE stocks are constructed by applying the CPE deflator to the real series.

The stocks for CPE have the virtue of focusing just on computers. However, because BEA does not publish the investment data for CPE prior to 1982, questions have been raised about the quality of the earlier data. More specifically, from the early 1970s forward, the investment data for CPE are of reasonably high quality because there is sufficient detail on manufacturers' shipments of OCA to break out CPE. Prior to 1972, however, the shipments data are more highly aggregated and the decomposition into CPE is more subjective. BEA actually tapers the CPE investment series down to zero in 1958, a year in which computers were clearly used in the business sector. Although these lower-quality investment data are potentially problematic, their influence on capital stocks quickly wanes after 1972 for two reasons. First, computers have short service lives. Thus, just a few years beyond 1972, the earlier vintages already have a low weight in the capital stock. Second, investment in CPE grows rapidly, implying that newer vintages are a much bigger portion of the capital stock than earlier, more problematic, vintages.

Baseline Net Rate of Return

The net return, i, solves the following equation for the nominal income share of nonresidential equipment and structures, s_{ES}, in the private nonfarm business sector:

$$\text{(A1)} \quad s_{ES} = [(i + \delta_C - \dot{p}_C)p_C K_C + (i + \delta_{OES} - \dot{p}_{OES})p_{OES}K_{OES}]/PY,$$

where the subscript OES refers to equipment and structures other than computers. Because we are measuring rates of return, net capital stocks—which measure the market value of existing assets—are used. Using the series for s_{ES} published by BLS, we solve the equation for i on a year-by-year basis from 1970 to 1992, conditional on estimates of all other variables. This method of imputing i forces the nominal net rate of return on computers to equal that for other fixed capital.

De Long and Summers' Nominal Net Return

To derive the estimate of the nominal return to capital implicit in De Long and Summers' work, we begin with the regression results for OECD countries shown in table 6 of De Long and Summers' 1992 paper. As shown in that table, a 1 percentage point increase in the ratio of real equipment investment to real GDP over 1960–85 would boost the average annual growth rate of real GDP by 0.151 percentage point over the period. Let β_E denote the effect of this ratio on GDP growth.

Auerbach, Hassett, and Oliner derived the relationship between i and β_E in a standard neoclassical growth model, which enables us to extract the value of i implied by $\beta_E = 0.151$.[79] As shown in equation 2 of Auerbach, Hassett, and Oliner,

$$\beta_E = [(1 - e^{-\lambda t})/\lambda t][i - \dot{p}_E + \delta_E], \tag{A2}$$

where t denotes the length of the sample period (25 years in this case), $\dot{p}_E$ is the annual rate of increase in equipment prices, δ_E is the annual rate of depreciation for equipment, and λ is a parameter that depends on the income share of equipment and structures, the growth rate of labor input, and δ_E. The notation in equation A2 matches that in Auerbach, Hassett, and Oliner, except that r has been replaced by $i - \dot{p}_E$.

Given values for λ, $\dot{p}_E$, and δ_E, we solve the equation for i as a function of β_E. The specific values we use for λ, $\dot{p}_E$, and δ_E are based on BEA and BLS data and can be obtained from the authors on request. With these values, if β_E equals 0.151, it implies that i equals 0.335, the value shown in table 5.

79. Auerbach, Hassett, and Oliner (1994).

Comments and Discussion

Jack E. Triplett: The Solow paradox—"You can see the computer age everywhere but in the productivity statistics"—provides the program for this research as it has for other recent work on the impact of the computer. Stephen Oliner and Daniel Sichel provide one answer to the paradox: you do not see computers "everywhere" in an economic sense, because the share of computers in the private capital stock is only about 2 percent. In the growth accounting framework the authors use, an input with so small a share cannot make a major contribution to output growth. Even after adding in computer software investment and extending the scope of the inquiry to include information equipment, the share of the capital stock accounted for by these progenitors of the "information economy" remains small.

Oliner and Sichel also consider whether the contribution of computers is masked because the output of computer-using sectors is badly measured. Zvi Griliches has said, in effect, that we may not see computers "everywhere," but that we see them in sectors where output is poorly measured, such as banking, insurance, and business services.[1] The authors point out that these poorly measured sectors do not account for a large proportion of final demand, so that mismeasurement of output would not much affect aggregate productivity measures and cannot account for the "missing" impact of the computer inherent in the Solow paradox.

Computers and Growth Accounting

Both major points that Oliner and Sichel make seem sound, even though some technical quibbles might be explored to drive the last nail in

1. Griliches (1994).

their case. They compute the computer share in the *wealth* capital stock rather than the comparable share in the *productive* capital stock. The distinction is between depreciation and deterioration. Depreciation determines the wealth capital stock, and depreciation of computers is very rapid because of their rapid obsolescence. However, the evidence suggests that computers deteriorate hardly at all—that is, the productive services they are capable of generating do not decline with age; the computer's yield of capital services determines its share in the productive capital stock.[2] Nevertheless, because the service lives of computers are so short, the authors' "small size" argument remains intact: Jorgenson and Kevin Stiroh report that the computer's share in capital services is only a little greater than 2 percent and has been *falling* since 1985, both as a share of total, and of producer durable, capital services.[3]

On the output side, one might list some additional final-output contributions of computers beyond those that the authors consider. Exports of services, which are final products, have shown rapid growth and in many areas (such as finance and insurance) fit precisely Griliches' model of inadequate measurement. Home computers have produced a vast increase in the consumption of entertainment, and most "home production" is not valued in economic accounts. It has also been observed that computers are in some sense "fun." It is not clear why calculating with those old Marchant desk calculators was drudgery, whereas watching columns transform themselves across a spreadsheet is interesting. But since it seems to be so, computers may have produced a large component of consumption on the job, which is also unmeasured output that would increase the computer contributions Oliner and Sichel have uncovered.

Yet, even if one measures the productive computer stock, and even if one were to add in more unmeasured outputs, it seems likely that Oliner and Sichel's conclusions would still stand, for the same fundamental reasons. The share of computers, software, and information equipment, even in the productive capital stock, remains relatively small, and the shares of unmeasured output in final demand, even as expanded, would probably also remain small. The paper is a valuable and

2. The distinctions in this paragraph are elaborated in Triplett (1994) but see also Jorgenson (1989) and Hulten (1990).

3. Jorgenson and Stiroh (1994).

thorough exploration of the impact of the computer within the conventional growth accounting framework that the authors employ.

Computers and Multifactor Productivity

My main reservation is methodological: Does this research confront the Solow paradox? The authors' use of the growth accounting framework implies that Solow's paradox refers to labor productivity. Within this framework, one looks for the effect of computers by examining the conventional effects of capital-labor substitution on labor productivity. As the authors have found, the computer substitution effects are small because the computer's share is so small.

Suppose, however, that the Solow paradox applies to multifactor productivity. Under this interpretation, seeing computers "everywhere" is a signal that we are finding new ways of doing things—in other words, computers are a signal of acceleration in technical change. If this is the appropriate interpretation of the Solow paradox, increased investment in computers should be associated with an increase in multifactor productivity, so the paradox says that multifactor productivity is lower than one would expect in an era of massive technical change. This is, for example, Paul David's interpretation of the paradox.[4] The growth accounting framework is not very useful in explaining the multifactor productivity form of the paradox, because in the growth accounting framework, multifactor productivity is hanging out, *constant*, at the end of Oliner and Sichel's equation 3.

The authors do examine whether multifactor productivity *as measured* might be too low (their discussion of mismeasured output). They also consider whether the computer's contribution to output might have been understated because the social rate of return to computers exceeds the private rate. The latter reallocation would *lower* the measured rate of multifactor productivity. But if the Solow paradox refers to multifactor productivity and implies that multifactor productivity is lower than expected, the growth accounting framework is not the vehicle to resolve the paradox.

One could usefully put the Solow paradox another way. Computers are part of a wider category of investment called "information equip-

4. David (1990, p. 355).

Table 1. Selected Investment Components in 1970 and 1993
Billions of dollars, unless otherwise indicated

	1970	*1993*
Fixed investment	148.1	866.7
Nonresidential investment	106.7	616.1
PDE (nonresidential)	66.4	442.7
Information equipment	14.3	151.5
Percent of fixed investment	9.7	17.5
Percent of nonresidential investment	13.4	24.6
Percent of PDE	21.5	34.2
Office, computing, and accounting equipment	4.1	53.7
Computer equipment	2.7[a]	47.0
Percent of fixed investment	1.8	5.4
Percent of nonresidential investment	2.5	7.6
Percent of PDE	4.1	10.6
Percent of office, computing, and accounting equipment	65.9	87.5
Industrial equipment	20.2	96.7
Transportation equipment	16.2	104.2

Sources: *Survey of Current Business*, July 1994, tables 5.4 and 5.8; U.S. Bureau of Economic Analysis (1992, vol. 2, tables 5.4 and 5.8).
a. Unpublished detail.

ment." Investment in information equipment is three times investment in computer equipment. The share of information equipment in private nonresidential investment has almost doubled since 1970, and its share is now larger than either the share of industrial equipment or the share of transportation equipment (table 1). The growth in information equipment implies an even greater growth in the quantity of information. Why are we shipping so much information around the economy? If information is productive, and it is not a final product, where does this utilization of information show up in multifactor productivity? That is an alternative form of the Solow paradox.

Although much as been written about the "information economy," there are few answers to the questions posed in the preceding paragraph. Perhaps the story of information equipment is a simple factor-substitution story, much like the substitution of one form of energy for another, and not a technical change story at all. We video conference, say, instead of travel; or computerized design, coupled with a machine tool, makes it possible to get by with fewer machine tools. We do the same things as before (meet and talk, drill holes and polish them), but we have substituted the cheaper equipment for the more expensive types. If this is the story, those who have written about the "information economy" have mistaken substitution around an unchanging production function for a shift in the production function (technical change). This is a possible resolution of the paradox; I am not so sure it is a plausible one.

Alternatively, information may not, or may not always, be productive. Improved communications and computers have greatly decreased the cost of financial transactions, but Timothy Bresnahan, Paul Milgrom, and Jonathan Paul, in a paper on measuring the output of the stock market, concluded that improved information did not have a social product in that case (which is not the same thing, of course, as saying that the stock market has no social product).[5] If cheaper information equipment has lowered the price of rent-seeking behavior, and increased its quantity, that ought not to show up in multifactor productivity.

Other research agendas present themselves. But the major message here is that in one form or another the Solow paradox is alive and well, despite the work by Oliner and Sichel.

Computing Power and Electric Power

A final point concerns the well-known analogy, associated with David and which the authors discuss, between the diffusion of electricity and computers.[6] It may be true that the computer's productive potential has yet to be realized fully, but I doubt that electricity provides an instructive analogy.

The computer differs fundamentally from electricity in its price behavior. We have reached the fortieth anniversary 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.[7]

No remotely comparable price decreases accompanied the introduction of electricity. David reports that electricity prices only began to fall in the fourth decade of electric power; and although Nordhaus 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.[8]

5. Bresnahan, Milgrom, and Paul (1992).
6. David (1990).
7. The time series on which this statement is based is Triplett (1989) and the computer equipment price series in the national income and product accounts.
8. Nordhaus (1994).

Precisely because their price histories are so different, the diffusions of electric power and computing power have fundamentally different 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, say, water 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, once into electrical energy and then into mechanical energy). 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 things. Only after a long lag did electricity generation affect the things that had been done before with water or steam power. David notes that 40 years after the introduction of electrical power, only half of factory mechanical drives were electrified.[9]

The computer diffusion process was different because the initial applications supplanted older technologies for computing. Water and steam power long survived the introduction of electricity; but old methods for doing the calculations that were done before the computer age disappeared long ago. Do our research assistants still use Marchant calculators? The vast and 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. In the computer diffusion process, extensions to new applications followed the displacement of old methods.

Although some of these new applications are quantum improvements in capabilities, price effects matter here as well, so other 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 com-

9. David (1990, p. 357).

puter 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.

The price histories of electric power and computing power during their respective first four decades differ by 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.

Robert J. Gordon: This paper argues convincingly that computers have not (yet) made a major contribution to economic growth, and that the reason is so obvious that no one should have ever suggested that there was a puzzle about the apparent failure of computers to create an acceleration in output and productivity growth. Before leaping to the defense of those who suggested six years ago that there was a puzzle, namely Martin Baily and myself, let me review the basic findings of the paper.[1]

The central message can easily be remembered if one sets forth a new axiom in the theory of economic growth, which I'd like to label the "Oprah Winfrey" axiom. The net worth of Oprah's company Harpo Enterprises has risen mightily over the past decade, perhaps at 50 percent a year, even when properly deflated by the PPI for talk show hosts. But I have never heard anyone in this room, or elsewhere, state that there is a puzzle because this explosion of Harpo revenues has not appeared to revive the growth rate of productivity in the nonfarm private economy. The reason is that Harpo is too small to matter.

The example restates not just one but two important points, both emphasized by the authors. First, no single piece of the capital stock can be a major source of growth unless it is a very large piece. The share of Harpo capital is trivial, of course, but even the share of computers (as the authors calculate it) is only about 2 percent of the total capital stock.

1. Baily and Gordon (1988).

So how could computers matter? The second point is that the services of talk show hosts, and indeed those of the entire TV industry, are treated in the national accounts as intermediate goods, and any delight created in the general population when Oprah interviews nymphomaniacs and child molesters is omitted from final output. In the same way, as Baily and Gordon have pointed out, something can be a source of productivity growth only if it affects final output, not just intermediate output, and much of what computers produce is in the form of intermediate goods and services.

There are two other reasons why the contribution of computers is small, both of which are recognized by the authors. First, the rapid growth of real computer output causes an acceleration, albeit a very small one, in both aggregate output and in capital input. Any contribution to the growth in multifactor productivity (MFP) of a particular type of investment good, or an error in the measurement of the growth rate of some or all of investment, can occur only to the extent that the income share of capital exceeds the share of investment in output. This point, originally made by Dale Jorgenson, hung like a cloud over my head when I was doing my book on durable goods prices.[2] No matter how large the upward bias in official price indexes for producer goods, there would be a contribution to MFP growth operating only on that tiny wedge between the two shares. I found that an estimated upward bias in official PDE price indexes of 290 basis points a year translated into a contribution to MFP growth of only 17 basis points.

The final reason why the contribution is small—and this is sufficient to reduce the authors' central estimate from 16 basis points to only 6—is that the welfare impact of a capital good depends on its contribution to net output, not gross output. The authors provide a great example to drive home this point: a huge machine that annually produces \$6 trillion of output but self-destructs after a year and costs \$6 trillion to replace. Since the huge machine contributes nothing to welfare, its contribution to net output is zero. One might add, as pointed out by Jack Triplett, that the authors' conversion from gross to net output is based on geometric depreciation, which surely overstates the rate of decay of the services provided by a given computer over its lifetime.

2. Jorgenson (1966).

The authors go on to provide every chance for the contribution of computers to be more than trivial. They allow for supernormal returns, positive externalities, and large private returns to individual firms and workers, and they still cannot find a major contribution for computers, especially to net (as opposed to gross) output. Along the way the authors provide some effective criticisms of the supernormal returns literature. In particular, they doubt that all of the 10–15 percent wage differential attributed by Krueger to computers can be considered a contribution of computer hardware, because it ignores training costs. I would add that since Krueger reports that the percentage of workers using computers at work was 37 percent in 1989, it must be very hard to untangle the wage premium of this 37 percent from all the other factors that contributed to the much-studied increase in wage dispersion between skilled and unskilled workers in the 1980s. As to estimates by Brynjolfsson and Hitt that computers earn returns of 24 to 57 percent, the authors ask correctly, what friction or market failure prevented these firms from investing even more in computers until the returns were driven down to those on other types of capital? And, I might add, why were there so many articles in *Fortune* and *Business Week* over the past decade about the difficulties encountered by many firms in structuring their organizations and work processes to use computers effectively?

In the middle section of the paper, my only objection is that the authors were so gentle on De Long and Summers, indeed that they even chose to introduce that disreputable research into their discussion, since one of them was a coauthor of a definitive paper that essentially destroyed the De Long and Summers result.[3] My own way of disputing De Long and Summers is to examine the excess returns–to-equipment hypothesis in the context of the U.S. time-series productivity puzzle. Let us say that only equipment produces output and that nonresidentical structures do not; instead nonresidential structures are a type of intermediate good that keeps equipment from getting wet when it rains. Attributing the entire income share of capital to equipment, and none to structures, is a way of saying that equipment earns excess returns. Well, the embarrassing fact is that the stock of equipment has grown rapidly throughout the postwar period, and its growth did not slow down appreciably after 1973. So the larger the weight attributed to the growth of equipment, the greater is the unexplained slowdown in MFP.

3. De Long and Summers (1991, 1992) and Auerbach, Hassett, and Oliner (1994).

What about those like Baily and myself who have suggested that there is a puzzle about the failure of computers to spur a productivity growth revival? To defend our 1988 puzzlement, our emphasis was not on computers explicitly but on the unexplained divergence of productivity behavior in manufacturing and nonmanufacturing. Computers came into the puzzle because of the heavy use of computers in particular parts of the service sector. But we came out in the same place as today's authors—too many of the various types of mismeasurement that we found were in intermediate inputs, and in sectors with final output shares that were too small, to allow the mismeasurement hypothesis to contribute more than, say, one-third of the overall post-1973 productivity growth slowdown. Along the way, we did come up with a nice list of the reasons that computers may not contribute to final output, including long lags in training workers to make effective use of them, the use of computers in market-share battles among firms that do not raise final output, the use of computers to improve working conditions, and the use of computers to produce consumer convenience (such as 24-hour money machines and advance airline boarding passes) and other unmeasured attributes of output.

The last part of the paper provides valuable new data and insights on the growth of software and computer-services labor. A surprising result is that the quality-adjusted prices of word processors dropped at a very slow rate, just 2.6 percent a year between 1986 and 1993, and at a somewhat faster 4.5 percent for spreadsheets and 4.7 percent for data base programs. There are two objections to these results. First, they are based on matched-model indexes of software programs having the same characteristics between one quarter and the next—for example, Wordperfect 5.1. But no attempt is made to value the many new features on new versions—Wordperfect 6.0—which represent an increase in quality with (typically) no increase in price. Second, the software price indexes are based on prices pulled from advertisements in computing magazines for stand-alone software purchases. But much, perhaps most, new software is not purchased at all but comes bundled (and preloaded) with hardware, so that its price is zero. I have not bought a new word processor in almost a decade and have paid for only occasional upgrades, yet I have at my disposal versions of both Word and Wordperfect that incorporate zillions of features that were unheard of ten years ago.

The paper concludes by asking if the best is yet to come, citing Paul David's oft-discussed example of the spread of electric motors. I find the

David's oft-discussed example of the spread of electric motors. I find the David analogy completely unconvincing. There were several truly important inventions in the late nineteenth and early twentieth centuries that revolutionized methods of production, how cities were organized, and how people spent their time. Among them were the electric motor, chemicals and plastics, motor cars and trucks, household appliances (a derivative of the electric motor), highways, and supermarkets.

I just do not think computers are in the same league. Let's apply the plausibility test. Ask yourself—over the next decade how could computers make a radically greater contribution to the large part of final output produced by the physical movement of pieces of machinery (including most of manufacturing, agriculture, mining, construction, transportation, utilities, and trade) or to services involving the physical proximity of people (including medicine, beauty shops, restaurants, lawn-care services, courtroom trials, auto repair shops, and professors sitting around this table puzzling over slow productivity growth)? I venture the prediction that we are already well down on the curve of diminishing returns to computers, both hardware and software, and that is a statement about both the economy and about myself: e-mail, although lots of fun, has certainly reduced my daily output of professional services, even taking account of a partial substitution away from leisure and sleep.

General Discussion

Stephen Oliner responded to Jack Triplett's argument that the paper does not really lay the Solow paradox to rest because that paradox involves growth in multifactor productivity. Oliner noted that, in the section of the paper that considers supernormal returns to computers, a substantial amount of output growth is attributed to computers that would be in the multifactor productivity residual under standard neoclassical assumptions. Even if much of the action of computers is expected to show up in multifactor productivity, the contributions calculated using supernormal returns should capture the output gain. Yet, even with supernormal returns, these gains would not be sufficient to raise multifactor productivity growth substantially.

William Nordhaus observed that the paper confirms a finding in Edward Denison's work on growth accounting: no single factor ever generates a large growth contribution. He also pointed out that the paper's bottom-line figure for the growth contribution of computers—including software and other information processing equipment—is larger than estimates for any factor usually cited in explaining the productivity slowdown, including regulation, oil prices, natural resources, sectoral shifts, and the investment slowdown.

William Dickens noted that, if the paper resolves the Solow paradox, it raises another paradox. The paper suggests that computers are too small a component of the capital stock to have a large impact on aggregate productivity. However, the labor literature suggests that technological change—including computerization—is an important factor behind the widening of the wage distribution. Put simply, if productivity growth has been slow, how can technological progress have had a significant effect in labor markets? Dickens wondered whether the estimates in the paper could generate significant changes in factor use and relative wages if combined with plausible production functions.

Some panelists commented on the "takeoff" scenario described in the paper. Nordhaus argued that it is too soon to judge the eventual contribution of computers. Computers are fundamentally different from other innovations because they represent a new form of intelligence. Also, if there are initial impediments to realizing the full potential of a new technology, the early rates of return from investing in the technology may be a poor forecast of the eventual returns. William Brainard cited network externalities as an example. Information technology should be more productive for each user the more widespread its use. For example, the more people who join the Internet, the more valuable it is for each user and the stronger the incentive is for new users to join. Thus, the rate of adoption of the technology and its contribution to productivity should be an increasing function of its prevalence. However, the authors agreed with Triplett and Robert Gordon that the takeoff story seems unconvincing when applied to computers today. Oliner noted that, if the rate of return to computers were now surging, we should observe unusually rapid growth of the computer capital stock, which we do not see.

Several members of the panel suggested that much of the return to computers would not be captured by official statistics because they do not capture many of the benefits of computers. Kevin Hassett noted that in automobile and airplane manufacturing a key benefit of the use of computers has been quality improvement, which is harder to measure than quantity increases. He also noted that computers have enhanced versatility; for example, machine tools controlled by computers can be reprogrammed easily to do different tasks. He doubted that this benefit of computers would show up in the national income and product accounts. Gordon added that computers provided unmeasured consumption on the job, such as the use of e-mail for friendly correspondence. But Triplett argued that such hidden benefits may be overstated. He suggested that the enhanced versatility mentioned by Hassett would be accounted for in typical data, because versatility would show up as a reduction in investment required to produce new goods. He also reiterated his belief that as the price of computers has fallen, so too has the value of the marginal computer application. That is, many of the recent applications of computers—including many that are difficult to measure—have been for uses of low value.

Several other measurement issues were discussed. Oliner agreed with Gordon that the software price index probably understates declines in software prices because of the practice of selling software in bundles and providing upgrades at a discount. He noted, however, that the index should accurately reflect changes in software prices once the proportion of software sold through these channels stabilizes. Once this happens, aggregate changes in software prices will occur only for reasons unrelated to marketing behavior. Gordon offered an analogy: once everyone has shifted to WalMart, there will no longer be outlet substitution bias in the consumer price index. Dickens suggested that the paper may underestimate the income share of computer-services labor, because it omits unofficial programming done by people whose job titles are not computer related. Daniel Sichel agreed, noting that this problem probably has become more important with personal computers and workstations because so many end users now do their own systems work.

Gregory Mankiw asked if the growth-accounting equation used in the paper can be trusted. Because the equation is implicitly derived from a Taylor expansion, it may be valid for small increases in the stock of computers but not for the massive jump seen between 1970 and 1992. But Sichel pointed out that the paper estimates each year's contribution to growth and then averages across years, rather than making one estimate using the entire 1970–92 growth in the capital stock. So, the question boils down to whether the growth-accounting equation is reasonable for changes in the capital stock of about 25 percent, which is roughly the annual growth rate of the stock of computers and peripheral equipment.

References

Auerbach, Alan J., Kevin A. Hassett, and Stephen D. Oliner. 1994. "Reassessing the Social Returns to Equipment Investment." *Quarterly Journal of Economics* 109(3): 789–802.

Baily, Martin Neil, and Robert J. Gordon. 1988. "The Productivity Slowdown, Measurement Issues, and the Explosion of Computer Power." *BPEA, 2:1988*, 347–420.

Baily, Martin Neil, and Charles L. Schultze. 1990. "The Productivity of Capital in a Period of Slower Growth." *BPEA, Microeconomics, 1990*, 369–406.

Bresnahan, Timothy F., Paul Milgrom, and Jonathan Paul. 1992. "The Real Output of the Stock Exchange." In *Output Measurement in the Service Sectors*, edited by Zvi Griliches. Chicago: University of Chicago Press.

Brynjolfsson, Erik. 1993. "The Productivity Paradox of Information Technology." *Communications of the ACM* 36(12): 67–77.

———, and Lorin Hitt. 1993. "New Evidence on the Returns to Information Systems." Technical Report. Cambridge, Mass.: Center for Coordination Science, Sloan School of Management, MIT.

Brynjolfsson, Erik, and Chris F. Kemerer. 1993. "Network Externalities in Microcomputer Software: An Econometric Analysis of the Spreadsheet Market." Working Paper 265. Cambridge, Mass.: Center for Information Systems Research, Sloan School of Management, MIT.

———. 1994. "Multifactor Productivity Measures, 1991 and 1992." USDL 94-327. Washington: Department of Labor.

David, Paul A. 1989. "Computer and Dynamo: The Modern Productivity Paradox in a Not-Too-Distant Mirror." Working paper 172. Palo Alto, Calif.: Center for Economic Policy Research, Stanford University.

———. 1990. "The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox." *American Economic Review* 80(2): 355–61.

De Long, J. Bradford, and Lawrence H. Summers. 1991. "Equipment Investment and Economic Growth." *Quarterly Journal of Economics* 106(2): 445–502.

———. 1992. "Equipment Investment and Economic Growth: How Strong Is the Nexus?" *BPEA, 2:1992*, 157–99.

Denison, Edward F. 1985. *Trends in American Economic Growth, 1929–1982*. Washington: Brookings.

Diewert, W. Erwin. 1987. "Index Numbers." In *The New Palgrave: A Dictionary of Economics*, edited by John Eatwell, Murry Milgate, and Peter Newman. New York: Stockton Press.

Dulberger, Ellen R. 1989. "The Application of a Hedonic Model to a Quality-Adjusted Price Index for Computer Processors." In *Technology and Capital Formation*, edited by Dale W. Jorgenson and Ralph Landau. Cambridge, Mass.: MIT Press.

Fishlow, Albert. 1966. "Productivity and Technological Change in the Railroad Sector, 1840–1910." In *Output, Employment, and Productivity in the United States after 1800*. NBER Studies in Income and Wealth, vol. 30. New York: National Bureau of Economic Research.

Flamm, Kenneth. 1989. "Technological Advance and Costs: Computers versus Communications." In *Changing the Rules: Technological Changes, International Competition, and Regulation in Communications*, edited by Robert W. Crandall and Kenneth Flamm. Washington: Brookings.

Gallman, Robert E. 1986. "The United States Capital Stock in the Nineteenth Century." In *Long-Term Factors in American Economic Growth*. NBER Studies in Income and Wealth, vol. 51, edited by Stanley L. Engerman and Robert E. Gallman. Chicago: University of Chicago Press.

Gandal, Neil. 1994. "Hedonic Price Indexes for Spreadsheets and an Empirical Test for Network Externalities." *RAND Journal of Economics* 25(1): 160–70.

Gordon, Robert J. 1990. *The Measurement of Durable Goods Prices*. Chicago: University of Chicago Press.

———. 1993. "The Jobless Recovery: Does It Signal a New Era of Productivity-Led Growth?" *BPEA, 1:1993*, 271–306.

Griliches, Zvi, ed. 1992. *Output Measurement in the Service Sectors*. NBER Studies in Income and Wealth, vol. 56. Chicago: University of Chicago Press.

———. 1994. "Productivity, R&D, and the Data Constraint." *American Economic Review* 84(1): 1–23.

Gurbaxani, Vijay C. 1990. *Managing Information Systems Costs: An Economic Analysis of Hardware/Software Trade-Offs*. Washington: International Center for Information Technologies.

Hulten, Charles R. 1990. "The Measurement of Capital." In *Fifty Years of Economic Management*, edited by Ernst R. Berndt and Jack E. Triplett. Chicago: University of Chicago Press.

———. 1992. "Accounting for the Wealth of Nations: The Net versus Gross Output Controversy and Its Ramifications." *Scandinavian Journal of Economics* 94(Supplement): 9–24.

Jorgenson, Dale W. 1966. "The Embodiment Hypothesis." *Journal of Political Economy* 74(1): 1–17.

———. 1989. "Capital as a Factor of Production." In *Technology and Capital Formation*, edited by Dale W. Jorgenson and Ralph Landau. Cambridge, Mass.: MIT Press.

———, and Kevin Stiroh. 1994. "Investment in Computers and U.S. Economic Growth." Unpublished paper. Harvard University.

Katz, Lawrence F., and Alan B. Krueger. 1994. "How Computers Have Changed the Workplace, 1984–93." Unpublished paper. Cambridge, Mass.: Harvard University (August).

Krueger, Alan B. 1993. "How Computers Have Changed the Wage Structure: Evidence From Microdata, 1984–1989." *Quarterly Journal of Economics* 108(1): 33–60.

Lau, Lawrence J., and Ichiro Tokutsu. 1992. "The Impact of Computer Technology on the Aggregate Productivity of the United States: An Indirect Approach." Unpublished paper. Stanford University (August).

Lichtenberg, Frank R. 1993. "The Output Contributions of Computer Equipment and Personnel: A Firm-Level Analysis." Working Paper 4540. Cambridge, Mass.: National Bureau of Economic Research (November).

Loveman, Gary W. 1988. "An Assessment of the Productivity Impact of Information Technologies." Working Paper 88-054, MIT Management in the 1990s. Cambridge, Mass.: Sloan School of Management, Massachusetts Institute of Technology.

Morrison, Catherine J., and Ernst R. Berndt. 1991. "Assessing the Productivity of Information Technology Equipment in U.S. Manufacturing Industries." Working paper 3582. Cambridge, Mass.: National Bureau of Economic Research (January).

National Bureau of Economic Research, Price Statistics Review Committee. 1961. *The Price Statistics of the Federal Government.* (Also known as the Stigler Report.) General Series No. 73. New York: National Bureau of Economic Research.

National Research Council. 1994. *Information Technology in the Service Society: A Twenty-First Century Lever.* Washington: National Academy Press.

Nordhaus, William D. 1994. "Do Real Output and Real Wage Measures Capture Reality? The History of Light Suggests Not." Unpublished paper. New Haven, Conn.: Yale University.

Oliner, Stephen D. 1994. "Measuring Stocks of Computer Peripheral Equipment: Theory and Application." Unpublished paper. Washington: Board of Governors of the Federal Reserve System.

———, and Daniel E. Sichel. 1994. "How Fast Have Prices Fallen for Computing Services? The Hardware-Software-Labor Nexus." Unpublished paper. Washington: Brookings.

Osterman, Paul. 1986. "The Impact of Computers on the Employment of Clerks and Managers." *Industrial and Labor Relations Review* 39(2): 175–86.

Roach, Stephen S. 1991. "Services Under Siege—The Restructuring Imperative." *Harvard Business Review* 69(5): 82–91.

Romer, Paul M. 1986. "Increasing Returns and Long-Run Growth." *Journal of Political Economy* 94(5): 1002–37.

———. 1987. "Crazy Explanations for the Productivity Slowdown." In *NBER Macroeconomics Annual: 1987*, edited by Stanley Fischer. Cambridge, Mass.: MIT Press.

———. 1994. "The Origins of Endogenous Growth." *Journal of Economic Perspectives* 8(1): 3–22.

Sichel, Daniel E. 1994. "The Computer Paradox and the Productivity Slowdown: Is Mismeasurement the Culprit?" Unpublished paper. Washington: Brookings.

Triplett, Jack E. 1989. "Price and Technological Change in a Capital Good: A Survey of Research on Computers." In *Technology and Capital Formation*, edited by Dale W. Jorgenson and Ralph Landau. Cambridge, Mass.: MIT Press.

———. 1994. "Depreciation in Production Analysis and in Income and Wealth Accounts: Resolution of an Old Debate." Unpublished paper. U.S. Bureau of Economic Analysis.

United States Bureau of Economic Analysis. 1992. *National Income and Product Accounts of the United States*. Washington: Department of Commerce.

———. 1993. *Fixed Reproducible Tangible Wealth in the United States, 1925–89*. Washington: Department of Commerce.

United States Bureau of Labor Statistics. 1983. *Trends in Multifactor Productivity, 1948–1981*. Bulletin 2178. Washington: Department of Labor.

United States Office of Management and Budget. 1987. *Standard Industrial Classification Manual: 1987*. Washington: Executive Office of the President.