Has the Surge in Computer Spending Fundamentally Changed the Economy?

By Joseph H. Haimowitz

The computer sector has been one of the fastest growing segments of the U.S. economy over the past two decades. Computers appear to be everywhere—on the desks of executives, on the factory floor, in the classroom, at home, and, these days, even in people's pockets. By all accounts, computers appear to be rapidly changing the way many of us conduct business, recreate, and communicate. The proliferation of computers has made the world seem much smaller, as computer related innovations, such as the Internet, let individuals on opposite sides of the world interact in ways that were unimagined 20 years ago. As a result, spending on computers has exploded.

The dynamic nature of the computer sector and the sector's increased prominence in overall spending in the economy have led some analysts to suggest that the economy is entering a New Era, where the economy will return to the high-growth, low-inflation conditions of the 1950s and 1960s.[1] Although spending on computers is spread throughout all sectors of the economy, the key channel through which the economy might be transformed is investment spending on computers by businesses. Spending on computers by businesses is key because the contribution of computers to output growth depends crucially on the quantity of computers used in the production process. If rapid spending on computers does lead to faster output growth, then understanding the magnitude of the contribution of computer capital to output growth will be crucial for long-run forecasting and policy analysis.

This article examines whether computers have fundamentally changed the economy. The first section documents the developments in the computer sector that have led many analysts to suggest that a computer-led surge in output growth is under way. In particular, it focuses on the rapid increases in investment spending on computing equipment by businesses and the importance of these increases for increases in overall investment spending. The second section uses a standard framework to show that the resulting growth in the capital stock of computing equipment has made only a modest contribution to

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output growth to date. Relaxing the assumptions underlying the standard framework, however, shows that the contribution of computers to output growth appears to have been somewhat larger. The third section discusses whether computers might generate a larger pickup in output growth in the future. The article concludes that computers have had only a modest impact on output growth until now, but the future impact could be larger.

I. THE SURGE IN COMPUTER SPENDING

The casual observation that computers seem to be everywhere is borne out by spending data. Spending on computers has been growing rapidly in all sectors of the economy.

How are computers defined in the National Income and Product Accounts?

Computers appear as a detailed category in most of the major components of GDP. The National Income and Product Accounts consist of six major components. These components are personal consumption expenditures, business fixed investment, residential fixed investment, government expenditures, net exports, and inventory investment. Each of these components can be divided into finer levels of detail. For example, the business fixed investment component of GDP consists of two major subcomponents, structures and producers' durable equipment, which themselves can be divided into finer levels of detail. The second column of Table 1 describes where computers appear in the NIPA accounts. For example, in the personal consumption expenditures component of GDP, computers appear as a detailed category within consumer durable goods.

Each major component of the NIPA accounts defines the computer sector somewhat differently. The third column of Table 1 lists how computers are defined in each of the major components of GDP. For personal consumption expenditures and net exports, computers include hardware and software. For business fixed investment and government spending, computers include hardware but exclude software that does not come preloaded with the hardware. In these sectors, spending on software is treated as an expense rather than as a capital investment.

How important is computer spending as a share of overall spending?

The computer sector's share of total spending has increased because growth in this sector, which includes all computing equipment and software as defined in Table 1, has outstripped growth in the rest of the economy (Chart 1). From 1982 to 1996, growth in the computer sector averaged over 26 percent annually, while growth in the economy as a whole averaged less than 2.6 percent annually.[2] The difference has been even more evident in recent years. For example, from 1994 to 1996 computer sector growth exceeded 55 percent, while the economy as a whole expanded 2.5 percent.

Some analysts have argued that the computer sector cannot have a large economic effect because its share of GDP is so small. While it is true that spending on computers as a share of total spending is small, this share has been rising rapidly over time. Table 2 shows how the share of computers in GDP and its major components, calculated as the ratio of real computer spending in each component to total real spending in each component, has expanded since the early 1980s.[3] The computer sector's average share of real spending increased over fivefold between the 1982-86 and 1992-96 periods. Although the computer sector only accounted for an average of 0.29 percent of total spending during the 1982-86 period, it accounted for over 1.58 percent of total spending during the 1992-96 period.

Table 1

COMPUTERS IN THE NATIONAL INCOME AND PRODUCT ACCOUNTS

Major component of GDP	Where do computers appear?	How are computers defined?
Personal consumption expenditures	Detailed level of consumer durables.	Computers include both hardware and software.
Business fixed investment	Detailed level of producer's durable equipment.	Computers include hardware but do not include software unless the software comes preloaded on the hardware.
Government	Detailed level of equipment investment in federal defense, federal nondefense, and state and local.	Computers include hardware but do not include software unless the software comes preloaded on the hardware.
Net exports	Detailed level of nonautomotive capital goods in exports and imports.	Computers include both hardware and software.

This large increase in the size of the computer sector as a share of the economy is mirrored in all of the economy's major components. The rate of increase, however, has varied widely across the components. For example, spending on computers as a share of total government spending increased less than fivefold, while spending on computers as a share of personal consumption expenditures increased over twentyfold.

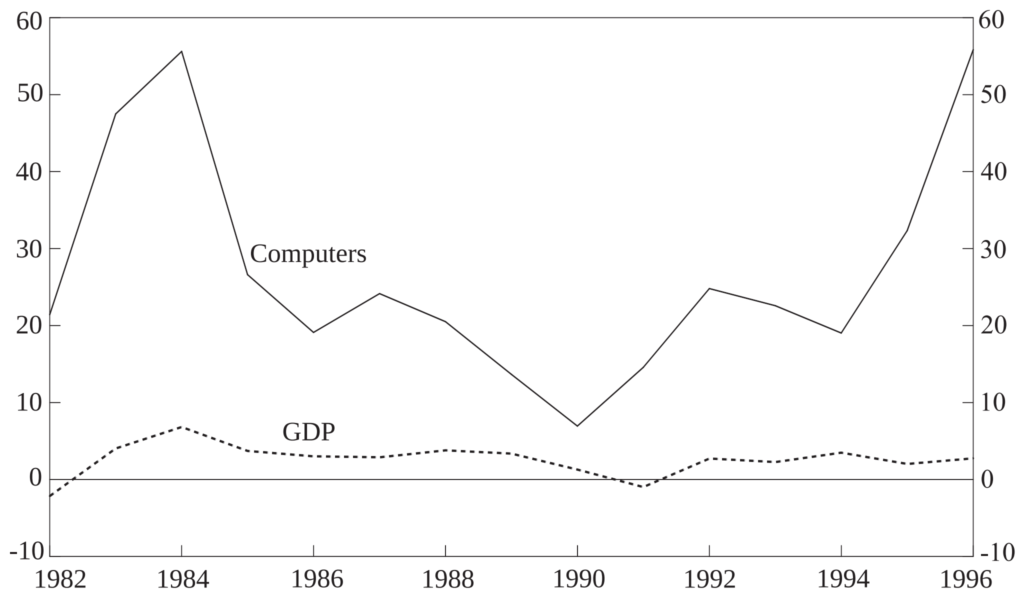
The most fundamental way in which spending on computers can have a long-run effect on the economy is through the investment in computers by businesses. The share of business investment spending on computers in total business investment spending has grown rapidly and has exceeded the share of computer spending in spending for all other major GDP categories (Table 2). From 1992 to 1996, real business investment in computers represented over 13 percent of all business investment and nearly 18 percent of business investment in equipment.

Thus, spending on computing equipment has become an increasingly important part of business investment spending. Some analysts suggest that this trend has important implications for output growth. The rest of this article analyzes the impact on economic growth of investment spending on computing equipment by businesses in the recent past and the potential impact of this spending in the future.

II. HOW HAS INVESTMENT IN COMPUTERS INFLUENCED OUTPUT GROWTH IN RECENT YEARS?

Output depends on many factors, including the total hours of labor, education of the work

Chart 1
GROWTH RATES OF GDP AND COMPUTERS
Percent change from year earlier



Source: Bureau of Economic Analysis.

force, technology, and the amount of capital. Output growth, in turn, depends on changes in these factors. In particular, the contribution of computers to output growth is the amount by which output growth would have been reduced if the stock of computer capital had not changed while all the other factors that affect output changed as they did. The size of this contribution depends on the importance of the stock of computer capital relative to the other factors and by how much the stock of computer capital increased. This section describes an analytical framework which formalizes this intuition and then uses the framework to analyze the contribution of computing equipment to output growth in the recent past.

Assessing the role of computers in economic growth: The analytical framework

The framework used to assess the role of computers in economic growth is the growth accounting framework pioneered by Denison.[4] This growth accounting framework was used to examine the contribution of computers by Oliner and Sichel and by Sichel. This section closely follows the framework used by those authors but uses different data. In addition to extending the sample they examined, this analysis uses new chain-weighted measures of the real capital stock published by the Bureau of Economic Analysis (BEA).[5] This is particularly important for the

Table 2

REAL COMPUTER SPENDING AS A SHARE OF SPENDING IN THE MAJOR GDP CATEGORIES

Category	1982-86	1987-91	1992-96
Total GDP	.29	.65	1.58
Personal consumption expenditures	.03	.13	.69
Durable goods	.26	1.08	5.56
Business fixed investment	2.12	4.81	13.11
Producer's durable equipment	3.53	7.36	17.88
Total government	.18	.41	.81
Net exports			
Exports	1.50	3.39	7.23
Imports	.72	2.59	8.24

Source: Author's calculations are based on data from the Bureau of Economic Analysis.

computer sector because of the rapid decline in computer prices. Also, the depreciation rates used here reflect a new BEA methodology for estimating the depreciation of capital assets.

The growth accounting framework is based on three important assumptions. First, constant returns to scale in production are assumed. Constant returns to scale in production imply, for example, that if the quantities of all inputs are doubled then output will also double. Second, the framework assumes that the last dollar spent on computer investment earns the same competitive rate of return as the last dollar spent on any other investment. Third, it assumes that no externalities exist. An externality occurs whenever the activities of one person or firm affect the activities of others in ways that are not taken into account by the operation of the market. In the case of computers, positive externalities exist if investment in computers by one firm increases productivity in other firms. The absence of externalities ensures that the social rate of return and private rate of return to investment in an asset are equal.

These three assumptions imply that the contribution of computing equipment to output growth can be calculated as

$$\begin{pmatrix} \textit{contribution of} \\ \textit{computing} \\ \textit{equipment} \end{pmatrix} = \begin{pmatrix} \textit{income share of} \\ \textit{computing} \\ \textit{equipment} \end{pmatrix} \times \begin{pmatrix} \textit{growth rate of the} \\ \textit{real capital stock of} \\ \textit{computing equipment} \end{pmatrix} \quad (1)$$

The first factor that determines the contribution of computers to output growth is the income share of computing equipment. The income share of computing equipment is the importance of the stock of computers relative to other factors such as labor, other capital inputs, the level of technology available, and the education of the work force. More precisely, it is the fraction by which output would increase if the real stock of computer capital increased by 1 percent. The second factor that determines the contribution of computers to output growth is the growth rate of the real capital stock of computing equipment.

Assessing the role of computers in economic growth: The analysis

The remainder of this section uses this framework to examine the contribution that computers have made to output growth in the recent past. First, the contribution of computing equipment to output growth under the standard framework is examined. Second, the contribution is examined with the standard framework modified by relaxing some of the assumptions.

Data. As detailed in the box, calculating the income share of computing equipment requires data on the nominal capital stock of computing equipment, nominal output, the nominal competitive net rate of return, the depreciation rate for computing equipment, and the growth rate of the price of computing equipment. Annual data on the nominal capital stock of computing equipment were obtained from data published by the BEA. Nominal output is the BEA series for the nominal output of the private nonfarm business sector. The nominal competitive net rate of return is unobserved and must be estimated.[6] The depreciation rate for computing equipment is the BEA's measure of depreciation for office, computing, and accounting machinery and takes the value of 27.29 percent prior to 1978 and 31.19 percent thereafter. The price measure for computing equipment was obtained by using annual BEA data on real and nominal business investment in computing equipment to calculate a deflator for computing equipment investment.

The second determinant of the contribution of computing equipment to output growth, the real capital stock of computing equipment, was calculated by deflating the nominal stock of computing equipment using the price measure for computing equipment.

Contributions under the standard framework. Table 3 shows how the contribution of computing equipment to the growth of real gross output has evolved since 1972. The first row of the table presents the income share of computing equipment. The growth rate of the real capital stock of computing equipment appears in the second row of the table. As shown in equation (1), the contribution of computing equipment to output growth is the product of the income share of computing equipment and the growth rate of the real capital stock of computing equipment. The resulting percentage-point contribution of computing equipment to output growth appears in the third row of the table. The last two rows of the table show the average growth rate of real output and the share of this growth attributable to computing equipment.

The results in the table suggest that computing equipment has made only a modest contribution to growth, adding an average of 0.31 percentage point to growth each year over the entire 1972-96 sample (row 3). Computing equipment made only a modest contribution toward growth despite the fact that the real capital stock of computing equipment grew at an average rate of 35 percent each year (row 2). This is a result of the small income share of computing equipment, which averaged less than 1 percent over the 1972-96 period (row 1). The income share of computing equipment is very small because the size of the capital stock of computing equipment is still very small relative to the size of the entire capital stock.

A second important feature of the results, evident in the last line of the table, is that, as a share of total output growth, the contribution of computing equipment to output growth has actually fallen since the late 1970s. This is largely the result of a slowdown in the growth rate of the real

DEVELOPING THE STANDARD GROWTH ACCOUNTING FRAMEWORK

The three assumptions on which the standard growth accounting framework are based imply that the contribution of computing equipment toward output growth is calculated as the product of the income share of computing equipment and the growth rate of the real capital stock of computing equipment.[7] This box develops this relationship more formally.

In any period, the return earned by $1 of computing equipment capital, after depreciation and changes in the price of the equipment have been factored in, is the gross rate of return to computing equipment which can be expressed as

$$\textit{gross rate of return} = (i + \delta_c - \dot{P}_c),$$

where i is the nominal competitive net rate of return, δ_c is the depreciation rate for computing equipment, and $\dot{P}_c$ is the rate of nominal capital gain on computing equipment.[8] Thus, the income flow, or dollar value of output, generated by the entire stock of computing equipment is simply the product of the gross rate of return to computing equipment and the nominal stock of computing equipment which can be represented as

$$\textit{income flow} = (i + \delta_c - \dot{P}_c)P_c K_c,$$

where P_c is the price of computing equipment and K_c is the real stock of computing equipment.

Since computing equipment is one of many types of inputs into the production process, the income flow generated by computing equipment is only one part of the total income flow generated by all inputs. The share of income generated by computing equipment can be calculated as the ratio of the income flow generated by computing equipment to total income flow,

$$\textit{income share} = \frac{(i + \delta_c - \dot{P}_c)P_c K_c}{PY},$$

where PY is nominal output. The contribution of computing equipment to output growth can then be expressed as the product of the income share of computing equipment and the rate of growth of the real capital stock of computing equipment:

$$\textit{contribution} = \frac{(i + \delta_c - \dot{P}_c)P_c K_c}{PY} \times \dot{K}_c,$$

where $\dot{K}_c$ is the growth rate of the real capital stock of computing equipment. To see why this is the case consider an economy where computing equipment is the only input into the production process. Then, assuming that there is no outside factors that increase the productivity of the stock of computing equipment, output will be unchanged if the stock of computing equipment is unchanged.

Table 3

CONTRIBUTION OF COMPUTING EQUIPMENT TO REAL OUTPUT OF THE PRIVATE NONFARM BUSINESS SECTOR

	1972-96	1972-76	1977-81	1982-86	1987-91	1992-96
(1) Income share of computing equipment	.0089	.0046	.0062	.0098	.0117	.0123
(2) Growth rate of the real stock of computing equipment	34.96	30.91	56.91	39.47	17.01	30.50
(3) Percentage point contribution of computing equipment (1) x (2)	.31	.14	.35	.39	.20	.38
(4) Growth rate of real output	2.90	3.42	2.34	3.40	1.75	3.59
(5) Share of total growth (3) ÷ (4)	.1069	.0409	.1496	.1147	.1143	.1059

Note: Author's calculations are based upon data from the Bureau of Economic Analysis and the Bureau of Labor Statistics. All figures are averaged over the indicated time period.

capital stock of computing equipment since the late 1970s. As the second line of Table 3 shows, growth in the real capital stock of computing equipment averaged almost 57 percent over the 1977-81 period, compared to a much lower 30.5 percent average growth rate during the 1992-96 period.[9] One factor that has partially mitigated the slowing growth of the real capital stock of computing equipment has been the steady rise in the income share of computing equipment. The income share of equipment has risen primarily because computing equipment has represented an increasingly larger part of the overall capital stock.

Contributions under alternative assumptions. The assumptions under which the standard framework was derived are somewhat restrictive. This subsection examines the sensitivity of the results under the standard framework to alternative, less restrictive assumptions.

One important feature of the standard growth framework used in this analysis is that it assumes there are no externalities. Some economists argue that capital may, in fact, generate substantial positive externalities. If capital does generate positive externalities, then the income share used in calculating the contribution of computing equipment to output growth is understated. The reason for this understatement is that the competitive nominal net rate of return used in calculating the income share of computing equipment only measures the private returns to firms from investing in capital. If capital investment generates positive externalities, then investment in capital generates social returns in excess of the private returns to firms that made the investment. These excess returns are not included when calculating the competitive nominal net rate of return. Therefore, to capture the positive externalities and to eliminate the understatement of the income share of computing equipment, the competitive nominal net rate of return is modified to reflect the returns to society from a businesses' investment as well as the return to the business from its own investment.

Table 4

ALTERNATIVE ESTIMATES OF THE CONTRIBUTION OF COMPUTING EQUIPMENT TO OUTPUT GROWTH, 1972-96

	Nominal net rate of return	Income share of computing equipment	Percentage-point contribution of computing equipment
Standard framework	.13	.0089	.31
Romer (lower bound case)	.42	.0136	.48
Romer (upper bound case)	.64	.0171	.60
DeLong and Summers	.47	.0142	.50
Brynjolfsson and Hitt	.36	.0127	.45

Notes: Author's calculations are based upon data from the Bureau of Economic Analysis and the Bureau of Labor Statistics. All figures are averaged over the 1972-96 period. In each of the alternative estimates, the real capital stock of computing equipment grew at an average rate of 34.96 percent per year.

In two papers Romer (1986,1987) argues that capital accumulation may result in knowledge spillovers where increases in a firm's capital stock not only increase the productive resources of the firm but also increase the level of technology available to other firms. For example, when Henry Ford designed the first assembly line for the mass production of the Model T, he was using technology that was already available but in a new, more efficient manner. As a result, other automobile makers learned to produce automobiles more efficiently. Romer suggests that capital's share of income in a standard growth accounting equation, when externalities are considered, is substantially larger than reported by the BLS.[10]

The effects of alternative assumptions on estimates of the contribution of computing equipment to output growth during the 1972-96 period are shown in Table 4. The table reports the average contribution of computing equipment to output growth as well as the two components of the contribution that are affected by changes in the assumption: the average nominal net rate of return and the average income share of computing equipment.[11] For the purposes of comparison, the first row of the table provides estimates of these items under the standard framework.

The second row of the table documents the contribution of computing equipment to output growth that is consistent with Romer's lower bound assumption about the effects of externalities.[12] Under this assumption, the average nominal rate of return is substantially larger than in the standard framework because the rate of return now includes the social returns to investment as well as private returns to investment. As detailed in the box, the net rate of return is a key determinant of the income share of computing equipment; therefore, the income share of computing equipment has also been substantially changed. The results of these modifications are summarized in the last column of table, which reports that the contribution of computing equipment to output growth under Romer's lower bound assumption averaged 0.48 percentage point over the 1972-96 period and was more than 50 percent larger than the contribution of computer equipment to output growth under the standard assumptions.

The third row of the table outlines the implications of using Romer's assumption about the upper bound of the effect of externalities for estimating the contribution of computing equipment to output growth. Under these more extreme assumptions, both the average nominal competitive net rate of return and the income share of computing equipment are larger than under the standard framework and under Romer's assumption about the lower bound of the effect of externalities. Hence, the contribution of computing equipment to output growth, which averaged 0.60 percentage point under Romer's upper bound case, is larger than in either of the two other cases.

DeLong and Summers (1991,1992) also suggest that investment in equipment generates substantial externalities. DeLong and Summers recognize the importance of knowledge spillovers in generating these externalities but also emphasize learning-by-doing as another channel through which externalities are generated. In this channel, using equipment provides feedback so that existing equipment can be more efficiently used and modifications to future versions of the equipment can be made. Rosenberg cites the production and development of the DC-8 aircraft as an example. As the producers of the DC-8 gained increasing confidence in and a greater understanding of the aircraft as a result of airlines flying the plane, they made substantial modifications to the plane's design, such as increasing the thrust and redesigning the wings. These changes helped increase the plane's efficiency by lowering fuel costs and increasing seating capacity.[13]

DeLong and Summers estimate that, over the 1960-85 period, a one-percentage-point increase in the ratio of real equipment investment to real GDP would boost the annual growth rate of real GDP by 0.151 percentage point.[14] The fourth row of Table 4 shows how incorporating the DeLong and Summers estimates into the growth framework alters the contribution of computing equipment to output growth. The average nominal net rate of return consistent with DeLong and Summers' estimates was 47 percent over the 1972-96 period, almost four times as large as in the standard framework.[15] As a result, when the standard framework is modified to incorporate externalities, the average contribution of computing equipment to output growth rises to 0.50 percentage point.

A second feature of the standard growth accounting framework used in this analysis is that all capital assets are assumed to yield the same nominal net rate of return. Some people argue that this assumption is inappropriate for a dynamic technology such as computers. They claim that computers generate nominal net returns that exceed the returns to other capital assets.

One study examines the possibility that computing equipment generates private nominal net rates of return in excess of the returns generated by other capital assets. Brynjolfsson and Hitt examine a group of 367 firms over the 1987-91 period. They estimate that the average annual gross rate of return to computing equipment over the period was 81 percent.

The bottom row of Table 4 documents the implications of incorporating the gross returns earned by computing equipment into the standard framework. The average nominal rate of return consistent with a gross rate of return for the entire 1972-96 period is 36 percent, almost three times the size of the net rate of return for other capital assets.[16] As a result, when it is assumed that the net rate of return to computing equipment exceeds that of other capital assets, the contribution of computing equipment to output growth is 0.45 percentage point.[17]

Summarizing, computing equipment has made only a modest contribution to the growth of output when measured using the standard framework. When modifications to this framework are made, however, these contributions become larger.[18] The next section examines whether the contribution of computing equipment to output growth might increase in the future.

III. WHAT MIGHT THE FUTURE HOLD?

Until now, although the share of investment spending on computing equipment has increased, investment in computing equipment has made only a modest contribution to overall output growth. A key question is whether the contribution of computing equipment to output growth will increase in the future. The answer to this question may help economists and policy analysts better assess future prospects for economic growth and inflation. This section discusses how large the contribution of computing equipment to output growth might be in the future. First, the section examines the output contribution of computing equipment in the standard framework under various assumptions about the future income share of computing equipment and the stock of computing equipment. Second, it discusses a popular argument that the output contribution of computing equipment is likely to increase significantly in the future.

What insight into the future does the standard framework give?

The standard growth accounting framework suggests that the key determinants of the contribution of computing equipment to output growth are the rate of growth of the real capital stock of computing equipment and the income share of computing equipment. Over the past 25 years the income share of computing equipment has risen steadily from 0.6 percent in 1972 to 1.5 percent in 1996. The effect of this steady rise on the contribution of computing equipment to output growth has been mitigated by slowing growth in the real capital stock of computing equipment.

One way to assess the possible future contributions of computing equipment to output growth is by using the same standard growth accounting framework. The framework will provide conservative estimates of the impact of computing equipment in the future because it assumes that computing equipment does not generate any externalities. The future contributions of computing equipment to output growth can be assessed by making assumptions about the future paths of the income share of computing equipment and the growth rate of the real capital stock.

First, consider a relatively pessimistic scenario where the share of income generated by computing equipment and the real capital stock of computing equipment grow at their average rates for the 1990s, about 4.1 percent and 24.8 percent, respectively. Under this scenario, the contribution of computing equipment to output growth is expected to rise modestly over the next decade, adding about 0.55 percentage point to output growth in 2006.

Second, consider a relatively optimistic scenario, where the share of income generated by computing equipment and the real stock of computing equipment grow at their average rates for the 1992-96 period, about 6.8 percent and 30.5 percent, respectively.[19] Under this scenario, the contribution of computing equipment to output growth is expected to rise more dramatically over the next decade, adding almost 0.9 percentage point to output growth in 2006.[20]

What insight into the future does history give?

The previous subsection offered two possible scenarios for the importance of computing equipment in growth in the future. However, some economists have suggested that even the relatively optimistic one might be a conservative vision of the future. This subsection outlines some of the arguments in support of that view.

Some economists argue that the contribution of computing equipment to output growth is likely to increase significantly in the future. These economists suggest that the real productivity gains and externalities from a radical new technology are not realized until decades after the technology has first been introduced.

Economic historian Paul David compares the innovations of the "computer revolution," fueled by advances in microprocessors and memory chips, to the innovations of the "second Industrial Revolution," which was fueled by the electric dynamo. Michael Faraday first demonstrated the principle of the electric motor in 1821; Zénobe Théophile Gramme demonstrated the first electric motor of commercial significance in 1873; the first central generating plant was built in New York in 1882; yet the impact of the dynamo on productivity was not felt until about 1920, when the extent of electrification attained the 50 percent diffusion level.[21]

David identifies a number of reasons why the contributions of computers, like those of the dynamo, might diffuse gradually. First, computers and dynamos are both central elements of transmission networks. As a result, these technologies give rise to "network externality effects," which may lead to slow diffusion. For example, businesses might be relatively unwilling to invest in a computer system unless a standard computer operating system has emerged, just as businesses were reluctant to buy electrical machinery until a standard electric outlet size emerged.

Second, like the dynamo, computers have become more effective as they have become more diffuse. For example, in the case of computers, the effectiveness of an airline's computer ticketing system is enhanced by the existence of compatible computer ticketing systems for other airlines. This feature suggests that diffusion is particularly slow during the early stages of the technology's dispersion.

Third, the adoption of a new technology is often slowed because it requires major reorganization of production. In the case of the dynamo revolution, many firms found it unprofitable to replace existing manufacturing plants powered by water and steam. Electric power made its greatest inroads into industries that were growing rapidly, and thus building new plants, around the turn of the century.

Jeremy Greenwood also argues that the greatest benefits from new technologies often take several decades to be realized. He cites the "Industrial Revolution" in Britain and the American Antebellum period as examples of this. In both of these episodes, productivity actually fell prior to the beginning of the episode and then rose dramatically near the end of the episode.

Greenwood suggests that two factors, which are very applicable to the current "computer revolution," explain this observation. First, one substantial cost of introducing new technologies is that they require a period of learning. The costs involved include the costs of foregoing production while training employees and making mistakes on the relatively unfamiliar equipment. As businesses and employees become more familiar with the new technology, they will require less training, make fewer mistakes, and be capable of speeding up production. Second, as David also observes, the diffusion of new technologies is often slow. The slow diffusion of a new technology makes learning about how to efficiently utilize the new technology more difficult. Over time, as the new technology becomes more widely used, learning about how to most efficiently use the technology becomes more rapid, leading to more rapid increases in productivity.

The analyses of David and Greenwood suggest that the largest productivity gains from computing equipment, and hence the largest gains in the contribution of computing equipment to output growth, might lie in the future. In some industries, investment in computers has already led to some productivity gains. In his analysis of the electric industry, Donald Allen finds that an acceleration of investment in information technology appears to have preceded an increase in productivity. Still, although it is appealing to try to draw conclusions about the future of productivity gains from computing equipment based on analogies with the past, another economic historian, Joel Mokyr, warns that "historical analogies often mislead as much as they instruct and in technological progress, where change is unpredictable, cumulative, and irreversible, the analogies are more dangerous than anywhere."

IV. SUMMARY AND CONCLUSIONS

The dramatic increase in spending on computers over the past several decades has led many analysts to suggest that the economy has entered a New Era in which computers have made a large impact on economic activity. In particular, the analysts cite rapid growth in computer investment as the motivation for this view. However, rapid growth in investment is only one of the conditions needed for computer equipment to make a large impact on the economy. Even if this rapid growth in investment in computing equipment translates into rapid growth in the capital stock of computing equipment, the income share of computer capital must be large.

This article has used an analytical framework to quantitatively assess the impact of computers on the economy. It shows that, under standard assumptions, the contribution of computing equipment to economic growth has been modest. This reflects the fact that the income share of computing equipment has been small, primarily because the stock of computer capital is quite small relative to the size of the economy. When modifications to the standard growth accounting framework are made to reflect the possibility that computers are "special," in the sense that computers generate significant positive external benefits or that they generate larger private rates of return than other capital equipment, the contribution of computing equipment to economic growth is somewhat larger. However, in both the standard and modified frameworks there is no evidence that the contribution of computing equipment to economic growth is any greater now than it was in the late 1970s.

Some argue, however, that even though computers have not yet led us into a New Era, the full benefit from past investment in computing equipment and continued development of computer technologies and applications of computer technologies may not yet have been realized. A computer-related productivity boom may be somewhere on the not-too-distant horizon. Whether or not these prophecies come true, it is likely that, as computer equipment becomes a larger part of the overall capital stock, the computer sector will grow in importance for economic growth.

ENDNOTES

1 For discussions of this view, see articles by Mandel and Shepard.

2 In this section, the 1982-96 period was used because 1982 was the earliest year in which data on computer spending are available for all of the major components of the NIPA accounts.

3 Under the new chain-weight measure of GDP, the sum of all real GDP components will not add up exactly to total real GDP. Therefore, it is impossible to calculate exact shares of real GDP. In practice, however, the reported shares are very close approximations to the exact shares. Although exact shares of chain-weighted real GDP cannot be calculated, the shares of real GDP calculated using chain-weighted data are not sensitive to the choice of the base year. Oliner and Sichel argued that under the fixed weight measure of GDP, the share of computers in real GDP was highly dependent on the choice of the base year. One advantage of examining real shares rather than nominal shares is that it gives a better sense of the proliferation of computers in the economy, particularly since the price of computers has declined so dramatically. For a discussion of the advantages of the chain-weighted measure of GDP, see papers by Landefeld and Parker; Steindel; and Parker and Triplett.

4 Growth accounting allocates the growth rate of national output among the determinants of output that changed and caused growth.

5 Prior to 1997, the BEA did not publish measures of the capital stock of computers and peripheral equipment.

6 The nominal competitive net rate of return is calculated for each year using the following identity:

$$s_E = [(i + \delta_c - \dot{p}_c)p_c K_c + (i + \delta_{OE} - \dot{p}_{OE})p_{OE} K_{OE}] \;/\; PY\,,$$

where s_E is the income share for nonresidential equipment, which is published by the BLS, and the subscript *OE* refers to equipment other than computers. The variable $\dot{p}_{OE}$ is the growth rate of the price deflator for equipment other than computers and is computed analogously to $\dot{p}_c$. The nominal net capital stock of computing equipment other than computers, $p_{OE}K_{OE}$, was calculated using BEA data. The depreciation rate for equipment other than computers, δ_{OE}, was obtained by weighting the depreciation rates for all the assets, except computing equipment, in the nonresidential equipment category, as reported in Fraumeni, by each of these assets' shares of the total nominal capital stock of equipment other than computing equipment. This series changes from year to year, reflecting the changing composition of the capital stock of equipment.

Estimates of the competitive nominal net rate of return ranged from a minimum of 6.6 percent in 1983 to a maximum of 28.9 percent in 1974 and averaged 13.3 percent over the 1972-96 period.

7 This relationship can be formally derived by assuming that the aggregate production function takes the simple form $Y = F(K, L, t)$ where K is the capital input, L is the labor input, and t represents the shift in the production technology over time. Differentiating the production function with respect to time yields $\dot{Y} = s_K\dot{K} + s_L\dot{L} + \dot{MFP}$ where $\dot{K}$, $\dot{L}$, and $\dot{MFP}$ represent the growth rates of the real capital stock, labor input, and multifactor productivity, respectively, and s_k and s_L are the income shares of the capital stock and labor input.

8 In the case of computing equipment this is actually a capital loss because, when adjusted for changes in quality, the prices of computing equipment have declined over time.

9 This decline in the growth of the capital stock of computing equipment is roughly consistent with Morrison's observation that, for many manufacturing industries, the ratio of benefits from investment in high-technology equipment to the benefits from investing in high-technology equipment declined between 1972 and 1991. Morrison finds that a surge in returns to high-technology investment in the late 1970s was followed by a slump, indicating some overinvestment in the early to late 1980s.

10 The BLS reports that the income share of capital is approximately 30 percent. Romer suggests that when externalities are included, the income share of capital could range from a lower bound of 70 percent to an upper bound of 100 percent.

11 For each set of alternative assumptions, the real capital stock of computing equipment grew at an average rate of 34.96 percent each year.

12 To modify the nominal competitive net rate of return so that it is consistent with Romer's estimates of the effect of externalities the procedure described in endnote 5 was slightly modified. The income shares for equipment used in calculating the nominal net rate of return have been adjusted. For the high-return case, the BLS income share for equipment was multiplied by 3.33, which represents the ratio of Romer's upper bound for the income share of capital to the average income share for capital published by the BLS. Similarly, for the low-return case the BEA income share for equipment is multiplied by 2.33.

13 Learning-by-doing can also affect how a firm uses its equipment. In the aircraft example, as airlines learn more about the aircraft they are flying they are able to develop more efficient maintenance schedules and operating procedures. David (1975) offers another example of learning-by-doing. He documents substantial increases in productivity for a cotton mill in Lowell, Massachusetts, between 1836 and 1856 despite the fact that no new equipment had been added. This suggests that the productivity increases for the mill were largely attributable to learning effects.

14 This estimate was taken from Table 6 in DeLong and Summers (1992).

15 To calculate the nominal net rate of return consistent with DeLong and Summers' estimates the analysis follows the procedure used in Oliner and Sichel and developed by Auerbach, Hassett, and Oliner. This procedure calculates the nominal rate of return, *i*, using the following formula:

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

where $\beta_E = 0.151$ is the DeLong and Summers estimate, $t = 25$ is the sample length used in DeLong and Summers' estimation, δ_E is the depreciation rate for equipment, and $\dot{p}_E$ is the annual rate of capital gain for equipment. λ is calculated as $\lambda = (1 - \alpha_E - \alpha_S)(g + \delta_E)$, where α_e and α_S are the shares of equipment and structures in the economy, g is the sum of the growth rates of labor force and labor productivity, and δ_E is the depreciation rate for equipment.

16 The nominal rate of return was chosen so that the gross rate of return averaged 81 percent, given annual depreciation and the annual rate of growth in computer prices.

17 For the period over which Brynjolfsson and Hitt's estimates were made, 1987-91, when computing equipment is assumed to generate larger net rates of return than other capital assets, computing equipment contributed an average of 0.30 percentage point to output growth. For the purposes of comparison, if computing equipment is assumed to generate the same returns as other capital assets, as in the standard framework, computing equipment contributed an average of 0.20 percentage point to output growth during the 1987-91 period.

18 The modifications made to the standard neoclassical framework are based on studies that have been criticized in some quarters. For example, Auerbach, Hassett, and Oliner have argued that DeLong and Summers provided no statistically significant evidence that equipment investment resulted in positive externalities for OECD countries. Furthermore, Romer (1994) appears to have backed off his earlier claims that investment in physical capital generates external benefits in favor of the hypothesis that research and knowledge gathering activities are an important source of external benefits.

19 The 1992-96 time period that is used to calculate the averages used in the relatively optimistic scenario reflects the growth of the income share of computing equipment and the real stock of computing equipment during an expansion.

20 Of course, these two scenarios do not encompass the entire range of possibilities. During various periods since 1972, the share of income generated by computing equipment and the growth rate of the real stock of computing equipment have been larger and smaller than in the two scenarios considered in the text. For example, over the 1987-91 period, the share of income generated by computing equipment actually fell by about 0.6 percent each year while the real capital stock of computing equipment rose 24.8 percent each year. Under this very pessimistic scenario, the contribution of computing equipment would be expected to decline slowly over the next decade, adding only 0.24 percentage point to growth in 2006. However, over the 1977-81 period, the share of income generated by computers rose 11.9 percent each year, while the real stock of computing equipment rose almost 57 percent each year. Under this extremely optimistic scenario, computing equipment might be expected to contribute an astounding 2.6 percentage points to growth.

Both of these two scenarios appear to be outliers. In the case of the very pessimist scenario, only the five-year period beginning in 1988 experienced slower average growth in the share of income generated by computing equipment or the real capital stock of computing equipment. In the case of the very optimistic scenario, only the five-year period beginning in 1978 experienced faster average growth in the share of income generated by computing equipment or in the real capital stock of computing equipment.

21 Diffusion is a measure of the degree to which a particular technology has penetrated the economy. In the example of the electric dynamo, the 50 percent diffusion level represents the point at which electric motor horsepower accounted for 50 percent of the total mechanical drive horsepower used in manufacturing establishments.

REFERENCES

Allen, Donald S. 1997. "Where's the Productivity Growth (from the Information Technology Revolution)?" Federal Reserve Bank of St. Louis, *Review*, March/April, pp. 15-25.

Auerbach, Alan J., Kevin A. Hassett, and Stephen D. Oliner. 1994. "Reassessing the Social Returns to Equipment Investment," *Quarterly Journal of Economics*, vol. 109, no. 3, pp. 789-802.

Brynjolfsson, Erik, and Lorin Hitt. 1993. "New Evidence on the Returns to Information Systems," Technical Report. Center for Coordination Science, Sloan School of Management, Massachussetts Institute of Technology.

David, Paul A. 1990. "The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox," *American Economic Review*, vol. 80, no. 2, pp. 355-61.

______________. 1975. "The 'Horndal Effect' in Lowell, 1834-1856: A Short-Run Learning Curve for Integrated Cotton Textile Mills," in *Technical Choice, Innovation and Economic Growth: Essays on American and British Economic Experience*. London: Cambridge University Press.

DeLong, J. Bradford, and Lawrence H. Summers. 1992. "Equipment Investment and Economic Growth: How Strong Is the Nexus?" *Brookings Papers on Economic Activity*, no. 2, pp. 445-502.

______________. 1991. "Equipment Investment and Economic Growth," *Quarterly Journal of Economics*, vol. 106, no. 2, pp. 445-502.

Fraumeni, Barbara M. 1997. "The Measurement of Depreciation in the U.S. National Income and Product Accounts," *Survey of Current Business*, July, pp.7-23.

Greenwood, Jeremy. 1997. *The Third Industrial Revolution*. Washington, D.C.: American Enterprise Institute Press.

Landefeld, J. Steven, and Robert P. Parker. 1995. "Preview of the Comprehensive Revision of the National Income and Product Accounts: BEA's New Featured Measures of Output and Prices," *Survey of Current Business*, July, pp. 31-38.

Mandel, Michael J. 1997. "The New Business Cycle," *Business Week*, March 31.

Mokyr, Joel. 1997. "Are We Living in the Middle of an Industrial Revolution?" Federal Reserve Bank of Kansas City, *Economic Review*, Second Quarter, pp. 32.

Morrison, Catherine J. 1997. "Assessing the Productivity of Information Technology Equipment in U.S. Manufacturing Industries," *Review of Economics and Statistics*, vol. 79 no.3, pp. 471-81.

Oliner, Stephen D., and Daniel Sichel. 1994. "Computers and Output Growth Revisited: How Big Is the Puzzle?" *Brookings Papers on Economic Activity*, no. 2, pp. 273-317.

Parker, Robert P., and Jack E. Triplett. 1996. "Chain-Type Measures of Real Output and Prices in the U.S. National Income and Product Accounts: An Update," *Business Economics*, vol. 31, October, pp. 37-43.

Romer, Paul M. 1994. "The Origins of Endogenous Growth," *Journal of Economic Perspectives*, vol. 8, no. 1, pp. 3-22.

______________. 1987. "Crazy Explanations for the Productivity Slowdown," in Stanley Fisher, ed., *NBER Macroeconomics Annual: 1987*. Cambridge, Mass.: MIT Press.

______________. 1986. "Increasing Returns and Long-Run Growth," *Journal of Political Economy*, vol. 94, no. 5, pp. 1002-37.

Rosenberg, Nathan. 1982. *Inside the Black Box: Technology and Economics*. London: Cambridge University Press.

Sichel, Daniel E. 1997. *The Computer Revolution: An Economic Perspective*. Washington: Brookings Institution Press.

Sinclair, James, and Brian Catron. 1990. "An Experimental Price Index for the Computer Index," *Monthly Labor Review*, October, pp. 16-24.

Shepard, Stephen B. 1997. "The New Economy: What It Really Means," *Business Week*, November 17.

Steindel, Charles. 1995. "Chain-weighting: The New Approach to Measuring GDP," *Current Issues in Economics and Finance*, vol. 1, December, pp. 1-6.

Yardeni, Edward. 1996. "The Bond Vigilantes Should Learn to Stop Worrying and Love Computer-Led Growth," *Barron's*, September 16.