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The Resurgence of Growth in the Late 1990s: Is Information Technology the Story?

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The performance of the U.S. economy over the past several years has been nothing short of remarkable. From 1995 through 1999, real gross domestic product rose at an annual rate of more than 4 percent (based on annual average data), a notable step-up from the pace during the first four years of this expansion (1991-95). The rapid advance in recent years has been driven by a rebound in the growth of labor productivity. In the nonfarm business sector—the part of the economy on which productivity studies typically focus—output per labor hour rose at about a 2½ percent annual rate between 1995 and 1999, nearly double the average pace of the preceding 25 years. Determining the source of this resurgence ranks among the key issues now facing economists.

An obvious candidate is the high-tech revolution spreading through the U.S. business sector. In an effort to reduce costs, to coordinate large-scale operations, and to provide new or enhanced services, American firms have been investing in information technology at a furious pace. Indeed, business investment in computers and peripheral equipment, measured in real terms, jumped more than four-fold between 1995 and 1999. Outlays have also risen briskly for software and communication equipment, which are crucial components of computer networks.

We first examined the link between computers and growth in Oliner and Sichel (1994). At that time, many observers were wondering why productivity growth had failed to revive despite the billions of dollars that U.S. companies had poured into information technology over the preceding decade. We concluded that, in fact, there was no puzzle—just unrealistic expectations. Using a standard neoclassical growth accounting framework, we showed that computers should not

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have been expected to have contributed much to growth through the early 1990s. We estimated the contribution to have been modest because computing equipment still represented an extremely small fraction of the total capital stock.

This paper updates our original analysis, using essentially the same framework. Now, however, the results place information technology at center stage. The stocks of computer hardware, software, and network infrastructure have swelled, boosting their contribution to growth. In addition, the producers of computers (and the embedded semiconductors) appear to have achieved huge efficiency gains in their operations. We estimate that these developments account for about two-thirds of the acceleration in labor productivity for the nonfarm business sector between the first and second halves of the 1990s. Thus, to answer the question posed in the title, information technology largely is the story.

We begin by describing our analytical framework and the data we employ. We then offer estimates of the contribution to growth from the use of computer hardware, software, and communication equipment, as well as estimates of the efficiency gains in producing computers and semiconductors. We then take a quick look at the role of electronic commerce in the productivity speed-up and offer some conclusions.

The Analytical Framework and Data

The Basics

The neoclassical framework used here was pioneered by Robert Solow (1957) and is similar to that used in Oliner and Sichel (1994), Oliner and Wascher (1995), and Sichel (1997, 1999). Our earlier work focused on computer hardware and software. However, in recent years, the most notable innovations have involved the convergence of computers and communication equipment. The Internet, intranets, and other networks allow businesses, their employees, and consumers to share or exchange vast amounts of information. Thus, to get a more complete picture of the role of information technology in the economy, we now group communication equipment with hardware and software.[1]

We calculate the contribution to output growth from five inputs: computer hardware, computer software, communication equipment, other capital, and labor hours. The growth rate of each input (expressed as the change in logarithms) is weighted by that input's income share; under neoclassical assumptions these income shares equal the output elasticity for each input and, assuming constant returns to scale, they sum to one. In addition, we calculate the contribution from labor quality, which reflects changes in the experience, gender, and educational

[1] Other researchers also have emphasized the importance of focusing on more than just hardware to understand the role of information technology in the economy. For example, in this symposium, Brynjolfsson and Hitt discuss the importance of complementary assets, broadly defined to include hardware, software, investments in worker training, and firm-specific capital created from these inputs.

mix of the workforce over time. The portion of output growth not attributable to the five inputs or labor quality is the so-called multifactor productivity (MFP) residual. It is a catch-all for technological or organizational improvements that increase output for a given amount of input.[2]

In this approach, the growth contribution from the *use* of information technology capital equals the sum of the contributions from computer hardware, software, and communication equipment. The contribution from efficiency gains related to the *production* of computers and semiconductors is embedded in the multifactor productivity residual. Later in the paper we describe our method for extracting that component of MFP growth.

The key assumption underlying the neoclassical approach is that businesses always maintain their capital stocks at or near their optimal long-run levels, which implies that all types of capital earn the same competitive rate of return at the margin, net of depreciation and other costs associated with owning each asset. If this assumption does not hold, then a business could increase its profits by reallocating its investment dollars toward the asset with the higher net returns. Of course, such a model will not apply to every business all of the time, but it does provide a baseline common to almost all prior growth-accounting research. Below, we will say more about the way we impose the neoclassical assumption regarding asset returns.

To estimate the growth contributions, we rely heavily on data from the Bureau of Economic Analysis (BEA) and the Bureau of Labor Statistics (BLS).[3] Our starting point is the dataset assembled by BLS for its estimates of multifactor productivity. These annual data cover the private nonfarm business sector in the United States and provide measures of the growth of real output, real capital input, labor hours, and labor quality. At the time we were writing, the BLS dataset ran only through 1997. We extended all necessary series through 1999; revised the output and price figures to be consistent with the October 1999 comprehensive revision of the National Income and Product Accounts (NIPAs); added in capital stocks of software; and made a few other adjustments. In making all of these modifications, our intent was to anticipate changes that BLS would incorporate in its next release of multifactor productivity data, scheduled for fall 2000.

Measurement issues related to the Consumer Price Index (CPI) deserve further

[2] In algebraic notation, we attribute growth in output (Y) in a given year to the contributions from computer hardware (K_C), computer software (K_{SW}), communication equipment (K_M), other capital (K_O), labor hours (L), labor quality (q), and multifactor productivity (MFP):

$$\dot{Y} = \alpha_C \dot{K}_C + \alpha_{SW} \dot{K}_{SW} + \alpha_M \dot{K}_M + \alpha_O \dot{K}_O + \alpha_L(\dot{L} + \dot{q}) + \dot{MFP},$$

where the dot over a variable indicates the rate of change expressed as a log difference and the terms in α represent income shares. Time subscripts on both the growth rates and the income shares have been suppressed for notational simplicity.

[3] Here we discuss only the bare essentials of our data. For additional detail, see Appendix A of our companion working paper, Oliner and Sichel (2000).

mention.[4] The index has been modified in recent years to reduce the amount by which it overstates the true rise in the cost of living. Because components of the CPI are used to deflate parts of nonfarm business output, these changes introduced discontinuities in the measurement of real output growth and inflation. The October 1999 NIPA revision took account of these changes in the CPI back to 1978. Thus, by forcing our output and price data to reflect the NIPA revision, we automatically folded in these changes back to that year; for earlier years, we adjusted for CPI revisions based on information in the Economic Report of the President (1999, p. 94).

Capital Stocks

The capital stocks that we use throughout the analysis are "productive" stocks, so named because they measure the income-producing capacity of the existing stock during a given period. This concept of capital stock differs from a "wealth" stock, which measures the current market value of the assets in use. For growth accounting, the productive stock is the appropriate measure because we are interested in how much computers and other assets produce each period, not in tracking their market value.

The following example illustrates the difference between these two types of capital stocks. Suppose that we had three personal computers: a Pentium that was just purchased and two 486s that were purchased three years ago. Assume, also, that the Pentium is twice as powerful as each 486 and that all units will be scrapped after four years of service with no residual value. To calculate either a wealth or a productive stock, these personal computers must first be converted to a comparable-quality basis. Using the Pentium as the numeraire, each 486 (when new) would count as one-half of a Pentium unit.[5] If the 486s suffer no loss of efficiency while in use, the total productive stock of computers would equal two units on a Pentium-equivalent basis (one unit for the Pentium and one unit for the two 486s). The wealth stock, however, would be less than two units. To see why, note that the 486s, being three years old in our example, have only one more year of service before retirement; in contrast, the currently new Pentium has four years of service remaining. This means that the future rental income to be earned by the two 486s together is only one-fourth that to be earned by the Pentium. (The two 486s produce the same income as a Pentium in any given period, but their remaining service life is only one-fourth as long.) Apart from the effects of discounting these future income flows, the two 486s together would sell today for only one-fourth of the Pentium's price, making the wealth stock equal to 1¼ Pentium-equivalent units. Thus, the wealth stock would be smaller than the productive stock, illustrating the need to distinguish between these two types of capital stock.

[4] The Winter 1998 issue of this journal contained a symposium on CPI measurement. For an overview of this topic, see Boskin et al. (1998).

[5] BEA's price indexes for computers make just such an adjustment; that is, nominal purchases of computers each year are deflated with a "constant quality" price series, so that a dollar of real investment in computers in a given year represents the same amount of computing power as a dollar of real investment in another year.

Although personal computers experience little, if any, physical decay, they may still lose productive efficiency as they age, in which case the 486s should be counted as less than one Pentium-equivalent unit in the productive stock. It may seem odd to argue that the 486s become less efficient if they can still run all the same software as when new. However, the assumption of no loss in efficiency actually imposes a strong condition—that the two 486s in our example remain a perfect substitute for the Pentium *throughout their entire useful life*. This condition need not hold. For example, if the two old 486s taken together cannot run the latest software, a single Pentium could be considerably more useful than two 486s. Thus, for the purposes of estimating a productive stock of capital, it may be appropriate to downweight somewhat the productive efficiency of older computers, even if there were no physical decay.

It is hard to know how much efficiency loss to build in for computers. BLS constructs productive stocks (for computers and all other tangible capital) that incorporate some decline in productive efficiency with age. We use the BLS estimates of productive capital stocks whenever possible and follow their methodology when we need to construct productive stocks from scratch.[6]

Our estimate of the growth contribution from computer hardware is built up from very detailed data on productive stocks. We start with the BLS estimates of productive stocks for mainframes, personal computers, terminals, printers, and three different types of storage devices.[7] Following the BLS methodology, we calculate the growth contribution of each such asset (as the product of its income share and the growth of the productive stock) and sum these growth contributions to estimate the total contribution of computer hardware. For software, no estimates of the productive stock were available at the time we were writing. However, in the 1999 NIPA revision, BEA did begin to publish data on aggregate investment in software. We used these investment data, and information from BEA about the service lives for software, to construct a productive stock of software capital. The growth contribution from software equals the product of the growth of this stock and the estimated income share for software. For communication equipment, the growth contribution is based on the BLS published series for the productive capital stock and our estimate of the income share. Finally, to measure the contribution of other capital, we start with the contribution from total capital (excluding software) and net out the contributions from computer hardware and communication equipment.

[6] In our earlier work, we incorrectly used wealth stocks to calculate the income share of computers. Had we used productive stocks, the growth contribution of computers reported in that earlier work would have been somewhat larger. Nonetheless, the basic conclusion in our prior papers—that computer use had not made a large contribution to growth through the early 1990s—would still hold.

[7] For personal computers, we recalculated the entire series for the productive stock. As part of the comprehensive NIPA revision in October 1999, BEA announced that it had shortened the assumed service life for personal computers, and in response, we calculated a productive stock of personal computers with a shorter (five-year) service life.

Income Shares

Our growth-accounting calculations depend importantly on the income shares of the various inputs. These income shares are not directly observable, and we estimate them in accord with the method used by BLS. To illustrate this procedure, consider the income share for personal computers. We begin with a measure of the nominal (productive) stock of this asset. This stock earns a gross rate of return that must cover the real net rate of return common to all capital, together with taxes and the loss of value that personal computers suffer over time. The product of the gross rate of return and the nominal productive stock equals the nominal income flow generated by personal computers, which we divide by total nominal income for the economy to obtain the desired income share. We estimate the income share for each type of capital in this way. The income share for labor input is then measured as one minus the sum of the income shares for the various types of capital.

As indicated in our example, the gross rate of return for a personal computer must cover, among other costs, the decline in its value over a given period (say, one year). This loss of value can be decomposed into two parts, reflecting the fact that a personal computer ages by one year with the passage of each year of calendar time. The time-related part captures the decline in prices of new personal computers, holding quality constant, while the age-related part captures the additional price decline due to depreciation. Together, these two terms account for the personal computer's full loss of value over the course of a year. The same decomposition holds for any asset, except that the capital loss term becomes a capital gain when the asset's constant-quality price rises over time.[8]

To measure the components of the gross return, we rely once again on data from BEA and BLS. With just a few exceptions, the depreciation rates for the various types of equipment and structures are those published by BEA.[9] For the capital gain or loss, we use a three-year moving average of the percent change in BEA's constant-quality price series for each asset relative to the price of nonfarm business output. The moving average smooths the often volatile yearly changes in prices and probably conforms more closely to the capital gain or loss that asset

[8] In the BLS framework, the income share for personal computers in a given year is

$$\alpha_C = [r + \delta_C - \pi_C] p_C K_C T_C / pY,$$

where r is a measure of the real net rate of return common to all capital, pY is total nominal output (or income), and all other terms refer specifically to personal computers: δ_C is the depreciation rate, π_C is the rate of capital gain (actually, capital loss for personal computers), $p_C K_C$ is the nominal capital stock, and T_C represents a variety of tax terms. Note that π_C represents the rate of price change for personal computers relative to inflation for total output in the nonfarm business sector. Thus, it measures the real change in personal computer prices, consistent with the use of a real return (r) in the equation. Alternatively, r and π_C both could have been specified in nominal terms.

[9] See Fraumeni (1997) for the BEA depreciation rates. Because BEA does not publish depreciation rates for the components of computers and peripheral equipment, we follow Whelan (2000) and set the depreciation rates equal to a geometric approximation calculated from capital stocks and investment flows, with the depreciation rate for personal computers set equal to that for mainframes.

owners expect to bear when they make investment decisions. Finally, to calculate the real net return, we mimic the BLS procedure, which computes the average realized return on the entire stock of equipment and structures. This estimate of the average real net return varies over time, but for recent years, it has averaged about 4 percent annually. By using this average return in the income share for each asset, we impose the neoclassical assumption that all types of capital earn the same net return in a given year.

Concluding the example for personal computers, consider the value of the gross return implied by our procedure for recent years. We start with the 4 percent net real return on all assets, and then add on a depreciation rate of about 30 percent and a capital loss term in the same neighborhood. This calculation implies a gross return for personal computers that exceeds 60 percent per year. Because personal computers become obsolete so rapidly, the gross return must be quite large to cover the sharp decline in their market value each year, while still providing a competitive return net of depreciation.

Growth Contribution From the Use of Information Technology

Table 1 presents our decomposition of the growth in nonfarm business output.[10] The first line of the table shows the output growth rate to be explained, while lines 2-9 allocate this growth among the contributions from the five inputs, labor quality, and multifactor productivity.[11] The contributions from the five inputs equal (approximately) the product of the income shares in lines 10-14 and the respective input growth rates in lines 15-19. The equality is approximate because the growth contributions are actually calculated on the basis of year-by-year data for the income shares and input growth rates, not period averages, and because all the figures in the table have been rounded.

The first two columns, which cover 1974-90 and 1991-95, tell a similar story to that in our earlier work. In these periods, real nonfarm business output rose at an average pace of around 3 percent per year. Computer hardware accounted for about 0.25

[10] Shortly before publication of this paper, BEA released its latest annual revision of the National Income and Product Accounts. All of the numbers reported here were calculated prior to that revision. Incorporating the revised data would not materially change the rates of growth we show for output and labor productivity, but the contribution of information technology capital to growth would be slightly greater than the results we present here.

[11] Note that the figures in line 1 of the table are based on the BLS published series for nonfarm business output. This series is a "product-side" measure of output, which reflects spending on goods and services produced by nonfarm businesses. Alternatively, output could be measured from the "income side" as the sum of payments to capital and labor employed in that sector. Although the two measures of output differ only slightly on average through the mid-1990s, a sizable gap has emerged in recent years. By our estimates, the income-side measure has grown more than one-quarter percentage point faster (at an average annual rate) since 1995. We employ the published product-side data because no one knows the appropriate adjustment (if any) to these data; using the published data also allows us to maintain consistency with other studies. Nonetheless, the true pickup in output growth after 1995 could be somewhat larger than that shown in the table.

Table 1
Contributions to Growth of Real Nonfarm Business Output, 1974–1999

	1974–90	*1991–95*	*1996–99*
1. Growth rate of output:[a]	3.06	2.75	4.82
Contributions from:[b]			
2. Information technology capital	.49	.57	1.10
3. Hardware	.27	.25	.63
4. Software	.11	.25	.32
5. Communication equipment	.11	.07	.15
6. Other capital	.86	.44	.75
7. Labor hours	1.16	.82	1.50
8. Labor quality	.22	.44	.31
9. Multifactor productivity	.33	.48	1.16
Memo:			
Income shares:[c]			
10. Hardware	1.0	1.4	1.8
11. Software	.8	2.0	2.5
12. Communication equipment	1.5	1.9	2.0
13. Other capital	27.9	26.8	26.7
14. Labor hours	68.9	67.9	66.9
Growth rate of inputs:[a]			
15. Hardware	31.3	17.5	35.9
16. Software	13.2	13.1	13.0
17. Communication equipment	7.7	3.6	7.2
18. Other capital	3.1	1.6	2.8
19. Labor hours	1.7	1.2	2.2

[a] Average annual log difference for years shown multiplied by 100.
[b] Percentage points per year.
[c] Percent.
Note: In lines 1 to 9, detail may not sum to totals due to rounding. Also, the product of growth rates of inputs (lines 15 to 19) and of income shares (lines 10 to 14) differs slightly from the value of growth contributions (lines 3 to 7), which are calculated on the basis of year-by-year data, not period averages.
Source: Authors' calculations based on BEA and BLS data.

percentage point per year of that growth. Software contributed 0.1 percentage point per year during 1974-90, with its contribution rising to 0.25 percentage point per year during 1991-95. These figures for software are a little bigger than in our earlier work. Previously, we counted only pre-packaged software, but the new software data from BEA also include custom software (produced when businesses hire outside consultants to write programs) and own-account software (produced in-house by employees). Communication equipment, the final component of information technology capital, contributed about 0.1 percentage point annually to output growth in both periods.[12]

[12] Some analysts, most recently Jorgenson and Stiroh (2000), have expressed concern that the BEA measure of price inflation for communication equipment may be biased upward because the agency uses "hedonic" price measures only for selected components of this aggregate. If the price series were biased in this way, the corresponding data on growth in real investment and capital stock would be biased downward. By implication, the contribution of communication equipment to output growth shown in Table 1 would understate the true contribution.

Adding these pieces, information technology capital accounted for roughly 0.5 percentage point of output growth per year during both 1974-90 and 1991-95 (line 2).

Calculations such as this were the basis for our earlier conclusion that the growth contribution from information technology had been relatively small through the early 1990s, especially if one focused on computer hardware alone. During the first half of the 1990s, the stock of computer hardware increased at an average rate of more than 17 percent per year, but its income share averaged just 1.4 percent (lines 10 and 15 of the table). Hence, the growth contribution from computer hardware to output growth, measured as the product of these figures, was only about 0.25 percentage point in this period.

However, the contribution from information technology capital to output growth surged in the second half of the 1990s. We estimate that the contribution from computer hardware alone more than doubled during 1996-99 to about 0.6 percentage point per year, while the total contribution from information technology capital nearly doubled to 1.1 percentage points. This step-up is even more evident in Figure 1, which plots the contributions year by year. The larger contributions since the mid-1990s reflect both the increased importance of information technology capital in the economy (as measured by their income shares) and the faster growth in the real stocks of computer hardware and communication equipment compared with the average pre-1995 pace.

These results pertain to a decomposition of output growth. A closely related decomposition focuses on growth in labor productivity, measured as output per hour worked. To derive this second decomposition, we subtract the growth in aggregate hours worked from the growth of output and from the growth of the various inputs (that is, from both sides of the original growth-accounting equation). In the resulting decomposition, growth in labor productivity reflects increases in the amount of capital per hour worked—referred to as capital deepening—and growth in labor quality and multifactor productivity. The capital deepening portion is further divided into the contribution from computer hardware, software, communication equipment, and other capital.[13]

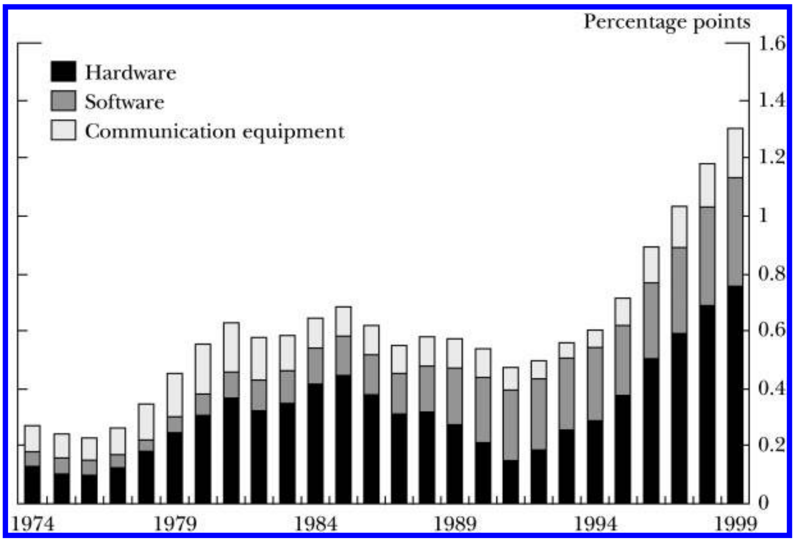
Table 2 presents this decomposition of productivity growth. As shown in the first line of the table, growth in labor productivity picked up from about 1.5 percent per year in the first half of the 1990s to nearly 2.6 percent in the second half. The rapid capital deepening related to information technology capital accounted for nearly half of this increase (line 3). Other types of capital (line 7) made almost no contribution to the step-up in labor productivity growth, while the contribution from labor quality

[13] The equation in note 2 can be transformed into one for labor productivity by subtracting the growth rate of total hours worked from both sides of that equation, yielding:

$$\dot{Y} - \dot{L} = [\alpha_C(\dot{K}_C - \dot{L}) + \alpha_{SW}(\dot{K}_{SW} - \dot{L}) + \alpha_M(\dot{K}_M - \dot{L}) + \alpha_O(\dot{K}_O - \dot{L})] + \alpha_L\dot{q} + M\dot{F}P.$$

Note that this decomposition spreads the entire workforce across the various types of capital in a uniform fashion; it does not associate any particular group of workers with a specific type of capital.

Figure 1
Contributions From the Use of Computer Hardware, Software and Communication Equipment to Growth of Real Nonfarm Business Output, 1974-1999



actually fell across the two periods. This leaves multifactor productivity to account for more than half of the recent improvement in labor productivity growth.

The exercises we have performed with this growth-counting framework have some limitations. First, they capture only the proximate sources of output growth: namely, the accumulation of capital and labor, plus multifactor productivity. In particular, this framework does not model the underlying technical improvements that have driven the accumulation of capital. In this sense, the neoclassical framework provides a superficial explanation of growth. Second, this framework cannot satisfactorily explain why growth slowed in the 1970s; it largely attributes this slowdown to a mysterious deceleration in multifactor productivity. We make no attempt to address this puzzle.[14] Our goal here is only to assess how much of the recent resurgence of growth can be explained, under reasonable assumptions, by factors related to information technology.

So far, we have shown that the *use* of information technology capital contributed importantly to this resurgence of growth. Later in the paper, we will discuss the separate contribution from the *production* of computers and semiconductors.

[14] Others have attempted to explain the earlier slowdown in MFP growth. For example, see Fischer (1988) and accompanying articles in a *Journal of Economic Perspectives* symposium. More recently, Greenwood and Yorukoglu (1997), Greenwood and Jovanovic (1998), and Kiley (1999) argue that the adoption of information technology in the 1970s was itself responsible for the slowdown because it took firms a long time to learn how to use the new equipment effectively. This view is controversial. Kortum (1997) questions the empirical importance of these adoption costs, while Hornstein (1999) shows that the theoretical results depend crucially on the specification of the learning process.

Table 2
Contributions to Labor Productivity Growth in the Nonfarm Business Sector, 1974–1999

	1974–90	*1991–95*	*1996–99*
1. Growth rate of labor productivity:[a]	1.37	1.53	2.57
Contributions from:[b]			
2. Capital deepening	.81	.62	1.10
3. Information technology capital	.44	.51	.96
4. Hardware	.25	.23	.59
5. Software	.09	.23	.27
6. Communication equipment	.09	.05	.10
7. Other capital	.37	.11	.14
8. Labor quality	.22	.44	.31
9. Multifactor productivity	.33	.48	1.16

[a] Average annual log difference for years shown multiplied by 100.
[b] Percentage points per year.
Note: Detail may not sum to totals due to rounding.
Source: Authors' calculations based on BEA and BLS data.

Comparisons to Other Studies: The Growth Contribution from Using Computer Hardware

Recently, several other researchers have estimated the growth contribution from the use of computer hardware. Two of our colleagues at the Federal Reserve Board, Michael Kiley and Karl Whelan, have taken sharply different approaches to address this question. In addition, Dale Jorgenson and Kevin Stiroh have produced estimates within the well-known framework that Jorgenson and various collaborators developed to measure the sources of economic growth.[15] Table 3 displays the widely varying results from the various studies. We will briefly explain why the other estimates in the table differ from our own.

Whelan's (2000) estimate of the growth contribution from computers exceeds ours mainly because of a difference in measurement. He uses a productive stock of computers that is roughly one-third larger than ours, which boosts his estimate of the income share (and, in turn, the growth contribution) by the same proportion. As noted above, we follow the BLS method for estimating productive capital stocks, which allows for some loss of efficiency before retirement. This allowance reflects the view that older vintages of assets, including computers, become less productive with age, even if they remain in perfect physical condition. Whelan assumes instead that each (quality-adjusted) dollar of investment in personal computers, mainframes, and most other types of computing equipment remains fully productive until retirement. Although we believe Whelan's measure of the productive stock is on the high side, we certainly

[15] See Jorgenson, Gollop, and Fraumeni (1987) for a detailed description of this framework; Ho, Jorgenson, and Stiroh (1999) provide a more abbreviated account.

Table 3
Contribution from Computer Hardware to Output Growth: Comparison to Other Studies

	Previous Period		Current Period	
Study	*Years Covered*	*Contribution*[a]	*Years Covered*	*Contribution*[a]
1. This paper	1991–95	.25	1996–99	.63
			1996–98	.59
2. Whelan (2000)	1990–95	.33	1996–98	.82
3. Jorgenson-Stiroh (2000)	1991–95	.19	1996–99	.49
4. Kiley (1999)	1974–84	−.34	1985–98	−.27

[a] Percentage points per year.
Sources: This paper: Authors' calculations based on BEA and BLS data. Whelan (2000): Table 4 (Column labeled "Obsolescence Model"), p. 34. Jorgenson-Stiroh (2000): Table 2 (Line labeled "Computers (K_c)"). Kiley (1999): Table 3 (Line labeled "Computers"); these figures refer to the version of his model with "moderate" adjustment costs.

cannot rule out that we have underestimated the growth contribution from computer hardware by a tenth of a percentage point or two.

Jorgenson and Stiroh (2000) estimate the growth contribution from computer hardware to be a little smaller than we do, both before and after 1995. This difference arises chiefly because their concept of output is broader than ours. Jorgenson and Stiroh include imputed service flows from owner-occupied housing and consumer durables, which are excluded from the BLS output series we use. With these additions to output, the income share attributed to business computers falls; in effect, business-owned computers are a smaller part of the economy they choose to measure.

Despite these differences, all three studies tell the same basic story—that the use of computer hardware made a substantially larger contribution to output growth during the second half of the 1990s than during the first half.

In contrast, Kiley (1999) estimates that the growth contribution from computer hardware has been negative since the mid-1970s. Kiley obtains this result by modifying the growth-accounting framework in an important way. He assumes that investment in new computers entails "adjustment costs," a phrase meant to capture any disruption to the firm's normal activities. As a result, his growth-accounting equation includes a term for the rate of computer investment, which has a negative coefficient. Because computer investment has been very strong, Kiley's model generates large adjustment costs—so large that they swamp the output from the existing stock of computers. The adjustment costs in Kiley's model will diminish only when the boom in computer investment comes to an end. When this eventually happens, he estimates that the growth contribution from computers will become positive, adding about 0.5 percentage point annually to the growth rate in the steady state.

In our view, Kiley's adjustment cost framework overstates the importance of start-up costs associated with the transition to new computer systems. His framework implies that the costs of managing these systems would drop back notably once the transition period of heavy computer investment is over. This implication seems at odds with the high level of "care and feeding" required by computer systems of all types, including ongoing costs for software upgrades, user training and support, and system upkeep.

Growth Contribution from the Production of Computers

So far, we have focused on the contribution from the *use* of information technology capital. However, this is only part of the story. An additional growth contribution can come through efficiency improvement in the *production* of computing equipment. In this section, we will identify the part of multifactor productivity growth that can be attributed to improvements in computer production, using a framework developed by Hulten (1978) and implemented recently by Stiroh (1998), among others. For our analysis, "computer production" encompasses not only the assembly of computers but also the production of the semiconductor chips that form the heart of computers. Including semiconductors is important because the extraordinary advances in chip technology (Triplett, 1996) ultimately account for a large share of computer-sector productivity gains.

We model the nonfarm business economy as having three sectors. One produces semiconductors, another manufactures computers, and the final sector represents all other industries. Each sector has its own production function, with output growth depending on the accumulation of inputs and growth in sectoral multifactor productivity. In a multisector model, one must specify the input-output connections among the sectors. Our primary focus is on the one connection that really matters for our analysis—the use of semiconductors as an input by the other two sectors. Our companion working paper, Oliner and Sichel (2000), fully describes this three-sector model; here, we discuss the main thrust of the work.

In our framework, aggregate multifactor productivity growth is a weighted average of MFP growth in the three sectors. The weight for each sector equals its gross output as a share of total nonfarm business output, in current dollars. This is the sectoral weighting scheme initially proposed by Domar (1961) and formally justified by Hulten (1978). In this framework, the weights sum to more than one, which may seem odd at first blush. However, this scheme is needed to account for the portion of each sector's output sold as an intermediate input to other sectors rather than as a final product. Without this "gross-up" of the weights, the MFP gains achieved in producing intermediate inputs would be omitted from the decomposition of aggregate MFP growth.

To implement this decomposition, we need estimates of the sectoral multifactor productivity growth rates and the output-share weights. Take the weights first. For the computer sector, we measure current-dollar output as final purchases of computers in the National Income and Product Accounts, with a small add-on to capture computer products that are sold as intermediate inputs. For current-dollar semiconductor output, we use internal Federal Reserve Board estimates developed to support the Fed's published data on U.S. industrial production. For the rest of nonfarm business, current-dollar output simply equals total nonfarm business output less final purchases of computers. We divide each output series by nonfarm business output to estimate the output-share weights.

We estimate sectoral multifactor productivity growth with the "dual" method employed by Triplett (1996), Macroeconomic Advisers (1999), and Whelan (2000). This method uses data on the prices of output and inputs, rather than their quantities, to calculate sectoral MFP growth. We opted for the dual method because the required price data are more readily available than are some of the quantity data. Our data on output prices consist of BEA and BLS price measures for final computer output and other nonfarm business output, plus internal Federal Reserve Board estimates of semiconductor prices.

To see how prices contain information about sectoral multifactor productivity growth, consider an example involving the semiconductor sector, where output prices have trended sharply lower over time. Assume that input prices for the semiconductor sector have been stable. Then, given the steep decline in the relative price of semiconductors, MFP growth in that sector must be rapid compared to that elsewhere. Were it not, semiconductor producers would be driven out of business by the ever-lower prices for their output in the face of stable input costs. This example illustrates the link between movements in relative output prices and relative growth rates of sectoral MFP, and we rely on this linkage to estimate MFP growth in the three sectors.

In the preceding example, we abstracted from changes in relative input costs across sectors. However, semiconductors loom large in the cost structure for computer producers, so we know that input costs for that sector are falling relative to those elsewhere. If we ignored this decline in input costs, we would overstate multifactor growth in the computer sector. To avoid this bias, our model accounts for differences in the use of semiconductor inputs across sectors.

Table 4 presents our estimates of the sectoral contributions to MFP growth for total nonfarm business. These contributions, shown in lines 2-4, equal (approximately) the product of the output shares in lines 6-8 and the corresponding estimates of sectoral MFP growth in lines 9-11. As in Table 1, these products differ a little from the contributions in the top half of the table because the contributions are based on year-by-year data, not period averages, and because all the figures have been rounded.

The results show that the multifactor productivity contributions from computer and semiconductor producers moved up sharply during 1996-99, reaching 0.26 and 0.39 percentage point per year, respectively. The increases largely reflect the faster decline in the relative prices of computers and semiconductors during this period—which this framework interprets as signaling a pickup in MFP growth—and the rising output shares of computer and semiconductor producers. As we noted above, the activities undertaken by the "computer sector" include not only the actual assembly of computers but also the development and production of the embedded semiconductors. Line 5 presents an estimate of the MFP contribution from such a vertically integrated computer sector. This estimate equals the

Table 4
Sectoral Contributions to Growth in Nonfarm Business Multifactor Productivity

	1974–90	*1991–95*	*1996–99*
1. Growth rate of nonfarm business MFP[a]	.33	.48	1.16
Contribution from each sector:[b]			
2. Computer sector	.12	.16	.26
3. Semiconductor sector	.08	.12	.39
4. Other nonfarm business	.13	.20	.50
5. Computer sector plus computer-related semiconductor sector	.17	.23	.49
Memo:			
Output shares:[c]			
6. Computer sector	1.1	1.4	1.6
7. Semiconductor sector	.3	.5	.9
8. Other nonfarm business	98.9	98.8	98.7
Growth of MFP:[a]			
9. Computer sector	11.2	11.3	16.6
10. Semiconductor sector	30.7	22.3	45.0
11. Other nonfarm business	.13	.20	.51

[a] Percent per year.
[b] Percentage points per year.
[c] Percent. Note that the shares sum to more than 100. See the text for details.
Note: In lines 1 to 4, detail may not sum to totals due to rounding. Also, the product of sectoral output shares (lines 6 to 8) and of sectoral MFP growth (lines 9 to 11) differs slightly from the value of growth contributions (lines 2 to 4), which are calculated on the basis of year-by-year data, not period averages.
Source: Authors' calculations based on data from BEA, BLS, and the Semiconductor Industry Association, along with internal Federal Reserve estimates for semiconductor output and prices.

MFP contribution from computer production, plus 60 percent of the MFP contribution from semiconductor production. (We use 60 percent because U.S. computer producers account for roughly that share of total U.S. consumption of semiconductors, according to data from the Semiconductor Industry Association.)

As can be seen by comparing lines 1 and 5, this vertically integrated computer sector accounted for roughly two-fifths of the growth in nonfarm business MFP during the second half of the 1990s. This sector accounted for an even larger part—about one-half—of the smaller MFP gains during 1974-90 and 1991-95. These are remarkable percentages given the tiny share of this integrated computer sector in total current-dollar output, and they attest to the extraordinary pace of innovation in this part of the economy.

In accord with the "dual" framework described above, we have interpreted the sharp decline in semiconductor prices after 1995 as signaling a pickup in that sector's MFP growth, but that is not the only possible interpretation. Our framework implicitly assumes that profit margins are fixed, so that any drop in output prices relative to input costs must be mirrored by an increase in MFP. However, one could question whether the fixed-margin assumption has held in recent years for the semiconductor industry. Worldwide capacity to produce semiconductors bulged in the mid-1990s, followed by financial crises during 1997-98 in Asia and

Latin America, which restrained demand for semiconductors. These developments created a glut for some semiconductor products (notably, memory chips) and intensified the downward pressure on prices.

If multifactor productivity growth had not picked up at the same time, we would expect profit margins for U.S. semiconductor producers to have narrowed. In fact, we find no such pattern in the data. For each year from 1990 to 1999, we computed the profit margin, defined as net income divided by net sales, for the five largest U.S. semiconductor producers (Intel, Texas Instruments, National Semiconductor, Advanced Micro Devices, and Micron Technology). The results differed widely across companies, but the aggregate profit margin for the five companies taken together *rose* from an average of 11.8 percent during 1990-95 to 15.6 percent during 1996-99. This evidence suggests that the sharp decline in semiconductor prices after 1995 was accompanied by rapid efficiency gains for U.S. producers.

To get behind these numbers, we consulted with some seasoned observers of the semiconductor industry. Their views varied somewhat, but the consensus was that U.S. semiconductor producers weathered the difficult market conditions in the late 1990s because they had been able to achieve substantial improvements in efficiency. On the whole, U.S. producers fared better than their foreign rivals, who tended to be less technologically advanced. In addition, our contacts indicated that the rapid increase in multifactor productivity was not driven by a single innovation, but instead reflected numerous breakthroughs that allowed producers to increase greatly the amount of circuitry on a single chip.

Growth Contributions: Our Full Story

We pull together the strands of our story in Table 5, which decomposes the roughly 1 percentage point acceleration in labor productivity between the first half and the second half of the 1990s. As shown, we attribute 0.45 percentage point of the pickup to the growing use of information technology capital throughout the nonfarm business sector. The rapidly improving technology for producing computers (and the embedded semiconductors) contributed another 0.26 percentage point to the acceleration. Taken together, these factors account for about two-thirds of the speed-up in labor productivity growth since 1995. The growth in other capital services per hour explains almost none of the acceleration, while multifactor productivity growth elsewhere in nonfarm business accounts for the remainder. These results suggest that information technology has been the primary force behind the sharp gains in productivity growth, especially if one includes MFP growth for the entire semiconductor sector, not just the part that feeds into the computer industry.

A Different View of the Recent Experience

Robert Gordon's paper in this issue argues that the productivity revival has been concentrated in the small part of the economy that produces information

Table 5
Acceleration in Labor Productivity from 1991–95 to 1996–99[a]

1. Labor productivity	1.04
Contributions from:	
2. Information technology capital services per hour	.45
3. MFP in computer production and computer-related semiconductor production	.26
4. Other capital services per hour	.03
5. Labor quality	−.13
6. MFP in other semiconductor production	.11
7. MFP in other nonfarm business	.30

[a] Percentage points per year.
Note: Detail may not sum to totals due to rounding.
Source: Results shown in tables 2 and 4.

technology capital and that elsewhere the influence of information technology has been slight. Gordon's story appears to conflict with our emphasis on the widespread benefits from the use of such capital, but his analysis actually has much in common with our own. Indeed, Gordon uses our numbers for capital deepening (which includes the contribution from the use of information technology) and for the contribution from computer production to multifactor productivity growth.

The key difference between Gordon's analysis and our own is that he focuses on *trend* productivity growth while we explain developments in *actual* productivity growth. At the outset, Gordon removes the sizable part of recent growth in labor productivity that he attributes to cyclical factors. He then subtracts our figures for the contributions from capital deepening and MFP growth in computer production. After these subtractions, Gordon finds that trend MFP growth outside the production of computers has not picked up. This finding forms the basis for his pessimistic conclusion about the role of information technology in the economy.

Separating cycle from trend is always difficult in the midst of an expansion, and it is particularly challenging now because the current expansion has not conformed to cyclical norms. Despite this uncertainty, Gordon takes a strong stand on how much of the recent improvement in the nation's productivity performance has been cyclical. Whatever opinion one has of the particulars of Gordon's cyclical adjustment, the fact remains that his numbers embed our basic finding—that the *production* and *use* of information technology have contributed importantly to the actual pickup in productivity growth since 1995.

E-Commerce

Over the past few years, the volume of e-commerce has exploded, giving rise to anecdotes about the huge productivity gains that have resulted from associated declines in transaction and information costs. Thus far, we have not explicitly considered e-commerce, but our data—and hence our results—already incorporate its impact to a large extent.

To see why, start with our output measure. Most business-to-consumer e-commerce would be included in the usual surveys of retail sales and consumer prices that underlie the National Income and Product Accounts. Business-to-business e-commerce mainly represents transactions in intermediate inputs. These transactions would not create new difficulties for estimating real GDP because the current system measures final demand, not the underlying intermediate sales. Moreover, in a competitive equilibrium, any efficiencies achieved in the distribution of intermediate inputs would show up in the prices or quantities of final goods and services. Similarly, on the input side, our series for the productive stocks of computer hardware, software, and communication equipment would include the infrastructure to support e-commerce, and our measure of labor input would cover workers involved in such activities.

Because the inputs and output related to e-commerce are embedded in our data, the multifactor productivity residual that we calculate would include the effect of e-commerce on business efficiency. If e-commerce enables goods and services to be produced and delivered using fewer total resources—rather than just representing a shift in distribution channels—it could be one factor that has pushed up MFP growth in recent years. However, a back-of-the-envelope calculation suggests that, to date, any such efficiency effects have been small.

Cross (1999) surveyed estimates of e-commerce transactions and provided "aggressive" and "conservative" estimates for 1999. Taking the "aggressive" estimates to get an upper bound, the business-to-business figure is $112 billion and the estimate for the business-to-consumer segment is $23 billion. Of this $135 billion in e-commerce, how much could represent a gain in efficiency and productivity?

To develop a rough estimate, we turn to a recent study that compared prices on the Internet to those at bricks-and-mortar outlets. Brynjolfsson and Smith (2000) examined prices for books and CDs in 1998 and 1999 and found that Internet prices were 9 to 16 percent lower than those in conventional stores. Of course, part of the current price differential between on-line and bricks-and-mortar outlets likely represents a short-term effort by on-line retailers to gain customers. Indeed, very few of the on-line retailers have turned a profit at the discounted prices they are offering to the public. Thus, we use a round figure of 10 percent, near the lower end of Brynjolfsson and Smith's range, as an estimate of the true resource saving associated with e-commerce. For lack of other information, we assume that this figure also represents the true resource saving in the business-to-business segment.

Putting together the pieces, a 10 percent resource reduction implicit in $135 billion of sales implies $15 billion in cost savings. (If sales after a 10 percent cost saving are $135 billion, the counterfactual base is $150 billion, and a 10 percent saving represents $15 billion.) With total output in the nonfarm business economy amounting to about $7 trillion, these cost savings represent only 0.2 percent of output. Assuming that these savings accrued as e-commerce built up during 1996-99, the effect of e-commerce on MFP growth would be considerably less than 0.1 percentage point per year.

This back-of-the-envelope calculation suggests that the spread of e-commerce has had little effect to date on MFP growth. Nevertheless, all indications are that the volume of e-commerce (including both business-to-business and business-to-consumer) will continue to grow in coming years, raising the possibility of more substantial efficiency gains in the future. Indeed, Brookes and Wahhaj (2000) use input-output analysis to argue that business-to-business e-commerce will make a considerable contribution to economic growth over the next ten years. However, their numbers, like ours, suggest that the effect has been small so far.

Conclusion

The growth of labor productivity rebounded in the second half of the 1990s, drawing attention to the role that information technology may have played. This attention appears to have been well-deserved, as we estimate that information technology accounted for about two-thirds of the step-up in labor productivity growth between the first and second halves of the decade.

What does the future hold? We have no crystal ball, but our best guess is that the growth contribution from information technology capital—including both its use and its production—will stay relatively strong for at least the next few years. Demand for information technology capital has remained robust (according to data through mid-2000), which suggests that the growth contribution from using such capital has not retreated from the historic high in 1999. Moreover, even if this contribution were to drop back a little in coming years, it would still be above the average in the second half of the 1990s. Turning to the production of computers and semiconductors, it is unclear whether the rapid efficiency gains in recent years can be sustained. Our discussions with industry observers yielded no consensus on this issue. But even allowing for some reversion to the historical average, the productivity gains in this sector would greatly outstrip those elsewhere in the economy. This fact, combined with the now-larger share of total output produced by this dynamic sector, would provide an ongoing boost to productivity growth for the economy as a whole.

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