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

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ABSTRACT

The performance of the U.S. economy over the past several years has been remarkable, including a rebound in labor productivity growth after nearly a quarter century of sluggish gains. To assess the role of information technology in the recent rebound, this paper re-examines the growth contribution of computers and related inputs with the same neoclassical framework that we have used in earlier work. Our results indicate that the contribution to productivity growth from the *use* of information technology — including computer hardware, software, and communication equipment — surged in the second half of the 1990s. In addition, technological advance in the *production* of computers appears to have contributed importantly to the speed-up in productivity growth. All in all, we estimate that the *use* of information technology and the *production* of computers accounted for about two-thirds of the 1 percentage point step-up in productivity growth between the first and second halves of the decade. Thus, to answer the question posed in the title of this paper, information technology largely is the story.

1. INTRODUCTION[1]

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 roughly 4 percent (based on annual average data). This rapid advance was accompanied by a rebound in the growth of labor productivity, with output per hour in nonfarm business rising at more than a 2-½ percent annual rate — nearly double the average pace over 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 better 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, has jumped more than four-fold since 1995. 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 have been expected to have contributed much to growth through the early 1990s. The contribution was modest because computing equipment still represented a small fraction of the total capital stock.

This paper updates our original analysis, using essentially the same framework as before. 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

[1]This paper draws heavily from Oliner and Sichel (1994) and Sichel (1997 and 1999), and includes text taken directly from that earlier work. The first two studies were published by the Brookings Institution and the last was published by the National Association for Business Economics.

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 nonfarm business between the first and second halves of the 1990s. Thus, to answer the question we posed in the title, information technology largely is the story.

The rest of the paper is organized as follows. The next section describes our analytical framework and the data we employ. Section 3 presents our estimates of the growth contribution from the use of computer hardware, software, and communication equipment; section 4 then assesses the contribution from efficiency gains in producing computers and semiconductors. In both sections, we compare our results with those from other recent studies. Section 5 takes a quick look at the role of electronic commerce in the productivity speed-up, and section 6 concludes the paper.

2. THE ANALYTICAL FRAMEWORK

The Neoclassical Growth-Accounting Expression

The 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 and 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.[2] In the decomposition for this paper, 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

[2]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, Brynjolfsson and Yang (1999) use stock market valuations of firms to identify the value of information technology assets broadly defined to include hardware, software, investments in worker training, and firm-specific capital created from these inputs.

multifactor productivity (*MFP*):

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

where the dot over a variable indicates the rate of change expressed as a log difference. The labor quality term captures changes in the composition of the workforce over time. The term for multifactor productivity identifies the portion of output growth left after accounting for growth in capital and labor. It is a catch-all for technological or organizational improvements that increase output for a given amount of input.[3] Finally, the α terms are income shares; under neoclassical assumptions these income shares equal the output elasticities for each input and they sum to one. (Time subscripts on both the growth rates and the income shares have been suppressed for notational simplicity.)

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 were not the case, 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.

The contribution of information technology — including computer hardware, software, and communication equipment — depends critically on the income shares, α_C, α_{SW}, and α_M. To illustrate how we calculate these income shares, consider the share for computing equipment, α_C. This share is not observable, but we estimate it for each year in accord with the methodology used by the Bureau of Labor Statistics (BLS). In the BLS framework, the income share for computing equipment in a given year is

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

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[3]Because the capital stocks we use are constructed from quality-adjusted investment flows, these stocks capture embodied technical improvements. If the quality adjustment were perfect, the *MFP* term would pick up only disembodied improvements. However, the investment data likely do not capture all quality improvement, with the unmeasured part being subsumed into *MFP*.

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 computing equipment: δ_C is the depreciation rate, π_C is the rate of capital gain (because computers actually suffer capital losses, this term is negative), p_C is the price level, and K_C is the real capital stock.[4] In this setup, it is the real net rate of return, r, that the neoclassical model equates across different asset classes. The intuition behind equation 2 can be easily explained. The term $p_C K_C$ is the nominal stock of computer hardware. This stock earns a gross rate of return equal to $(r + \delta_C - \pi_C)$. The product of $p_C K_C$ and the gross rate of return equals the nominal income flow generated by computers, which is divided by total nominal income (pY) to obtain the income share.

The exercise we perform with equations 1 and 2 has a few limitations. First, it captures only the proximate sources of output growth — namely, the accumulation of capital and labor, plus *MFP*. In particular, it does not model the underlying technical improvements that have helped to spur 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 *MFP*. We make no attempt to address this puzzle, and instead pursue a less ambitious goal: To assess how much of the recent resurgence of growth can be explained, under reasonable assumptions, by factors related to the use of information technology and the production of computers and semiconductors.[5]

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[4]Although we include tax terms in our actual calculations, they are excluded in the discussion for simplicity. Note also that π_C represents the rate of price change for hardware ($\dot{p}_C$) relative to inflation for overall output in the nonfarm business sector ($\dot{p}$). Thus, it measures the real change in hardware prices, consistent with the use of a real return (r) in equation 2. Alternatively, r and π_C both could have been specified in nominal terms.

[5]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) have argued 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

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 PCs: 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 PCs 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.[6] 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 1-¼ Pentium-equivalent units.

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importance of these adoption costs, while Hornstein (1999) shows that the theoretical results depend crucially on the specification of the learning process.

[6]BEA's hedonic price indexes for computers make just such an adjustment; that is, nominal purchases of computers each year are "quality-adjusted" with BEA's deflator 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.

Thus, the wealth stock would be smaller than the productive stock, illustrating the need to distinguish between these two types of capital stock.

Although PCs experience little, if any, physical decay, they may still lose productive efficiency as they age, in which case the two 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 can not 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.

Exactly how much efficiency loss to build in for computers is a difficult question, for which there is little empirical guidance. In constructing productive stocks (for computers and all other tangible capital), BLS assumes some decline in productive efficiency with age. We follow BLS and use their measures of productive capital stocks whenever possible.[7]

Data for Estimating the Growth Contribution of Information Technology Capital[8]

We rely heavily on data from the Bureau of Economic Analysis (BEA) and the BLS to estimate the terms in equations 1 and 2. Our starting point is the dataset assembled by the BLS for its estimates of multifactor productivity. These annual data cover the private nonfarm business sector in the United States and provide superlative index measures of the growth of real output, real capital input, and labor input. BLS' measure of capital input is very broad, encompassing producers' durable equipment, nonresidential structures, residential rental structures, inventories, and land.

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[7]In our earlier work, we used wealth stocks to calculate the income share of computers, as in equation 2 above. If we had used productive stocks, the growth contribution of computers that we 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.

[8]This section provides a brief overview of our data. See Appendix A for additional detail.

At the time we were writing, the BLS dataset ran only through 1997. We extended all necessary series through 1999, revised the data for real output and output prices 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.[9] In making these modifications, our intent was to anticipate the changes that BLS would incorporate in its next release of multifactor productivity data.

Our estimate of the growth contribution from computer hardware is built up from very detailed data. We start with BLS' productive stocks for mainframes, personal computers, terminals, printers, and three different types of storage devices.[10] 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 to output growth. For software, no estimates of the productive stock have yet been published. However, in the comprehensive NIPA revision, BEA did begin to publish data on investment in software. Based on these investment data, and information from BEA about the service lives for software, we constructed a productive stock of software capital in accord with the BLS methodology. We use this stock to estimate the growth contribution from software. For communication equipment, the estimated growth contribution is based on BLS' published series for the productive capital stock. Finally,

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[9]The most important adjustment accounts for changes in the methodology used for the Consumer Price Index. Over time, the CPI has been improved to measure inflation more accurately. Because the CPI is used to deflate parts of nonfarm business output, these changes introduced discontinuities in the measurement of real output growth. In the BLS dataset that we used, these CPI revisions had been carried back only to 1995. We adjusted the output data for earlier years to make them methodologically consistent with the more recent data, using information in BEA's comprehensive revision of the NIPAs and the *Economic Report of the President* (1999, p. 94).

[10]For personal computers, we recalculated the entire series for the productive stock. As part of the recent comprehensive revision, BEA announced that it had shortened the assumed service life for personal computers, and we expect BLS — in its next release of data — to estimate the productive stock of PCs using this shorter service life. To be consistent with what we expect BLS to do, we calculated a productive stock of personal computers with a shorter (five-year) service life.

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.

We estimate the income share for each type of capital from its analogue to equation 2. With a couple of exceptions, the depreciation rate, δ, for each type of equipment and structure comes from BEA.[11] For the expected capital gain or loss, π, we use a three-year moving average of the percent change in the investment price index for each asset relative to the price index for nonfarm business output. The other critical piece is the net real rate of return, r. We calculate r by equating BLS' estimate of the income share for all nonresidential equipment and structures to the sum of the asset-specific income shares defined by equation 2. The resulting value of r, which represents the ex post net return earned each year on the entire stock of nonresidential equipment and structures, is then used to calculate the income share for each asset, including computer hardware, software, and communication equipment. By so doing, the neoclassical assumption — that all types of capital earn the same net return in a given year — is imposed by construction.

Consider the gross return to personal computers implied by this procedure. In 1997, r is estimated to have been about 4 percent. Taking that figure, adding on a depreciation rate of about 30 percent and a capital loss term of 34 percent, we obtain a gross return for personal computers of 68 percent for 1997. Because computers become obsolete so rapidly, the gross return must be quite large in order to cover the sharp decline in a personal computer's market value each year, while still providing a competitive return net of depreciation.

[11] 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 PCs set equal to that for mainframes.

3. GROWTH CONTRIBUTION FROM THE *USE* OF INFORMATION TECHNOLOGY

Contribution to Output Growth

Key results are shown in table 1. The first two columns, which cover 1974-90 and 1991-95, tell a similar story to that in our earlier work. Across these periods, real nonfarm business output rose at an average pace of almost 3 percent per year. And, in these periods, computer hardware accounted for about ¼ percentage point per year of that growth, as shown on line 3. Computer software contributed 0.1 percentage point per year during 1974-90, with its contribution rising to ¼ percentage point per year during 1991-95.[12] Communication equipment contributed about 0.1 percentage point per year in both periods.[13] Adding up these pieces, information technology capital accounted for about ½ percentage point of output growth per year during both 1974-90 and 1991-95.

Calculations such as these 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 real stock of computer hardware increased at an average rate of more than 17 percent per year, but its nominal income share averaged just 1.4 percent (see lines 10 and 13 of the table). Hence, the contribution of computer hardware to output growth, the product of these figures, was only ¼ percentage point in this period.

However, the contribution of information technology capital to output growth surged in the second half of the 1990s. As shown in the last column, we estimate that the contribution of computer hardware to output growth during 1996-99 was about 0.6 percentage point per year,

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[12]The contribution of software is a little bigger than in our earlier work. Previously, we counted only pre-packaged software, while BEA's new software figures include custom and own-account software as well. Custom software is produced when businesses hire outside consultants to write programs, while own-account software is produced in-house by a business' employees.

[13]BEA uses hedonic price measures only for selected components of communication equipment and software. Thus, the investment data for both assets likely do not fully capture embodied quality improvements. If so, the "true" productive stocks would grow more rapidly than those based on the published investment data, and the contributions to output growth would be larger than those shown above. See Jorgenson and Stiroh (2000) for further discussion.

while the contribution of information processing capital as a whole was 1.1 percentage points, a considerable step-up from the pace earlier in the decade.[14] This increase is even more evident in figure 1, which plots the contributions year by year.

Contribution to Productivity Growth

Table 1 showed a decomposition of output growth. A closely related decomposition focuses on growth in labor productivity. In particular, equation 1 can be transformed into an equation for labor productivity (output per hour) by subtracting the growth rate of total hours from both sides of the equation, yielding:

$$(3) \qquad \dot{Y} - \dot{L} = [\alpha_C(\dot{K}_C - \dot{L}) + \alpha_{SW}(\dot{K}_{SW} - \dot{L}) + \alpha_M(\dot{K}_M - \dot{L}) + \alpha_O(\dot{K}_O - \dot{L})] + \alpha_L \dot{q} + \dot{MFP}.$$

In this decomposition, growth in labor productivity reflects increases in the amount of capital per hour worked — referred to as capital deepening and captured by the terms within square brackets — and growth in labor quality and *MFP*. In equation 3, the capital deepening portion is further divided into the contribution of computer hardware, software, communication equipment, and other capital.

Table 2 presents this decomposition of productivity growth. As can be seen 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 more than two-fifths 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 actually fell across the two

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[14]Note that the results in table 1 are based on 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 about ½ 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 this series; using the product-side 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 table 1. An "income-side" version of table 1 and our other results is available from the authors on request.

periods. This leaves *MFP* to account for more than three-fifths of the recent improvement in labor productivity growth.

So far, we have focused on the contribution from the *use* of information technology capital. Later in the paper, we will discuss the separate contribution from the *production* of computers and semiconductors, which is embedded in the *MFP* term.

The Growth Contribution from Computer Hardware: Comparison to Other Studies

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 compares the results from the various studies. For each one, we show the contribution to output growth from computer hardware for the latest period covered by that study and for the immediately preceding period. As can be seen, the estimates vary widely. At the top end, Whelan (2000) estimates that the use of computer hardware contributed more than 0.8 percentage point, on average, to output growth during the latest period (1996-98) — somewhat above our own estimate. In contrast, Kiley (1999) estimates that computer hardware has consistently made a *negative* contribution to growth since the mid-1970s. Jorgenson and Stiroh (2000) are in the upper part of this wide range. We briefly explain why these estimates differ from ours.

Whelan (2000) analyzes the growth contribution within a vintage model of production. Quite apart from his empirical results, Whelan's paper provides a nice micro-foundation for the growth-accounting framework that we implement. Whelan derives an expression for the optimal service life of computers (and, thus, for the depreciation rate) that depends on the rate of quality improvement in new vintages, the cost of maintaining existing vintages, and the rate of physical decay as vintages age. These structural parameters appear in his expression for the gross return on computer capital, making it look different from our expression ($r + \delta_c - \pi_c$). However, his

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

numerical estimate of the gross return closely resembles ours because the depreciation rate (δ_c) is, in effect, a summary statistic for these parameters.

Whelan's estimate of the growth contribution exceeds ours because of a difference in measurement, not concept. His measure of the productive stock of computers 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 described above, we use BLS' productive stocks, which allow for some loss of efficiency before retirement; this allowance reflects, however crudely, the view that older vintages of 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 PCs, 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, our estimate could be too low. One cannot rule out that we have underestimated the growth contribution from computer hardware by a tenth or two.

Consistent with our estimates and Whelan's, Jorgenson and Stiroh (2000) find that the growth contribution from computer hardware has risen substantially in recent years. However, their estimate of this contribution is a little smaller than ours, both before and after 1995. For example, during 1996-99, they figure that computer hardware contributed 0.49 percentage point annually to growth, 0.14 percentage point less than our estimate. This difference arises mainly because Jorgenson and Stiroh employ a broader concept of output than we do. They 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 (α_C) falls, all else equal. Business-owned computers are simply a smaller part of the economy that they choose to measure.

In contrast to the other studies, Kiley (1999) estimates that the contribution of computers to growth has been negative since the mid-1970s. Kiley obtains this result by modifying the growth-accounting framework in one important way. He assumes that investment in new computers entails "adjustment costs," a catch-all 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 happens (at some point in the future), he estimates that the growth contribution from computers will become positive, reaching about ½ percentage point annually in the steady state.

As Kiley notes, there certainly are some start-up costs associated with the transition to new types of hardware or software. However, in our view, Kiley's adjustment cost framework overstates their importance. His framework implies that the costs associated with software, user training and support, and system upkeep would all drop 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, including mature ones.

4. 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 the efficiency improvement in the *production* of computing equipment. As we will show, this second channel works through the *MFP* residual. In this section, we will identify the part of *MFP* growth that can be attributed to improvements in computer production, using a framework that draws on Hulten (1978), Triplett (1996), Stiroh (1998), and Whelan (2000).

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 advances in chip technology ultimately account for a large share of computer-sector productivity gains.[16] We model the nonfarm business economy as having three sectors. One produces semiconductors, another manufactures computers, and a third represents all other industries; these sectors are indexed by the superscripts s, c, and o, respectively. Each sector has its own production function, with output growth depending on the accumulation of inputs and growth in sectoral *MFP*. In a multi-sector

[16]See Triplett (1996) for estimates of the extraordinary pace of *MFP* growth in the semiconductor industry.

model, one must specify the input-output connections among the sectors. We focus on one connection that really matters for our analysis — the use of semiconductors as an intermediate input by the other two sectors. We also account for the computing equipment embedded in final goods produced by sector *o*. However, to keep the model simple, we abstract from all other input-output relationships; this assumption implies that sector *o* produces only final output in our model. Appendix B presents and analyzes this three-sector model; here, we discuss the main results.

The key expression relates *MFP* growth for nonfarm business as a whole to that in each sector. Let μ^i ($i = c$, s, or o) denote the gross output of sector i as a share of total nonfarm business output, in current dollars. Gross output includes final products and intermediate inputs sold to other sectors. With this notation, appendix B shows that

$$\dot{MFP} = \mu^c \dot{MFP}^c + \mu^o \dot{MFP}^o + \mu^s \dot{MFP}^s. \tag{4}$$

Aggregate *MFP* growth equals a weighted sum of *MFP* growth in each sector. This result is a special case of the weighting scheme proposed by Domar (1961) and formally justified by Hulten (1978).[17] If our model economy produced only final goods and services, μ^c and μ^o would sum to one, and μ^s would equal zero. That is, aggregate *MFP* growth would be a weighted average of *MFP* growth in the two sectors that make final products. However, once we account for intermediate inputs, the weights sum to more than one and the term for semiconductors appears in equation 4. To see why the term for semiconductors is needed, assume that the aggregate stocks of capital and labor are fixed. Growth in semiconductor *MFP* would either allow capital and labor to be reallocated to the other sectors (with no change in semiconductor production) or it would increase the volume of semiconductors supplied to those sectors (with no reallocation of capital and labor). Either way, total nonfarm business output would rise with no change in aggregate capital and labor. The final term in equation 4 identifies the source of this increase in aggregate *MFP*.

[17]For other examples of the use of Domar weights, see Gullickson and Harper (1999), Jorgenson, Gollop, and Fraumeni (1987), and Stiroh (1998).

To decompose aggregate *MFP* growth in accord with equation 4, we need estimates of the current-dollar output shares and the sectoral *MFP* growth rates. Using NIPA data, we measure the final output of computer producers as the sum of current-dollar computer spending by U.S. businesses, households, and all levels of government, plus net exports of computers; we then add an estimate, based on BEA's input-output tables, of computer products sent to other industries as intermediate input. To meaure current-dollar semiconductor output, we use internal Federal Reserve Board estimates developed to support the Fed's published data on U.S. industrial production. Finally, we estimate current-dollar output for the rest of nonfarm business as total output for that sector minus the final output of computer producers. We divide each series by current-dollar nonfarm business output to obtain estimates of μ^c, μ^o, and μ^s.

To estimate sectoral *MFP* growth, we employ the so-called "dual" method used by Triplett (1996), Whelan (2000), and Macroeconomic Advisers (1999). 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 it can be implemented with relatively little data. To see why prices contain information about sectoral *MFP* growth, consider an example involving the semiconductor sector, where output prices have trended sharply lower over time. Also, assume that input prices for the semiconductor industry have been stable. Given the steep decline in the relative price of semiconductors, *MFP* growth in semiconductor production 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*. More formally, appendix B shows that

(5) $$\dot{MFP}^s = \dot{MFP}^o - (\dot{p}^s - \dot{p}^o) + \text{terms for relative growth in sectoral input costs}$$

(6) $$\dot{MFP}^c = \dot{MFP}^o - (\dot{p}^c - \dot{p}^o) + \text{terms for relative growth in sectoral input costs,}$$

where the $\dot{p}$ terms denote growth in the sectoral output prices. If input costs grew at the same rate in all three sectors, the change in relative output prices would fully characterize the differences in sectoral *MFP* growth. However, because semiconductors loom large in the cost structure for computer producers, we know that input costs for that sector are falling relative to those for the other sectors. The final terms in equations 5 and 6 (see appendix B for details) take account of these differences in sectoral input costs. Equations 4 through 6 form a system of three equations, which we solve for the three sectoral *MFP* growth rates; all other terms can be calculated using the data described above and are treated as known in these equations.

Table 4 presents our estimates of the sectoral contributions to growth in *MFP*. As shown on lines 2 and 3, the 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 pick-up in *MFP* growth (lines 9 and 10).[18] Note that our estimate of *MFP* growth for semiconductors covers the output that feeds into computer production and that used elsewhere in the economy. Only the first piece is relevant for measuring the *MFP* contribution of the computer sector, broadly defined to include the production of the embedded semiconductors. Line 5 presents an estimate of the *MFP* contribution from this vertically-integrated computer sector. This estimate includes the *MFP* contribution from computer manufacturing (line 2), plus 60 percent of the *MFP* contribution from semiconductor production (line 3).[19] As can be seen by comparing lines 1 and 5, this

[18]Alternatively, one might argue that the sharp price declines reflect, at least in part, factors other than a rise in *MFP* growth. For example, the economic problems during 1997-98 in Asia and Latin America likely did depress semiconductor demand for a while, and heightened competition in the microprocessor market at that time also could have put downward pressure on chip prices. However, if either of these alternative stories were the main source of price declines — rather than faster *MFP* growth — we might expect profit margins for semiconductor producers to have narrowed. In fact, data for Intel, the world's largest semiconductor producer, do not show that pattern. Intel's profit margin, defined as net income divided by net sales, averaged 25 percent during 1996-99, up from 20 percent during 1990-95. This evidence, while far from definitive, does suggest that the sharp decline in semiconductor prices since 1995 has been accompanied by rapid efficiency gains in production.

[19]The 60 percent share is based on the following data from the Semiconductor Industry Association (SIA). During 1990-94, U.S. computer producers accounted for almost 60 percent of total U.S. consumption of semiconductors. For 1995-98, the SIA data cover a broader region that

vertically-integrated computer sector accounted for more than two-fifths of the growth in nonfarm business *MFP* during the second half of the 1990s — a remarkable portion given its tiny share of total current-dollar output.

Growth Contributions: The 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 on line 2, we attribute almost ½ percentage point of the pickup to the growing use of information technology capital throughout the nonfarm business sector. In addition, as noted above, the rapidly improving technology for producing computers (and the embedded semiconductors) has contributed another ¼ percentage point to the acceleration (line 3). 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 (line 4) explains very little of the acceleration, leaving *MFP* growth elsewhere in nonfarm business (lines 6 and 7) to account 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.[20]

A Different View of the Recent Experience

In a widely cited paper, Robert Gordon (1999) also emphasized the role of information technology, but with an important twist from our explanation. He argued that improvements in the *production of computer hardware* accounted for the entire acceleration in labor productivity

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includes all of North and South America; the share of semiconductors consumed by computer producers in this broader region remained around 60 percent.

[20]As we noted above, the post-1995 pickup in the growth of output (and, hence, in output per hour) would be larger on the "income side" than is indicated by the published product-side data. If so, the share of the pickup attributed to information technology likely would be smaller than in table 5, though it would still be quite sizable. As indicated earlier, an "income-side" version of our tables is available upon request. These tables were constructed on the assumption that the additional growth in output per hour all flows through to *MFP* growth rather than capital deepening. Of course, the actual mix of adjustments to *MFP* growth and capital deepening would depend on the fraction of the extra output that takes the form of business investment.

in nonfarm business (after adjusting for the cyclical component of productivity and for changes in the methodology of price measurement). From this result, Gordon inferred that the increasing *use* of computers throughout nonfarm business had contributed nothing to the acceleration of trend productivity.

Gordon wrote this paper before the comprehensive revision of the national accounts in October 1999; he has since recalculated his numbers using the new data. We will discuss his original results and the new numbers reported in Gordon (2000). In both papers, Gordon compares the growth of productivity since 1995 to that during 1972-95.

According to the pre-revision data, the average annual growth of labor productivity in nonfarm business increased about 1 percentage point after 1995, compared with growth in the period extending back to 1972. Gordon attributed 0.7 percentage point of this acceleration to cyclical factors or to changes over time in price measurement, leaving only 0.3 percentage point as the true pickup in trend productivity growth. This increase matched his estimate of the contribution from computer producers, leading Gordon to conclude that trend productivity growth had not risen in the rest of nonfarm business.

However, this result did not survive the NIPA revision. The post-1995 acceleration in labor productivity was revised up to nearly 1.4 percentage points.[21] After recalculating his adjustments for cyclical factors and price measurement, Gordon (2000) estimates that trend productivity in nonfarm business accelerated about 0.7 percentage point after 1995. With little change in the estimated contribution from computer producers, the rest of nonfarm business now accounts for 0.4 percentage point of the pickup. Hence, Gordon's original conclusion — that the production of computer hardware accounted for the entire rise in trend labor-productivity growth — no longer stands. This is an important change, given the widespread attention paid to the earlier results.

In response to this new arithmetic, Gordon has modified his story. Whereas he initially focused on movements in *labor* productivity, Gordon (2000) concentrates on *multifactor*

[21]This acceleration slightly exceeds the magnitude shown in our table 2. The difference arises, in large part, because Gordon calculates the acceleration based on quarterly data, while we use annual averages. The underlying BLS data that Gordon employs are the same as ours.

productivity. Gordon now stresses that trend *MFP* has not accelerated outside the computer sector; he attributes the entire increase in trend labor-productivity growth for nonfarm business to capital deepening, changes in labor quality, and computer-sector *MFP* growth. Gordon argues that the narrowness of the *MFP* pickup means that investment in information technology has not generated super-normal returns (which would show up in *MFP* growth rather than the contribution from capital deepening). However, as we showed above, the use of information technology has contributed importantly to the step-up in productivity growth even without assuming super-normal returns. In addition, Gordon's new figures embed *our* estimate of the growth contribution from the use of information technology capital. Thus, whatever view one takes regarding super-normal returns, Gordon's results for nonfarm business essentially retell *our* story about the use of such capital.

Gordon (2000) also presents results for a narrower sector — nonfarm business excluding durable goods manufacturing — to argue that information technology capital may have earned *lower* net returns than other assets in recent years. If true, this result would imply we have overstated the contribution of this capital to the pickup in labor-productivity growth. But Gordon's case for this assertion appears to be weak. He repeats the same exercise that he conducted for total nonfarm business and finds that trend *MFP* growth for this narrower sector slowed by 0.3 percentage point after 1995. Because Gordon doubts this really happened, he speculates that measured *MFP* for this sector has been held down since 1995 by poor returns on information technology capital. The decline in trend *MFP* growth, however, could reflect the manner in which Gordon has separated trend from cycle. Gordon attributes nearly three-quarters of the post-1995 acceleration in this sector's labor productivity to cyclical factors.[22] The modest step-up that remains is more than explained by capital deepening.[23] Separating trend from cycle

[22]Note that Gordon's cyclical adjustment is larger for nonfarm business excluding durable manufacturing than for total nonfarm business. Thus, Gordon is implicitly assuming that durable manufacturing is *less* cyclical than the rest of the economy.

[23]Gordon should use a cyclically adjusted measure of the contribution from capital deepening, but he again uses our measure, which is not cyclically adjusted. If some of the recent investment boom has been cyclical, Gordon is subtracting an upward biased figure for the contribution from capital deepening, thus biasing down his estimate of trend *MFP* growth.

is always difficult in the midst of an expansion — and is particularly hazardous now because the current expansion has not conformed to cyclical norms. In the face of this uncertainty, Gordon imposes a strong assumption that effectively pre-ordains his result.

Unlike Gordon, we have not attempted to distinguish trend from cycle. Rather, we have tried to explain the speed-up of *actual* productivity growth during the late 1990s. We have shown that, under reasonable assumptions, the *use* of information technology has contributed importantly to this speed-up. Gordon's original results, which might have raised doubts about this conclusion, no longer hold. Moreover, in our view, Gordon (2000) presents no compelling evidence that information technology capital has been unproductive.

5. THE INTERNET AND E-COMMERCE

In the past few years, the Internet has spread rapidly, e-commerce has exploded, and computer networks have become ever more extensive. And, according to the anecdotes, these developments have led to some spectacular gains in productivity, as transaction and information costs have plummeted. Thus far, we have not explicitly considered these developments. In principle, however, our results already incorporate their impact to a large extent.

To see why, reconsider equation 1, which decomposed the growth of output into contributions from different types of capital, labor, and *MFP*. Our output measure should largely capture the effects of e-commerce. Most *business-to-consumer* e-commerce would be included in the usual surveys of retail sales and consumer prices that underlie the NIPAs. *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. Any indirect effects of business-to-business e-commerce on real GDP would be picked up by current procedures.[24] Moving to the right-hand side of equation 1, the computer and communication infrastructure needed to support the Internet

[24] For example, if an automaker purchased steel via the Internet, GDP would include the value of the car produced (the final good), but — to avoid double counting — would not separately count the value of the steel (the intermediate input). Any efficiencies in procuring steel would, in a competitive equilibrium, show up in the price or quantity of the cars produced.

and e-commerce is included in our measure of capital stocks for those assets. Indeed, the rapid growth of activity over the Internet surely helps explain the surging investment in these categories in recent years. Similarly, our measure of labor input should cover workers involved in e-commerce.

To the extent that output, capital input, and labor input are properly measured, *MFP* — the residual in equation 1 — 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, it could be one factor that has pushed up *MFP* growth in recent years. However, as described below, a back-of-the-envelope calculation suggests that, to date, any such efficiency effects have been small.

There are many different estimates of the volume of e-commerce transactions using widely differing definitions of what should be included in such a measure. A recent article in *Business 2.0* [Cross (1999)] surveyed estimates of e-commerce 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 therefore in *MFP*? To the extent that these transactions only represent a shift in distribution channels without any cost savings, they would have no effect on *MFP*. Of course, sales activity is shifting to these electronic channels precisely because costs are perceived to be lower than through traditional channels.

To get a very rough gauge of the possible size of these efficiency gains, we turn to a recent study that compared prices on the Internet to those at bricks-and-mortar outlets. Brynjolfsson and Smith (1999) examined prices for books and CDs in 1998 and 1999 and found that Internet prices were about 9 to 16 percent lower than those in conventional stores. This range could well over-estimate the efficiency gains in the retail sector because much 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, and — 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 [=(135/.90)x.10]. With total output in the nonfarm business economy amounting to about $7 trillion, these cost savings represent only 0.2 percent of output. And, assuming that these savings accrued during 1996-99, the impact 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 gains in efficiency related to the spread of e-commerce have had, to date, only a small impact on multifactor productivity. Nevertheless, all indications are that the volume of e-commerce (including both business-to-business and business-to-consumer) will continue to grow rapidly in coming years, raising the possibility of more substantial efficiency gains in the future.[25]

6. 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 paper examined that role with the same neoclassical framework we used in earlier work. Once again, we find that the *use* of information technology — including computer hardware, software, and communication equipment — made a relatively small contribution to output and productivity growth through the early 1990s. However, our results indicate that this contribution surged in the second half of the decade. In addition, technological advance in the *production* of computers (including the production of the embedded semiconductors) appears to have contributed importantly to the speed-up in productivity growth. All in all, we estimate that the *use* of information technology and the *production* of computers accounted for about two-thirds of the 1 percentage point step-up in productivity growth between the first and second halves of the decade. Thus, we conclude that

[25]In a recent study, Brookes and Wahhaj (2000) used 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, like our analysis, their numbers suggest that the effect to date has been small.

information technology has been the key factor behind the improved productivity performance of the U.S. economy in recent years.

How much of the boost to productivity growth from information technology can be expected to persist for the next several years? This crucial question cannot be answered with any certainty, but we suspect that a sizable portion will. The recent surge in the growth contribution likely reflects the interaction of a strong economy and investment opportunities created by the convergence of communication and computer technology. Assuming that business cycles will remain a feature of the economic landscape, the growth contribution will vary over time. However, against that cyclical backdrop, the continued expansion of the Internet and e-commerce likely will support the contribution of information technology to growth for some time to come.

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
Growth rate of inputs:[a]			
13. Hardware	31.3	17.5	35.9
14. Software	13.2	13.1	13.0
15. Communication equipment	7.7	3.6	7.2

[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 13 to 15) and of income shares (lines 10 to 12) differs slightly from the value of growth contributions (lines 3 to 5), which are calculated on the basis of year-by-year data, not period averages.

Source: Authors' calculations based on BEA and BLS data.

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.

Table 3

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

Study	Previous Period: Years Covered	Previous Period: Contribution[a]	Current Period: Years Covered	Current Period: 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.

Table 4

Sectoral Contributions to Growth in Nonfarm Business MFP

	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.

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

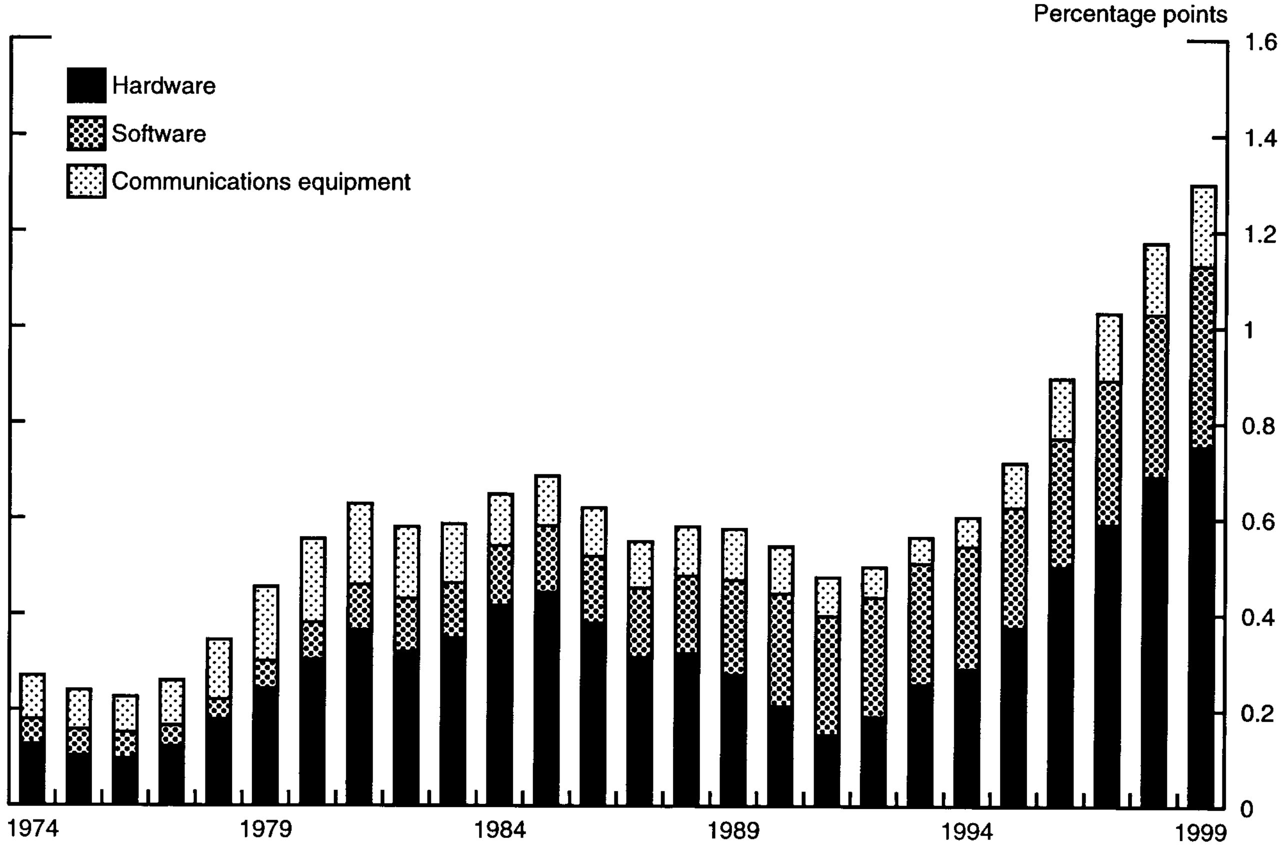
[a]Percentage points per year.

Note: Detail may not sum to totals due to rounding.

Source: Results shown in tables 2 and 4.

Figure 1

Contributions of Computer Hardware, Software and Communications Equipment to Growth of Real Nonfarm Business Output, 1974-1999



REFERENCES

Brookes, Martin and Zaki Wahhaj. 2000. "The Shocking Economic Effect of B2B." Global Economics Paper No. 37, Goldman Sachs, February.

Brynjolfsson, Erik and Michael Smith. 1999. "Frictionless Commerce? A Comparison of Internet and Conventional Retailers." Mimeo, MIT Sloan School.

Brynjolfsson, Erik and Shinkyu Yang. 1999. "The Intangible Costs and Benefits of Computer Investments: Evidence from the Financial Markets." Mimeo, MIT Sloan School, April.

Bureau of Labor Statistics. 1983. *Trends in Multifactor Productivity, 1948-81.* Bulletin 2178.

Cross, Kim. 1999. "B-to-B By the Numbers," *Business 2.0.* September, p. 109.

Domar, Evsey. 1961. "On the Measurement of Technological Change." *Economic Journal.* December, 71, pp. 309-329.

Economic Report of the President. 1999. Washington, D.C.: Government Printing Office.

Fischer, Stanley. 1988. "Symposium on the Slowdown in Productivity Growth." *Journal of Economic Perspectives.* Fall, 2:4, pp. 3-7.

Flamm, Kenneth. 1997. "More for Less: The Economic Impact of Semiconductors." Semiconductor Industry Association, December.

Fraumeni, Barbara M. 1997. "The Measurement of Depreciation in the U.S. National Income and Product Accounts." *Survey of Current Business.* July, 77:7, pp. 7-23.

Gordon, Robert J. 1999. "Has the 'New Economy' Rendered the Productivity Slowdown Obsolete?" Working paper, Northwestern University, June 14. <http://faculty-web.at.nwu.edu/economics/gordon/researchhome.html>

Gordon, Robert J. 2000. "Does the 'New Economy' Measure up to the Great Inventions of the Past?" Working paper, Northwestern University, April 25. Forthcoming in *Journal of Economic Perspectives.*

Greenwood, Jeremy and Boyan Jovanovic. 1998. "Accounting for Growth." NBER Working Paper no. 6647, July.

Greenwood, Jeremy and Mehmet Yorokoglu. 1997. "1974." *Carnegie-Rochester Conference Series on Public Policy.* June, 46, pp. 49-95.

Grimm, Bruce. 1998. "Price Indexes for Selected Semiconductors, 1974-96." *Survey of Current Business.* February, 78:2, pp. 8-24.

Gullickson, William and Michael J. Harper. 1999. "Possible Measurement Bias in Aggregate Productivity Growth." *Monthly Labor Review.* February, 122:2, pp. 47-67. <http://www.bls.gov/opub/mlr/1999/02/contents.htm>

Ho, Mun S., Dale W. Jorgenson, and Kevin J. Stiroh. 1999. "U.S. High-Tech Investment and the Pervasive Slowdown in the Growth of Capital Services." Mimeo, September 14.

Hornstein, Andreas. 1999. "Growth Accounting with Technological Revolutions." *Federal Reserve Bank of Richmond Economic Review.* Summer, 85:3, pp. 1-22.

Hulten, Charles R. 1978. "Growth Accounting with Intermediate Inputs." *The Review of Economic Studies.* October, 45:3, pp. 511-518.

Jorgenson, Dale W., Frank M. Gollop, and Barbara M. Fraumeni. 1987. *Productivity and U.S. Economic Growth.* Cambridge, MA: Harvard University Press.

Jorgenson, Dale W. and Kevin J. Stiroh. 2000. "Raising the Speed Limit: U.S. Economic Growth in the Information Age," Forthcoming in *Brookings Papers on Economic Activity.*

Kiley, Michael T. 1999. "Computers and Growth with Costs of Adjustment: Will the Future Look Like the Past?" Federal Reserve Board, Finance and Economics Discussion Series Paper 1999-36, July. <http://www.bog.frb.fed.us/pubs/feds/1999/index.html>

Kortum, Samuel. 1997. "1974: A Comment." *Carnegie-Rochester Conference Series on Public Policy.* June, 46, pp. 97-105.

Macroeconomic Advisers. 1999. "Productivity and Potential GDP in the 'New' U.S. Economy." September. <http://www.macroadvisers.com/reading.html>

Oliner, Stephen D. and Daniel E. Sichel. 1994. "Computers and Output Growth Revisited: How Big is the Puzzle?" *Brookings Papers on Economic Activity* 2, pp. 273-317.

Oliner, Stephen D. and William L. Wascher. 1995. "Is a Productivity Revolution Under Way in the United States?" *Challenge.* November-December, pp. 18-30.

Parker, Robert and Bruce Grimm. 2000. "Software Prices and Real Output: Recent Developments at the Bureau of Economic Analysis." Paper presented at the National Bureau of Economic Research Program on Technological Change and Productivity Measurement, revised April 7.

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

Sichel, Daniel E. 1999. "Computers and Aggregate Economic Growth: An Update." *Business Economics.* April, 34:2, pp. 18-24.

Solow, Robert. 1957. "Technical Change and the Aggregate Production Function." *Review of Economics and Statistics.* August, 39:3, pp. 65-94.

Stiroh, Kevin J. 1998. "Computers, Productivity, and Input Substitution." *Economic Inquiry.* April, 36:2, pp. 175-191.

Triplett, Jack E. 1996. "High-Tech Industry Productivity and Hedonic Price Indices," in *Industry Productivity: International Comparison and Measurement Issues*, Proceedings of May 2-3, 1996 OECD workshop. Paris: Organisation for Economic Cooperation and Development, pp. 119-142.

Whelan, Karl. 1999. "Tax Incentives, Material Inputs, and the Supply Curve for Capital Equipment." Federal Reserve Board, Finance and Economics Discussion Series Paper 1999-21, April. <http://www.bog.frb.fed.us/pubs/feds/1999/index.html>.

Whelan, Karl. 2000. "Computers, Obsolescence, and Productivity." Federal Reserve Board, Finance and Economics Discussion Series Paper 2000-6, February. <http://www.bog.frb.fed.us/pubs/feds/2000/index.html>

APPENDIX A: DATA SOURCES

This appendix describes the key data series used in the paper. Unless noted otherwise, all data are annual and cover the period from 1973 to 1999. We use subscripts to denote specific asset types and superscripts to denote specific sectors of the economy.

Data for Estimation of Growth Contributions (in Section 3)

a. Real output in the nonfarm business sector (Y)

Data through 1997 are from the BLS multifactor productivity dataset. (The version we use was released in mid-1999.) In constructing output, BLS primarily relies on the BEA real output series for nonfarm business less housing. Both the BEA and BLS series are superlative indexes of output. For 1998 and 1999, we extended the BLS series using annual growth rates of BEA's series for real output in nonfarm business less housing (NIPA table 1.8).

The BLS output data were published prior to the October 1999 comprehensive NIPA revision. To capture the effects of the revision (and the corrections released in March 2000), we adjusted the growth rate of the BLS series for each year through 1997 by adding, in percentage points, the revision in the growth rate of the BEA real output series for nonfarm business less housing for that year.

The comprehensive NIPA revision incorporated the effect of technical changes to the CPI back to 1978 (specifically, the introduction of geometric means in the CPI). Thus, the adjustment described in the previous paragraph implicitly included technical changes to the CPI from 1978 forward. According to the *Economic Report of the President* (1999, p. 94), the introduction of geometric means prior to 1978 would hold down CPI inflation by 0.2 percentage point per year. From 1973 to 1977, nominal consumption expenditures accounted for 85 percent of nominal nonfarm business output. Thus, the incorporation of geometric means prior to 1978 would hold down inflation in nonfarm business prices by about 0.17 percentage point per year (=0.2x0.85) and would boost real growth in nonfarm business output by the same amount each year. To account for this effect, we added 0.17 percentage point to the growth rate of the BLS series for nonfarm business output for each year before 1978.

b. Price index for nonfarm business output (p)

Through 1997, we start with the ratio of nominal nonfarm business output to real nonfarm business output from the BLS multifactor productivity dataset. For 1973-77, we then adjusted down the growth of this series by 0.17 percentage point annually to build in the effects of the CPI revision, as described in the previous paragraph. Next, to incorporate the effects of the NIPA revision through 1997, we used a procedure parallel to that used for output growth. Specifically, we adjusted the growth rate of the BLS series by adding, in percentage points, the revision in the growth rate of the BEA price index for nonfarm business output less housing. For 1998 and 1999, we extended the (adjusted) BLS series using the annual growth rate of BEA's price index for nonfarm business less housing.

c. Productive stocks for detailed types of capital

General comments. For most categories of capital, we took data through 1997 directly from the BLS multifactor productivity dataset. BLS constructs productive stocks for highly disaggregated asset categories, starting with data on real investment for 58 different types of capital and then translating these investment flows into productive stocks with the use of hyperbolic age-efficiency profiles. We first describe the procedure we used to extend the BLS productive capital stocks to 1998 and 1999.[1] We then discuss personal computers and software, for which we constructed our own productive stocks back to 1973.

Assets other than personal computers and software. For nonresidential fixed capital, we extended the detailed BLS investment series to 1998 and 1999 using NIPA investment data for four broad categories of nonresidential fixed investment: computers and peripheral equipment, communication equipment, other equipment, and nonresidential structures. The next paragraph describes this procedure in detail for computers and peripheral equipment; the same method was used for other types of nonresidential fixed investment.

To begin, we used the BLS dataset to calculate the average growth of real investment in 1996 and 1997 for each type of computer and peripheral equipment — mainframes, personal

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[1]BLS actually starts with a two-way disaggregation by type of asset and by industry. For our extension to 1998-99, we use the data by asset that have already been aggregated across industries.

computers, printers, terminals, and three different types of storage devices. These growth rates represented our estimate of "trend" growth in real investment for 1998 and 1999 for each detailed category. Then, we scaled these "trend" rates so that they would chain aggregate to the level of total real investment in computers and peripheral equipment in 1998 and 1999.

Given an estimate of real investment in 1998 and 1999 for each type of nonresidential fixed capital, we extended the BLS productive capital stocks to 1998 and 1999 with the perpetual inventory method. Specifically, for each detailed asset type, we calculated a translation factor (f_t) for each year through 1997 from the following equation:

$$K_t = f_t K_{t-1} + (I_t + I_{t-1})/2,$$

where (following BLS methodology) K_t is measured as the average of the stocks at the end of years t and $t-1$. We used the value of f_t in 1997 and the detailed investment data to construct productive stocks for each type of nonresidential fixed capital for 1998 and 1999.

For tenant-occupied rental housing, we extended the BLS productive stock to 1998 and 1999 with a simple regression equation. This equation regressed the BLS productive stock on its own lag and on real investment in multifamily structures from the NIPAs. The coefficients from this equation, combined with NIPA data on investment in multifamily structures for 1998 and 1999, generated the estimate of the stock of tenant-occupied rental housing for those years. For the stock of inventories, we extended the BLS series to 1998 and 1999 using NIPA inventory data. For the stock of land, we extended the BLS series to 1998 and 1999 with the average growth rate of this stock for the five years through 1997.

Personal computers. As of this writing, the BLS productive stock for PCs was based on an assumed mean service life of seven years. However, in the comprehensive NIPA revision, BEA decreased its assumed service life for personal computers. We anticipate that the next release of the BLS multifactor productivity dataset will incorporate this change. Thus, we constructed a productive capital stock for personal computers using a five-year service life, combined with the hyperbolic age-efficiency profile that BLS uses for all types of equipment. BLS assumes a truncated normal distribution of service lives around the mean service life; in contrast, we calculated age-efficiency weights using the mean service life and did not assume a distribution around the mean. (See Bureau of Labor Statistics (1983), pp. 41-45).

Software. BLS had not published a productive capital stock for software as of this writing. We used the BEA data on real investment in software to construct our own productive capital stock. As reported in Parker and Grimm (2000), BEA used a service life of 3 years for prepackaged software and a service life of 5 years for custom and own-account software. Parker and Grimm also provided a breakdown of software investment into prepackaged, custom, and own-account for the years 1959, 1979, 1992, and 1998. To construct a complete time series of shares, we interpolated the shares between these years. For prepackaged software, BEA's share is zero in 1959, and we assume that this share remains zero until 1975. With these shares, we constructed a service life for total software. Next, we combined this service life with the hyperbolic age-efficiency profile BLS uses for all types of equipment to construct a productive stock for software. (As for personal computers, we used the mean service life in the BLS formula for age-efficiency weights and did not assume a distribution of service lives around the mean.)

d. Capital aggregates (K_C, K_{SW}, K_M, K_O)

BLS uses the Tornquist formula to aggregate the detailed productive capital stocks into an aggregate measure of capital services. This measure is a weighted average of the growth rates of the various productive stocks, with the weight for each asset type equal to its estimated share of total capital income. To construct our capital aggregate for computer and peripheral equipment (K_C), we applied the Tornquist formula to the seven components of such equipment. For software and for communication equipment, the capital aggregates (K_{SW} and K_M) just equal the respective productive stocks; the Tornquist formula is not needed because we have no asset detail within each aggregate. Finally, to construct K_O, our first step was to extend the BLS measure of aggregate capital services to 1998 and 1999 (using the Tornquist formula). Then, we stripped out computer and peripheral equipment and communication equipment from aggregate capital services to arrive at K_O (software need not be stripped out because, as of this writing, it was not included in BLS' capital aggregate).

e. Labor hours (L)

Through 1997, labor hours are from the BLS multifactor productivity dataset. We extended the data to 1998 and 1999 using the growth rate in hours of all persons in the nonfarm business sector from the BLS Productivity and Cost release.

f. Labor quality (q)

BLS measures labor quality as the difference in the growth rate of labor *input* and labor *hours*. Labor input is constructed as a weighted average of growth in hours worked in each age-sex-education cell, with the weight for each cell equal to its share of total labor compensation. Through 1997, our measure of labor quality is from the BLS multifactor productivity dataset. We extended the data to 1998 and 1999 using the assumption that labor quality generates a contribution of 0.3 percentage point per year in these two years.

g. Income shares (α_i)

The income share for each type of nonresidential fixed capital is calculated from the following equation:

$$\alpha_i = \{[r + \delta_i - \pi_i]p_i K_i\} T_i / pY.$$

We discuss each component of this equation. Note that these income shares vary from year to year, and are not fixed at a period-average value. For land, inventories, and tenant-occupied rental housing, we use the BLS income shares through 1997 and extrapolate these forward for 1998 and 1999. Once we estimate the income-share series for each capital asset, the income share for labor equals unity minus the total income share for capital.

Depreciation rate (δ_i). With a couple of exceptions, the depreciation rate for each type of equipment and structures comes from BEA (as presented in Fraumeni (1997), pp. 18-19.) Because BEA does not publish depreciation rates for the components of computers and peripheral equipment, we follow Whelan (2000) and set these depreciation rates equal to a geometric approximation calculated from BEA capital stocks and investment flows, with the depreciation rate for PCs set equal to that for mainframes. For software, we set the (annual) depreciation rate equal to 0.37.

Expected real capital gain/loss **(π_i).** To calculate this term, we first construct the ratio of the price of asset i (p_i) to the price of nonfarm business output (p). The output price series was described above. Through 1997, the p_i series for each asset is the investment price index from the BLS multifactor productivity dataset. For 1998 and 1999, each p_i series is extended using its average growth rate for 1996 and 1997. π_i is then calculated as a three-year moving average of the annual log difference of p_i/p, where the moving average is used as a proxy for the unobserved expectation.

Current-dollar productive capital stock **(p_iK_i).** For each asset, this series is simply the product of the real productive stock (K_i) and the asset price index (p_i), both of which are discussed above.

Tax adjustment **(T_i).** For each asset, this adjustment equals $(1 - k - \tau z)/(1 - \tau)$, where k is the rate of investment tax credit, τ is the corporate tax rate, and z is the present value of $1 of tax depreciation allowances. Karl Whelan kindly provided these series. See Whelan (1999) for details about their construction.

Current-dollar nonfarm business output **(pY).** Through 1997, this series is from the BLS multifactor productivity dataset. For 1998 and 1999, we extended the BLS series using the annual growth rate of BEA's series for current-dollar output in nonfarm business less housing.

Real net return **(r).** We calculate r as the ex post net return earned on the productive stock of nonresidential equipment and structures. Thus, we obtain r as the solution to the following equation:

$$\Sigma_i \{[r + \delta_i - \pi_i]p_iK_i\}T_i/pY = \text{BLS series for } \Sigma_i \alpha_i$$

where the summations are over all types of nonresidential equipment and structures (excluding software). This procedure yields an annual series for r through 1997. For 1998 and 1999, we assume that r remains at its 1997 value.

Data for Estimation of Sectoral MFP Growth (in Section 4)

a. Current-dollar output shares (μ^c, μ^s, and μ^o)

Computer producers. $\mu^C = p^C Q^C/pY$, the ratio of current-dollar computer output to total current-dollar output in the nonfarm business sector. The data source for pY was described above. $p^{C}Q^{C}$ includes both final sales of computers and shipments of intermediate inputs to other industries. Final sales, denoted $p^{C}Y^{C}$, are measured (using NIPA data) as the sum of current-dollar spending on computers and peripheral equipment in the following categories: private fixed investment, personal consumption expenditures, government expenditures, and net exports of goods and services. This sum omits the small portion of final computer output that ends up in business inventories, as the NIPA inventory data do not break out computing equipment from other inventories.

Next, we use BEA's input-output (I-O) tables to estimate the current-dollar value of intermediate computer sales from domestic computer producers to other industries. Our estimate excludes intermediate sales to companies that provide computer and data processing services. These service providers buy computer equipment and software and then sell integrated systems to end-users. Because these systems are already counted as a final computer purchase in the NIPAs, we exclude the intermediate transaction between the computer producer and the system integrator to avoid double-counting a given piece of computing equipment. We express the resulting measure of intermediate computer sales as a ratio to final computer sales for years with I-O tables (1977, 1982, 1987, 1992, and 1996) and interpolate the ratio for intervening years. Prior to 1997, we set this ratio to its 1977 value, and for 1997-99 we employ the 1996 value. Finally, we use this series of ratios to blow up the final sales figure ($p^{C}Y^{C}$) described above to obtain total output of computers, including that sold to other sectors as intermediate input.

Semiconductor producers. $\mu^{S} = p^{S}Q^{S}/pY$, the ratio of current-dollar semiconductor output to total current-dollar output in the nonfarm business sector. Our series for $p^{S}Q^{S}$ is current-dollar shipments from U.S. establishments in SIC category 36741 (integrated microcircuits). Ana Aizcorbe and Charles Gilbert, our colleagues at the Federal Reserve Board, kindly provided the shipments data, which they compiled from Census Bureau reports. Because this series is not available before 1977, we set the value of μ^{S} during 1973-76 equal to its 1977 value.

Other nonfarm business. $\mu^{O} = p^{O}Y^{O}/pY = (pY - p^{C}Y^{C})/pY$, the ratio of nonfarm business output excluding computers to total nonfarm business output. The data sources for both pY and $p^{C}Y^{C}$ were described above.

b. Sectoral output prices (p^c, p^s, p^o).

Computer sector **(p^c).** This is an implicit price deflator for outlays on computers in the NIPAs. We calculate this deflator as the ratio of current-dollar outlays (the series p^cY^c described above) to a chain aggregate of real outlays for the same spending categories (which we construct and denote by Y^c).

Semiconductor sector **(p^s).** For 1977-99, we use internal Federal Reserve price deflators for SIC 36741 constructed by Ana Aizcorbe; this series generates the annual percent change in p^s for 1978 through 1999. For years before 1978, we calculate the percent change by extrapolating Aizcorbe's series back in time using data from Grimm (1998). Specifically, we calculate the average annual percent change between 1974 and 1977 in Grimm's "Summary price index for MOS memory chips" (p. 12), and then take the ratio of this average 1974-77 percent change to the percent change for 1978. We multiply this ratio by the 1978 percent change in Aizcorbe's series, and use the resulting value as the percent change in p^s for each year from 1974 to 1977.

Other nonfarm business **(p^o).** We calculate this implicit deflator as the ratio of current-dollar output for this sector (pY - p^cY^c) to a chain aggregate of the sector's real output, which we construct by stripping out the contribution of real computer spending (Y^c) from the series for real nonfarm business output (Y).

Relative prices. The rates of change in *relative* prices are constructed from these series as $\pi^c = \dot{p}^c - \dot{p}^o$ and $\pi^s = \dot{p}^s - \dot{p}^o$.

c. Rate of change in aggregate capital and labor input costs in nonfarm business ($\dot{Z}$)

We calculate $\dot{Z}$ from the "dual" for nonfarm business. That is, $\dot{Z} = \dot{MFP} + \dot{p}$, where p is the price series for nonfarm business output described above.

d. Share of current-dollar input costs associated with semiconductor inputs (α_s^o, α_s^c)

Nonfarm business other than computer production **(α_s^o).** The numerator of this share represents the current-dollar value of semiconductors used to produce all final output in nonfarm business excluding computers. We estimate this semiconductor input as the product of worldwide semiconductor shipments and the fraction of such shipments consumed by all sectors in the United States excluding computer producers and the government. The data on worldwide semiconductor shipments and U.S. semiconductor consumption are from the Semiconductor

Industry Association (SIA). The resulting estimate of semiconductor purchases is divided by current-dollar output in nonfarm business excluding computers ($pY - p^c Y^c$). The SIA data allow us to calculate α_s^o in this manner back to 1976. For 1973-75, we set α_s^o equal to its 1976 value.

Computer production **(α_s^c).** We set α_s^c equal to 0.3 for all years. That is, we assume that semiconductors account for 30 percent of the current-dollar input cost of computer producers. This value lies at the middle of the range employed by Triplett (1996). We did not use an estimate of semiconductor usage based on the SIA data for the following reason. As noted by Flamm (1997), p. 11, the SIA data cover only the semiconductors sold by "merchant" producers in the open market; these data exclude "captive" production by U.S. computer manufacturers, notably IBM. Thus, the SIA-based measure would greatly understate semiconductor use during the 1970s and 1980s, when IBM was the dominant U.S. computer producer.

e. Share of current-dollar input costs associated with computer inputs (α_c^o)

The numerator of this share represents the current-dollar value of computers used as an intermediate input in nonfarm business excluding producers of computers and semiconductors. Using the I-O tables, we calculate the value of domestically produced computers used as intermediate input in the United States excluding that used by the computer industry itself, the electronic components and accessories industry (i.e., semiconductors), the agriculture sector, and the government sector. (Agriculture and government are subtracted because we are interested in the consumption of computers as intermediate input in the nonfarm business sector.) The next step is to account for imported computers used as intermediate input. Because of data limitations, we assume that the ratio of imported to domestically produced intermediate computer input matches the ratio of total computer imports to domestic computer production. We calculate the latter ratio for each year with an I-O table (1977, 1982, 1987, 1992, and 1996) and interpolate to obtain values for intervening years. Prior to 1977, we set this ratio equal to its 1977 value, and for 1997-99 we employ the 1996 value. With this series of ratios, we blow up the value of intermediate computer input produced in the U.S. to obtain an estimate of $p^c C^o$ each year, including the part that is imported. Finally, we divide this estimate of $p^c C^o$ by current-dollar output in nonfarm business excluding computers ($pY - p^c Y^c$).

APPENDIX B: MODEL OF SECTORAL PRODUCTIVITY

This appendix presents the model used in Section 4 to calculate the contributions of computer and semiconductor producers to the growth of *MFP* in the nonfarm business sector. The model divides nonfarm business into three sectors: Semiconductor producers, computer producers, and all other industries, which are indexed by *s*, *c*, and *o*, respectively. All semiconductor output is assumed to be consumed as an intermediate input by the other two sectors. In addition, the model recognizes that the computer sector not only produces final goods, but also sells computers as an intermediate input to sector *o*. (These intermediate sales include computers or peripherals that are embedded in other products, such as a personal computer built into a piece of medical diagnostic equipment.) To avoid cluttering the model with unessential details, we abstract from all other intermediate inputs. This implies that sector *o* produces only final goods in our model.

Details of the Model

Let Q^i ($i = s,c,o$) denote the total output of sector *i*, and let Y^i denote the output that is sold as final product. Given the assumptions of our model, $Y^o = Q^o$, $Y^s = 0$, and $0 < Y^c < Q^c$. Also, let K^i and L^i denote capital and labor inputs in sector *i*, let S^i ($i = c,o$) denote the semiconductors used as an intermediate input in sector *i*, and let C^o denote the computers used as an intermediate input in sector *o*. The sectoral production functions then can be written as:

$$(1) \qquad Q^s = S^c + S^o = F^s(K^s, L^s, t)$$

$$(2) \qquad Q^c = Y^c + C^o = F^c(K^c, L^c, S^c, t)$$

$$(3) \qquad Q^o = Y^o = F^o(K^o, L^o, S^o, C^o, t),$$

where *t* enters each production function as a proxy for the level of *MFP*. The capital and labor used across all three sectors must exhaust the aggregate amount of capital and labor employed in nonfarm business:

$$(4) \qquad K = K^s + K^c + K^o$$

$$(5) \qquad L = L^s + L^c + L^o.$$

Note that equation 4 directly aggregates the capital used in each sector, and equation 5 does the same for labor. By so doing, we have implicitly assumed that each sector employs the same mix of capital goods and the same mix of workers (otherwise, we would have to aggregate each input across sectors with superlative indexes).[1] As we discuss below, ignoring sectoral differences in capital and labor use likely has no material effect on our results. This assumption of identical capital and labor use implies a common rental rate (r) for capital in each sector and a common wage rate (w) for labor:

$$r = r^s = r^c = r^o \tag{6}$$

$$w = w^s = w^c = w^o. \tag{7}$$

Finally, let p^s, p^c, and p^o denote the price of output in the three sectors. This completes the set-up of the sectoral aspects of the model.

The aggregate production relation in our model is entirely standard. We assume that output is a function of capital input, labor input, and the level of *MFP*. Under the usual assumptions of perfect competition in input and output markets, this implies the standard growth-accounting identity for nonfarm business as a whole:

$$\dot{MFP} = \dot{Y} - \left[\frac{wL}{pY}\right]\dot{L} - \left[\frac{rK}{pY}\right]\dot{K}, \tag{8}$$

where the "dot" signifies a growth rate, i.e., $\dot{X} = (\partial X/\partial t)/X$ for any variable X. We measure the growth in aggregate final output as a superlative index of growth in sectoral final output:

$$\dot{Y} = \left[\frac{p^c Y^c}{pY}\right]\dot{Y^c} + \left[\frac{p^o Y^o}{pY}\right]\dot{Y^o}, \tag{9}$$

[1] The measure of labor input in each sector (L^i) should be viewed as embedding both labor hours and labor quality.

where $p^i Y^i$ $(i = c,o)$ is sectoral final output in current dollars and $pY = p^c Y^c + p^o Y^o$ is aggregate final output in current dollars. The following proposition derives the relationship between aggregate and sectoral *MFP* growth.

Proposition 1: Given the model specified in equations 1-9,

$$\boldsymbol{\dot{MFP} = \mu^c \dot{MFP^c} + \mu^o \dot{MFP^o} + \mu^s \dot{MFP^s}}$$

where $\mu^c = (p^c Q^c)/pY$, $\mu^o = (p^o Y^o)/pY$, and $\mu^s = (p^s Q^s)/pY$.

Proof. To begin, totally differentiate equations 1-3, imposing the standard condition that the marginal revenue product of each input equals its one-period cost, i.e., that $p^i(\partial F^i/\partial K^i) = r$ and $p^i(\partial F^i/\partial L^i) = w$ for $i = s,c,o$, $p^i(\partial F^i/\partial S^i) = p^s$ for $i = c,o$, and $p^o(\partial F^o/\partial C^o) = p^c$. This generates:

$$(10) \qquad \dot{Q^s} = \left[\frac{p^s S^c}{p^s Q^s}\right]\dot{S^c} + \left[\frac{p^s S^o}{p^s Q^s}\right]\dot{S^o} = \left[\frac{rK^s}{p^s Q^s}\right]\dot{K^s} + \left[\frac{wL^s}{p^s Q^s}\right]\dot{L^s} + \dot{MFP^s}$$

$$(11) \qquad \dot{Q^c} = \left[\frac{p^c Y^c}{p^c Q^c}\right]\dot{Y^c} + \left[\frac{p^c C^o}{p^c Q^c}\right]\dot{C^o} = \left[\frac{rK^c}{p^c Q^c}\right]\dot{K^c} + \left[\frac{wL^c}{p^c Q^c}\right]\dot{L^c} + \left[\frac{p^s S^c}{p^c Q^c}\right]\dot{S^c} + \dot{MFP}$$

$$(12) \qquad \dot{Q^o} = \dot{Y^o} = \left[\frac{rK^o}{p^o Y^o}\right]\dot{K^o} + \left[\frac{wL^o}{p^o Y^o}\right]\dot{L^o} + \left[\frac{p^s S^o}{p^o Y^o}\right]\dot{S^o} + \left[\frac{p^c C^o}{p^o Y^o}\right]\dot{C^o} + \dot{MFP^o}.$$

Next, totally differentiate equations 4 and 5, yielding:

$$(13) \qquad \dot{K} = \sum_{i=s,c,o} \left[\frac{rK^i}{rK}\right]\dot{K^i}$$

$$(14) \qquad \dot{L} = \sum_{i=s.c.o} \left[\frac{wL^i}{wL}\right]\dot{L^i}.$$

Now, substitute equation 9 into equation 8, and then substitute equations 11-14 into the resulting equation, which produces:

$$(15)\quad \dot{MFP} = \left[\frac{p^cQ^c}{pY}\right]\dot{MFP^c} + \left[\frac{p^oY^o}{pY}\right]\dot{MFP^o} + \sum_{i=c,o}\left[\left[\frac{rK^i}{pY}\right]\dot{K^i} + \left[\frac{wL^i}{pY}\right]\dot{L^i} + \left[\frac{p^sS^i}{pY}\right]\dot{S^i}\right]$$

$$- \sum_{i=s,c,o}\left[\left[\frac{rK^i}{pY}\right]\dot{K^i} + \left[\frac{wL^i}{pY}\right]\dot{L^i}\right].$$

After cancelling terms, equation 15 becomes:

$$(16)\quad \dot{MFP} = \left[\frac{p^cQ^c}{pY}\right]\dot{MFP^c} + \left[\frac{p^oY^o}{pY}\right]\dot{MFP^o} + \left[\sum_{i=c,o}\left[\frac{p^sS^i}{pY}\right]\dot{S^i}\right] - \left[\frac{rK^s}{pY}\right]\dot{K^s} - \left[\frac{wL^s}{pY}\right]\dot{L^s}$$

$$= \left[\frac{p^cQ^c}{pY}\right]\dot{MFP^c} + \left[\frac{p^oY^o}{pY}\right]\dot{MFP^o} + \left[\frac{p^sQ^s}{pY}\right]\left[\dot{Q^s} - \left[\frac{rK^s}{p^sQ^s}\right]\dot{K^s} - \left[\frac{wL^s}{p^sQ^s}\right]\dot{L^s}\right],$$

where the final equality follows from the first part of equation 10. Applying the second part of equation 10 yields

$$(17)\quad \dot{MFP} = \left[\frac{p^cQ^c}{pY}\right]\dot{MFP^c} + \left[\frac{p^oY^o}{pY}\right]\dot{MFP^o} + \left[\frac{p^sQ^s}{pY}\right]\dot{MFP^s},$$

which completes the proof. ■

We have proved that Proposition 1 holds when all three sectors are perfectly competitive (this assumption is built into equations 8 and 10-12). However, the proof would go through for *any* assumed market structure. One would modify the share weights in equations 8 and 10-12 to reflect imperfect competition in some or all of the sectors, and then repeat the rest of the proof with this modified set of equations.

Measuring Sectoral MFP

Proposition 1 shows the relationship between the growth of aggregate and sectoral *MFP* in our model. To make use of Proposition 1 we need to measure *MFP* growth in each sector. This can be done either from the sectoral production functions, as in equations 10-12, or from the sectoral cost functions — the so-called "dual" approach. We opt for the dual approach because the required data are more readily available. The dual counterparts to equations 10-12 are:

$$(18) \qquad \dot{p}^{S} = \left[\frac{rK^{s}}{p^{s}Q^{s}}\right]\dot{r} + \left[\frac{wL^{s}}{p^{s}Q^{s}}\right]\dot{w} - \dot{MFP}^{S}$$

$$(19) \qquad \dot{p}^{C} = \left[\frac{rK^{c}}{p^{c}Q^{c}}\right]\dot{r} + \left[\frac{wL^{c}}{p^{c}Q^{c}}\right]\dot{w} + \left[\frac{p^{s}S^{c}}{p^{c}Q^{c}}\right]\dot{p}^{S} - \dot{MFP}^{C}$$

$$(20) \qquad \dot{p}^{O} = \left[\frac{rK^{o}}{p^{o}Y^{o}}\right]\dot{r} + \left[\frac{wL^{o}}{p^{o}Y^{o}}\right]\dot{w} + \left[\frac{p^{s}S^{o}}{p^{o}Y^{o}}\right]\dot{p}^{S} + \left[\frac{p^{c}C^{o}}{p^{o}Y^{o}}\right]\dot{p}^{C} - \dot{MFP}^{O}.$$

These equations state that the growth in each sector's output price equals the growth in the (share) weighted average of its input costs, minus the growth in *MFP*. *MFP* growth enters with a negative sign because efficiency gains hold down a sector's output price given its input costs.

To simplify matters, we impose the following dual assumption on equations 18-20. Let $\dot{Z}$ denote the growth in the share-weighted cost of capital and labor input for the nonfarm business sector as a whole; that is,

$$(21) \qquad \dot{Z} = \left[\frac{rK}{pY}\right]\dot{r} + \left[\frac{wL}{pY}\right]\dot{w}.$$

We assume that the share-weighted growth of capital and labor costs for semiconductor producers equals $\dot{Z}$. Equation 18 then becomes:

$$(22) \qquad \dot{p}^{S} = \dot{Z} - \dot{MFP}^{S}.$$

We also impose this assumption on the other two sectors, so that equations 19 and 20 become:

$$\dot{p}^C = (1-\alpha_S^c)\dot{Z} + \alpha_S^c \dot{p}^S - \dot{MFP}^C \tag{23}$$

$$\dot{p}^O = (1-\alpha_S^o-\alpha_C^o)\dot{Z} + \alpha_S^o \dot{p}^S + \alpha_C^o \dot{p}^C - \dot{MFP}^O, \tag{24}$$

where $\alpha_s^c = p^S S^C / p^C Q^C$ is the cost share for semiconductors in the computer sector, $\alpha_s^o = p^S S^O / p^O Y^O$ is the cost share for semiconductors in sector *o,* and $\alpha_c^o = p^C C^O / p^O Y^O$ is the cost share for computer input in sector *o*. $\dot{Z}$ is scaled by (1- α_s^c) in equation 23 because capital and labor, taken together, account for (1- α_s^c) percent of total input costs in the computer sector. Likewise, in sector *o*, capital and labor account for (1 - α_s^o - α_c^o) percent of total input costs.

Our simplifying assumption — that capital and labor costs rise at the same rate in each sector — likely introduces only a slight approximation error into the estimates of *MFP* growth for computer and semiconductor producers. Consider equation 22 for semiconductor producers. This equation can be rearranged to show that growth in semiconductor *MFP* equals $\dot{Z}$ minus the percent change in semiconductor prices. These prices have trended sharply lower since the mid-1970s, falling at an average annual rate of more than 25 percent. Even if $\dot{Z}$ misstated the true growth in capital and labor costs for semiconductor producers by a couple percentage points per year, this error would be insignificant compared to the decline in semiconductor prices. The same argument applied to equation 23 suggests that the approximation error for computer-sector *MFP* growth would be relatively small as well.

We now use the dual equations to derive expressions for sectoral *MFP* growth that, when aggregated in accord with Proposition 1, add up exactly to our independent measure of aggregate *MFP* growth from the Bureau of Labor Statistics.

Proposition 2: Given the dual equations 22-24 and Proposition 1,

$$\dot{MFP}^S = \dot{MFP}^O - \pi^S - \alpha_s^o(\dot{p}^S - \dot{Z}) - \alpha_c^o(\dot{p}^C - \dot{Z})$$

$$\dot{MFP}^C = \dot{MFP}^O - \pi^C + (\alpha_s^c - \alpha_s^o)(\dot{p}^S - \dot{Z}) - \alpha_c^o(\dot{p}^C - \dot{Z})$$

$$\dot{MFP}^O = \left[\frac{1}{\mu^C + \mu^O + \mu^S}\right]\left[\dot{MFP} + \mu^C\pi^C + \mu^S\pi^S - \left[\mu^C(\alpha_s^c - \alpha_s^o) - \mu^S\alpha_s^o\right](\dot{p}^S - \dot{Z}) + (\mu^C + \mu^S)\alpha_c^o(\dot{p}^C - \dot{Z})\right]$$

where $\pi^C = \dot{p}^C - \dot{p}^O$ and $\pi^S = \dot{p}^S - \dot{p}^O$.

Proof. The result is nearly immediate. Subtract equation 24 from 22 and then subtract equation 24 from 23, obtaining:

$$\dot{MFP}^S = \dot{MFP}^O - \pi^S - \alpha_s^o(\dot{p}^S - \dot{Z}) - \alpha_c^o(\dot{p}^C - \dot{Z}) \tag{25}$$

$$\dot{MFP}^C = \dot{MFP}^O - \pi^C + (\alpha_s^c - \alpha_s^o)(\dot{p}^S - \dot{Z}) - \alpha_c^o(\dot{p}^C - \dot{Z}). \tag{26}$$

This establishes the expressions for $\dot{MFP}^S$ and $\dot{MFP}^C$ in the proposition. The final step is to measure $\dot{MFP}^O$ such that the relationship in Proposition 1 holds for a pre-specified estimate of *MFP* growth for nonfarm business as a whole. To do this, substitute equations 25 and 26 into the expression for *MFP* growth in Proposition 1:

$$(27) \qquad \dot{MFP} = \mu^c\left[\dot{MFP}^o - \pi^c + (\alpha_s^c - \alpha_s^o)(\dot{p}^S - \dot{Z}) - \alpha_c^o(\dot{p}^C - \dot{Z})\right] + \mu^o \dot{MFP}^o$$

$$+ \mu^S\left[\dot{MFP}^o - \pi^S - \alpha_s^o(\dot{p}^S - \dot{Z}) - \alpha_c^o(\dot{p}^C - \dot{Z})\right].$$

Solving equation 27 for $\dot{MFP}^o$ completes the proof. ■