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 the end of 1995 through the end of 1999, real gross domestic product rose at an annual rate of more than 4 percent. This rapid advance was accompanied by a rebound in the growth of labor productivity, with output per hour in nonfarm business rising at about a 2-¾ 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

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[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.

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 ballooned and, by our estimates, are earning greater returns than in the early 1990s. In addition, the producers of computers (and the embedded semiconductors) appear to have achieved huge efficiency gains in their operations. Focusing on the nonfarm business sector, we estimate that the growing use of information technology equipment and the efficiency improvements in producing computers account for about two-thirds of the acceleration in labor productivity 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 multifactor productivity (MFP):

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

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

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[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.

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

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

where r is a measure of the real net rate of return common to all capital, pY is total nominal

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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*.

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 (actually capital loss for computers), 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 driven the accumulation of capital. In this sense, the neoclassical framework provides a superficial explanation of growth. Second, this framework cannot satisfactorily explain why growth slowed in the 1970s; it largely attributes this slowdown to a mysterious deceleration in 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

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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.

computers and semiconductors.[5]

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. 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

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[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) argue that the adoption of information technology in the 1970s was itself responsible for the slowdown because it took firms a long time to learn how to use the new equipment effectively. This view is controversial. Kortum (1997) questions the empirical importance of these adoption costs, while Hornstein (1999) shows that the theoretical results depend crucially on the specification of the learning process.

[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.

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. 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 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. BLS constructs productive stocks (for computers and all other tangible capital) that assume 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 Contribution of Computing Services to Growth[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.

At the time we were writing, the BLS dataset ran only through 1997. We extended all necessary series through 1999, revised the output figures to be consistent with the October 1999 comprehensive revision of the National Income and Product Accounts (NIPAs), added in capital stocks of software, and made a few other adjustments.[9] In making these modifications, our

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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. Additional detail can be found in a data appendix available from the authors.

[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

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 aggregate investment in software. Based on these aggregate 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, to measure the contribution of other capital, we start with the contribution from total capital (excluding software) and net out the contributions from computer

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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 boosted the depreciation rate of personal computers, and we expect BLS — in its next release of data — to shorten the service life used to estimate the productive stock of PCs. 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.

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 price of each asset relative to the price of 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.

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[11] See the *Survey of Current Business*, July 1997. Because BEA does not publish depreciation rates for the components of computers and peripheral equipment, we follow Whelan (1999) 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. In these periods, real nonfarm business output rose at an average pace of around 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 almost 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 this were the basis for our earlier conclusion that the growth contribution from information technology had been relatively small through the early 1990s, especially if one focused on computer hardware alone. During the first half of the 1990s, the stock of computer hardware increased at an average rate of about 17 percent per year, but its income share averaged just 1.4 percent (see lines 10 and 13 of the table). Hence, the

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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. Thus, it seems probable that the data on investment and capital stock do not fully capture the quality improvements in communication equipment. If that is the case, the "true" stock of communication equipment would grow more rapidly than that shown in the published numbers, and the contribution of communication equipment to output growth would be larger than that shown above.

contribution of computer hardware to output growth, computed as 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, while the contribution of overall information processing capital to output growth was about 1.1 percentage points, a considerable step-up from the pace earlier in the decade.[14] This step-up 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

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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 published data also allows us to maintain consistency with other studies. Nonetheless, the true pickup in output growth after 1995 could be somewhat larger than that shown in table 1.

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 1.6 percent per year in the first half of the 1990s to nearly 2.7 percent in the second half. The rapid capital deepening related to information technology capital accounted for nearly half of this increase (line 3). Other types of capital (line 7) made almost no contribution to the step-up in labor productivity growth, while the contribution from labor quality actually fell across the two periods. This leaves *MFP* to account for more than half 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 (1999) 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 (1999) are close to the middle of this wide range. We briefly explain why these estimates differ from ours.

Whelan (1999) 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 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-

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

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.

Jorgenson and Stiroh's (2000) estimate of the growth contribution is smaller than ours. During 1996-98, the latest period covered by their estimates, they figure that computer hardware contributed 0.36 percentage point annually to growth, about double their contribution for 1974-95. In the 1996-98 period, their estimate is roughly three-fifths the size of ours, reflecting their smaller income share for computer hardware — 1.12 percent during 1996-98 compared to our estimate of 1.65 percent — and their slower growth rate for capital services from computer hardware.

Two factors largely explain these differences. First, they employ a broader concept of output than we do. Jorgenson and Stiroh include imputed service flows from owner-occupied housing and consumer durables, which are excluded from the BLS output series we use. With these additions to output, the income share attributed to business computers falls, all else equal. Business-owned computers are simply a smaller part of the economy that they choose to measure. Second, Jorgenson and Stiroh assume that capital put in place only becomes productive with a lag, and therefore their capital stock numbers are lagged one year relative to ours; that is, for the 1998 contribution to growth, we use an estimate of computer capital and its growth rate for 1998 while they use figures for 1997. This convention causes their estimate of the current-dollar computer stock, and hence the income share, to be smaller than ours. In addition, because the growth of the real stock of computer hardware has picked up in recent years, their estimate of $\dot{K}_C$ for 1996-98 actually reflects the slower growth recorded over 1995-97.

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 (1999).

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 model, one must specify the input-output connections among the sectors. We focus on the one connection that really matters for our analysis — the use of semiconductors as an input by the other two sectors — and

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

abstract from all others. Our companion working paper, Oliner and Sichel (2000), fully describes 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^{c} denote computer output as a share of total nonfarm business output, in current dollars, and let μ^{o} denotes the corresponding share for the rest of nonfarm business (excluding semiconductors). Because these two sectors produce all final output in our model, $\mu^{c} + \mu^{o} = 1$, so that $\mu^{o} = 1 - \mu^{c}$. Also, let μ^{s} denote the value of semiconductors used as inputs by the other two sectors, scaled by nonfarm business output, again in current dollars. With this notation, our companion working paper shows that

$$(4) \qquad M\dot{F}P = \mu^{c}\, M\dot{F}P^{c} + (1-\mu^{c}) M\dot{F}P^{o} + \mu^{s}\, M\dot{F}P^{s}.$$

Aggregate *MFP* growth is a weighted average of *MFP* growth in the two sectors that produce final goods, plus a term for the semiconductor sector. To see why this additional term is needed, assume that there were no *MFP* growth in the other two sectors and that the aggregate stocks of capital and labor were 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*.

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 BEA data, we approximate current-dollar computer output with the sum of computer spending by U.S. businesses, households, and all levels of government, plus net exports of computers. For current-dollar semiconductor output, we use internal Federal Reserve Board estimates developed to support the Fed's published data on U.S. industrial production. We divide both series by current-dollar nonfarm business output to obtain estimates of μ^s and μ^c.

To estimate sectoral *MFP* growth, we employ the so-called "dual" method used by Triplett (1996) and Whelan (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, our companion working paper shows that

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

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

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 the companion paper 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 0.22 and 0.41 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).[17] 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

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[17] Alternatively, one might argue that the sharp price declines merely reflect weak worldwide demand rather than a rise in *MFP* growth. The economic problems during 1997-98 in in Asia and Latin America likely did depress semiconductor demand for a while. However, if weak demand — rather than faster *MFP* growth — were the main story, 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.

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).[18] As can be seen by comparing lines 1 and 5, this vertically-integrated computer sector accounted for nearly two-fifths of the growth in nonfarm business *MFP* during the second half of the 1990s — a remarkable percentage 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 pick-up 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 less than 0.05 percentage point of the acceleration, while *MFP* growth elsewhere in nonfarm business (lines 6 and 7) accounts for the remainder. These results suggest that information

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

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.[19]

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 in nonfarm business (after adjusting for the cyclical component of productivity and for changes in the methodology of price measurement). Elsewhere in nonfarm business, Gordon argued there has been no rise in trend productivity growth. Based on this decomposition, Gordon inferred that the increasing *use* of computers across the nonfarm business sector had contributed nothing to the recent acceleration of trend productivity. We will briefly explain why Gordon reaches a conclusion so different from ours.

Gordon wrote his paper before the comprehensive revision of the national accounts in October 1999; he has since recalculated his numbers using the new data, and we shall refer to his new numbers unless noted otherwise. As for the contribution from producers of computer hardware, Gordon's results are actually quite consistent with our own. He calculates that this sector accounts for about 0.3 percentage point of the acceleration in labor productivity for

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[19] As we noted above, the post-1995 pickup in the growth of output (and, hence, in output per hour) could be larger 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. The extent of any adjustment in this share would depend on both the size of the upward revision to output growth and on the fraction of the extra output that takes the form of investment in information technology capital.

nonfarm business after 1995.[20] We estimate that the increase in *MFP* growth for producers of computer hardware and the embedded semiconductors accounts for 0.26 percentage point of this pickup (see table 5, line 3). Capital deepening in this sector, not shown separately in the table, would boost this contribution a bit — leaving our estimate of the sector's total contribution to labor-productivity growth very close to Gordon's.

In his paper, Gordon estimated that trend productivity growth for nonfarm business as a whole increased about 0.3 percentage point, the size of the step-up he attributed to the production of computers. This left no room for any other factor — such as the *use* of computers or *MFP* growth in other industries — to have contributed to the pickup. Using the new data through 1999:Q3, Gordon now estimates that the post-1995 acceleration in trend productivity for nonfarm business was about 0.5 percentage point, 0.2 percentage point more than his estimate of the contribution from computer producers. Thus, Gordon's original conclusion — that the production of computer hardware accounted for the entire pickup in trend labor-productivity growth — no longer stands.

Whether he uses the new or the old data, Gordon attributes much of the recent acceleration in productivity to cyclical factors. Unlike Gordon, we have made no attempt to distinguish trend from cycle. Rather, we have tried to explain the speed-up of *actual* productivity

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[20] Specifically, using the new data, Gordon estimates that labor productivity for computer manufacturers grew at a 35.1 percent annual rate from 1995:Q4 to 1999:Q3 and that the nominal share of computers in nonfarm business output averaged about 1.5 percent. Over 1972:Q2-1995:Q4, Gordon estimates that labor productivity for computer manufacturers increased at a 25.1 percent annual rate and that the share of computers in output averaged 0.9 percent. These numbers imply a pickup in the contribution of computer producers to overall productivity growth of 0.3 percentage point (=0.015x35.1 - 0.009x25.1). The comprehensive revision had little effect on this estimate.

growth during the late 1990s. Separating cycle from trend is difficult, particularly in the midst of an expansion. In Gordon's framework, as in ours, the production of computer hardware does not come close to accounting for the entire rise in *actual* productivity growth, leaving plenty of room for the *use* of computers to have boosted this growth in recent years. Indeed, as our results show, the *use* of computers and other information technology makes an important contribution to the acceleration in productivity after 1995.

5. THE INTERNET AND E-COMMERCE

In the past few years, the Internet has spread rapidly, e-commerce appears to have exploded, and telecommunications links connecting computer networks have become ever more extensive. And, according to the anecdotes, these developments have led to some spectacular increases 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. Also, the indirect effects of business-to-business e-commerce on real GDP would be picked up without any change in current procedures.[21] Moving to the right-hand side of equation 1, the computer and communication infrastructure needed to support the Internet 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. An article by Kim Cross in a recent issue of *Business 2.0* 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

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[21] For example, if an automaker purchased steel via the Internet, the GDP measure in the national accounts would include the value of the car produced — the final good — but would not separately count the value of the steel— the intermediate input — in order to avoid double counting. Any additional efficiencies in the distribution of intermediate inputs would, in a competitive equilibrium, show up in the price or quantity of the final good produced.

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. Of course, 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.[22] 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/.9)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

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[22] Also, one recent study actually found that prices are higher on the Internet. For example, Bailey (1998) compares prices of books, compact discs, and software sold on the Internet and through conventional channels. He found that in 1996 and 1997 prices were higher on the Internet. This result seems counterintuitive, and Bailey argues that it reflected the immaturity of the electronic marketplace.

had, to date, only a small impact on 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.[23]

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

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[23] 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.

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]	3.13	2.82	4.90
Contributions from:[b]			
2. Information technology capital	.51	.54	1.08
3. Hardware	.28	.24	.62
4. Software	.11	.23	.31
5. Communication equipment	.12	.07	.15
6. Other capital	.85	.44	.76
7. Labor hours	1.15	.82	1.51
8. Labor quality	.22	.44	.31
9. Multifactor productivity	.40	.57	1.25
Memo:			
Income shares:[c]			
10. Hardware	1.0	1.4	1.8
11. Software	.9	1.9	2.4
12. Communication equipment	1.6	2.0	2.1
Growth rate of inputs:[a]			
13. Hardware	31.4	17.5	36.0
14. Software	13.2	12.8	13.1
15. Communication equipment	7.7	3.6	7.1

[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 income shares (lines 10 to 12) differ 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

Conbtributions to Labor Productivity Growth in the Nonfarm Business Sector, 1974-1999

	1974-90	1991-95	1996-99
1. Growth rate of labor productivity:[a]	1.43	1.61	2.66
Contributions from:[b]			
2. Capital deepening	.81	.60	1.09
3. Information technology capital	.45	.48	.94
4. Hardware	.26	.22	.58
5. Software	.10	.21	.26
6. Communication equipment	.09	.05	.10
7. Other capital	.36	.12	.16
8. Labor quality	.22	.44	.31
9. Multifactor productivity	.40	.57	1.25

[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

	Previous Period		Current Period	
Study	Years Covered	Contribution[a]	Years Covered	Contribution[a]
1. This paper	1974-95	.27	1996-99 1996-98	.62 .58
2. Whelan (1999)	1980-95	.37	1996-98	.82
3. Jorgenson-Stiroh (2000)	1974-95	.17	1996-98	.36
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 (1999): Table 4 (Column labeled "Obsolescence Model"), p. 35. The figure shown for 1980-95 is a weighted average of figures presented by Whelan for 1980-89 and 1990-95.

Jorgenson-Stiroh (2000): Table 5 (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]	.40	.57	1.25
Contribution from each sector:[b]			
2. Computer sector	.12	.13	.22
3. Semiconductor sector	.08	.13	.41
4. Other nonfarm business	.20	.30	.62
5. Computer sector plus computer-related semiconductor sector	.17	.21	.47
Memo:			
Output shares:[c]			
6. Computer sector	1.0	1.1	1.3
7. Semiconductor sector	.3	.6	.9
8. Other nonfarm business	99.0	98.9	98.7
Growth of MFP:[a]			
9. Computer sector	11.6	11.6	16.3
10. Semiconductor sector	30.9	22.7	45.0
11. Other nonfarm business	.21	.31	.63

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[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 sectoral MFP growth (lines 9 to 11) differ 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, and on 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	1.05
Contributions from:	
2. Information technology capital services per hour	.46
3. MFP in computer production and computer-related semiconductor production	.26
4. Other capital services per hour	.04
5. Labor quality	-.13
6. MFP in other semiconductor production	.11
7. MFP in other nonfarm business	.32

[a] Percentage points per year.

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

Source: Results shown in tables 2 and 4.

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APPENDIX A: 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, both of which produce only final products. To avoid cluttering the model with unessential details, we abstract from the use of materials or purchased services in all three sectors.

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, $Y^c = Q^c$ and $Y^o = Q^o$, while $Y^s = 0$. Also, let K^i and L^i denote capital and labor inputs in sector i, and let S^i ($i = c,o$) denote the semiconductors used as an input in sector i. The sectoral production functions then can be written as:

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

$$Q^c = Y^c = F^c(K^c, L^c, S^c, t) \tag{2}$$

$$Q^o = Y^o = F^o(K^o, L^o, S^o, t), \tag{3}$$

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:

$$K = K^s + K^c + K^o \tag{4}$$

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

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:

(6) $$r = r^s = r^c = r^o$$

(7) $$w = w^s = w^c = w^o.$$

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:

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

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[1] This assumption does not imply that all workers are the same, only that each sector employs the same mix of heterogeneous workers. The measure of labor input in each sector (L^i) should be viewed as embedding both labor hours and labor quality.

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:

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

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

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

$$\boldsymbol{\dot{MFP} = \mu^c\,\dot{MFP}^c + (1-\mu^c)\,\dot{MFP}^o + \mu^s\,\dot{MFP}^s}$$

where $\mu^c = (p^cY^c)/pY$ and $\mu^s = (p^sQ^s)/pY$.

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 $i = s,c,o$, and $p^i(\partial F^i/\partial S^i) = p^s$ for $i = c,o$. This generates:

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

$$\dot{Q}^c = \dot{Y}^c = \left[\frac{rK^c}{p^cY^c}\right]\dot{K}^c + \left[\frac{wL^c}{p^cY^c}\right]\dot{L}^c + \left[\frac{p^sS^c}{p^cY^c}\right]\dot{S}^c + \dot{MFP}^c \tag{11}$$

$$\dot{Q}^o = \dot{Y}^o = \left[\frac{rK^o}{p^oY^o}\right]\dot{K}^o + \left[\frac{wL^o}{p^oY^o}\right]\dot{L}^o + \left[\frac{p^sS^o}{p^oY^o}\right]\dot{S}^o + \dot{MFP}^o. \tag{12}$$

Next, totally differentiate equations 4 and 5, yielding:

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

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

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

$$(15)\qquad \overset{\bullet}{MFP} = \sum_{i=c,o} \left[\left[\frac{rK^{i}}{pY}\right] \overset{\bullet}{K}{}^{i} + \left[\frac{wL^{i}}{pY}\right] \overset{\bullet}{L}{}^{i} + \left[\frac{p^{s}S^{i}}{pY}\right] \overset{\bullet}{S}{}^{i} + \left[\frac{p^{i}Y^{i}}{pY}\right] \overset{\bullet}{MFP}{}^{i} \right]$$

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

After cancelling and rearranging terms, equation 15 becomes:

$$(16)\qquad \overset{\bullet}{MFP} = \sum_{i=c,o} \left[\left[\frac{p^{i}Y^{i}}{pY}\right] \overset{\bullet}{MFP}{}^{i} + \left[\frac{p^{s}Q^{s}}{pY}\right]\left[\frac{p^{s}S^{i}}{p^{s}Q^{s}}\right] \overset{\bullet}{S}{}^{i} \right] - \left[\frac{rK^{s}}{pY}\right] \overset{\bullet}{K}{}^{s} - \left[\frac{wL^{s}}{pY}\right] \overset{\bullet}{L}{}^{s}$$

$$= \sum_{i=c,o} \left| \left[\frac{p^{i}Y^{i}}{pY}\right] \overset{\bullet}{MFP}{}^{i} \right| + \left[\frac{p^{s}Q^{s}}{pY}\right] \left| \overset{\bullet}{Q}{}^{s} - \left[\frac{rK^{s}}{p^{s}Q^{s}}\right] \overset{\bullet}{K}{}^{s} - \left[\frac{wL^{s}}{p^{s}Q^{s}}\right] \overset{\bullet}{L}{}^{s} \right| ,$$

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

$$\dot{MFP} = \sum_{i=c,o} \left[\left[\frac{p^i Y^i}{pY}\right] \dot{MFP}^i \right] + \left[\frac{p^s Q^s}{pY}\right] \dot{MFP}^s \tag{17}$$

$$= \left[\frac{p^c Y^c}{pY}\right] \dot{MFP}^c + \left[1 - \frac{p^c Y^c}{pY}\right] \dot{MFP}^o + \left[\frac{p^s Q^s}{pY}\right] \dot{MFP}^s ,$$

where the second equality follows from $p^o Y^o = pY - p^c Y^c$. This completes the proof. ■

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:

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

$$\dot{p}^c = \left[\frac{rK^c}{p^c Y^c}\right] \dot{r} + \left[\frac{wL^c}{p^c Y^c}\right] \dot{w} + \left[\frac{p^s S^c}{p^c Y^c}\right] \dot{p}^s - \dot{MFP}^c \tag{19}$$

$$\dot{p}^o = \left[\frac{rK^o}{p^o Y^o}\right] \dot{r} + \left[\frac{wL^o}{p^o Y^o}\right] \dot{w} + \left[\frac{p^s S^o}{p^o Y^o}\right] \dot{p}^s - \dot{MFP}^o . \tag{20}$$

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 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:

$$(23) \qquad \dot{p}^{c} = (1-\alpha_{s}^{c})\dot{Z} + \alpha_{s}^{c}\,\dot{p}^{s} - \dot{MFP}^{c}$$

$$(24) \qquad \dot{p}^{o} = (1-\alpha_{s}^{o})\dot{Z} + \alpha_{s}^{o}\,\dot{p}^{s} - \dot{MFP}^{o},$$

where $\alpha_{s}^{i} = p^{s}S^{i}/p^{i}Y^{i}$ is the cost share for semiconductors in sector i ($i = c,o$). $\dot{Z}$ is scaled by $(1-\alpha_{s}^{i})$ because capital and labor, taken together, account for $(1-\alpha_{s}^{i})$ percent of total input costs in each sector.

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,

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

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

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

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:

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

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

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:

$$\begin{aligned} \dot{MFP} = {} & \mu^C \left[\dot{MFP}^O - \pi^C + (\alpha_s^c - \alpha_s^o)(\dot{p}^S - \dot{Z}) \right] + (1-\mu^C)\, \dot{MFP}^O \\ & + \mu^S \left[\dot{MFP}^O - \pi^S - \alpha_s^o(\dot{p}^S - \dot{Z}) \right]. \end{aligned} \tag{27}$$

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

Figure 1

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