

# The IT Revolution: Is It Evident in the Productivity Numbers?

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There is little doubt that we are witnessing a technological revolution. The question is, does this technological revolution have revolutionary economic consequences? In particular, is economic productivity growing at a much faster rate today, and if so, will it continue to do so in the future? In this article, we review recent literature on the measurement of productivity growth in the United States. We find considerable evidence that the internet technology (IT) revolution has had an impact on productivity.

In order to understand the effects of IT on today's economy, one should look at the past century. When we consider postwar U.S. productivity movements, two events stand out: the impressive productivity growth performance from the end of World War II up to the early seventies, and the ensuing productivity slowdown, which lasted until the mid-nineties. Labor productivity growth, which averaged about 2 percent per year from the fifties on, suddenly decreased to nearly 0 percent, and then seemed to settle at a rate around 1 percent. Moreover, this postwar productivity pattern is observed not only for the U.S. but throughout the western world.

This productivity slowdown remains quite poorly understood (for an overview and detailed data, see Hornstein and Krusell [1996]). One interpretation of the productivity data is that the fast postwar growth was a transitional period that made up for the losses during the Great Depression, and the post-1974 period of low productivity growth rates is really the normal state of the

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economy. We are not convinced that this view is correct. From our perspective, the productivity slowdown is interesting because it occurred at the same time that IT applications became more widespread in the economy. The paradox is that new technology developments since that time have been associated with a productivity slowdown, and not an upturn, at least until quite recently. In other words, economists have had legitimate reasons to challenge those talking about a technology revolution on economic grounds: for it to have had significance, productivity growth (or economic welfare measured in some other way) ought to have gone up.

This article points to a number of reasons why the technology revolution may have had a significant impact on the economy's production structure despite its apparent insignificance in aggregate productivity statistics. First, we emphasize a number of methodological issues that may have prevented standard accounting procedures from detecting increases in productivity. Second, we take the view that the technology revolution may have affected the production structure in a quite asymmetric form, mainly showing its economic impact through changes in relative prices. Given this view, we investigate the hypothesis that the technology revolution, after all, has had important consequences on productivity: (1) it has led to radical changes in productivity among different sectors/factors of production; and (2) a number of factors related to the technology developments themselves have resulted in measures of *aggregate* performance that do not accurately reflect the (positive) effects on the economy. We find that while there is some support for this hypothesis, the evidence is not conclusive.

In Section 1 we review recent methodological and measurement advances in standard growth accounting, also known as "total factor productivity" accounting, which uses some basic economic theory to account for changes in productivity. The central question is the extent to which we have been, and are still, witnessing a technology revolution that has a large impact on the productivity of our economies. The IT boom has radical implications not just as an example of rapid structural change, but also from a measurement perspective. In particular, it seems to have brought about, and promises to bring many more, large changes in a range of products used as both inputs and outputs. Existing measurement methods may quickly become obsolete as products change and new products are introduced, and substantial work to improve these methods, both theoretically and with new forms of data collection, becomes of first-order importance. An increasingly large part of the output of our economy now has a quality-improvement aspect to it that is nontrivial to capture quantitatively. Quality mismeasurement is a long recognized problem, especially in the service sector (where output is often measured directly by input), and we can learn from attempts by economists to deal with this sector. In this article we discuss—at a broad level—what the main problems are and what advances have been implemented so far. We then present the

most recent estimates of aggregate productivity change for the United States using improved methods.

In Section 2 we review some recent literature on factor-specific productivity (FSP) accounting. The FSP approach imposes additional theoretical structure on the measurement of productivity and attempts a more detailed account of the sources of the productivity change. The motivation for moving from TFP to FSP measurement is based on the large changes in various relative prices that we have observed during the past few decades. First, equipment prices have fallen at a rapid rate; the seminal work by Gordon (1990) documents these developments in detail, based on careful quality measures of a large range of durable goods. Second, relative prices of skilled and unskilled labor have gone through large swings, most recently with a large increase in the relative wage of educated workers. These relative price changes suggest that there are factor-specific productivity changes. More theory is needed—that is, more assumptions need to be made—in order to gain more precise insights into the nature of the technology changes. We therefore spend time developing some theory necessary to shed light on these issues on a conceptual level, before discussing some recent practical applications.

## 1. TOTAL FACTOR PRODUCTIVITY

### Concept

Standard economic theory views production as the transformation of a collection of inputs into outputs. We are interested in how this production structure is changing over time. In this section we derive the basic concepts used in productivity accounting.

We keep things simple and assume that there is one output,  $y$ , and two inputs, capital  $k$  and labor  $n$ . The production structure is represented by the production function,  $F$ :  $y = F(k, n, t)$ . Since the production structure may change, the production function is indexed by time  $t$ . Productivity changes when the production function shifts over time, i.e., there is a change in output that we cannot attribute to changes in inputs. More formally, the marginal change in output is the sum of the marginal changes in inputs, weighted by their marginal contributions to output (marginal products), and the shift of the production function  $\dot{y} = F_k \dot{k} + F_n \dot{n} + F_t$ .<sup>1</sup> This is usually expressed in terms of growth rates as

$$\hat{y} = \eta_k \hat{k} + \eta_n \hat{n} + \hat{z}, \text{ with } \hat{z} = F_t/F,$$

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<sup>1</sup>The marginal change of a variable is its instantaneous rate of change over time; that is, if we write the value of a variable at a point in time as  $x(t)$ , then the marginal change is the time derivative  $\dot{x}(t) = \partial x(t)/\partial t$ . Nothing is lost in the following if the reader interprets  $\dot{x}(t)$  as the change of a variable from year to year, that is,  $x(t) - x(t-1)$ .

where hats denote growth rates and the weight on an input growth rate is the elasticity of output with respect to the input:  $\eta_k = F_k k / F$  and  $\eta_n = F_n n / F$ . Alternatively, if we know the elasticities we can derive productivity growth as output growth minus a weighted sum of input growth rates. Indeed, it was Solow's (1957) important insight that under two assumptions we can replace an input's output elasticity, which we do not observe, with the input's share in total revenue, which we do. First, we assume that production is constant returns to scale, i.e., if we double all inputs, then output will double. This implies that the output elasticities sum to one:  $\eta_k + \eta_n = 1$ . Second, we assume that producers act competitively in their output and input markets, i.e., they take the prices of their products and inputs as given. Profit maximization then implies that inputs are employed until the marginal revenue product of an input is equal to the price of that input. In turn, this implies that the output elasticity of an input is equal to the input's revenue share. For example, for the employment of labor, profit maximization implies that  $p_y F_n = p_n$ , which can be rewritten as  $\eta_n = F_n n / F = p_n n / p_y y = \alpha_n$  ( $p_i$  stands for the price of good  $i$ ). With these two assumptions we can calculate productivity growth, also known as total factor productivity (TFP) growth, as

$$\hat{z} = \hat{y} - (1 - \alpha_n) \hat{k} - \alpha_n \hat{n}.$$

Implementation of the Solow growth accounting procedure thus requires reliable information on the prices and quantities of inputs and outputs. We discuss below some of the issues that arise in productivity accounting and how they are affected by the current advances in information technologies.

### Implementation and Weaknesses

In this section we discuss issues of aggregation, changes of quality versus quantity, missing inputs, and available observations on prices. Finally, we briefly discuss the underlying assumptions of constant returns to scale and perfect competition.

#### *Aggregation*

Any modern economy produces a large variety of commodities and uses an equally large variety of commodities as inputs in production. In order to make useful statements on the overall performance of the economy, we have to define broad commodity aggregates. The theoretically preferred aggregation procedure is the construction of Divisia indexes (see, for example, Jorgenson, Gollop, and Fraumeni [1987] or Hulten [1973]).<sup>2</sup> In practice we approximate a Divisia index with a chain-linked price and quantity index.

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<sup>2</sup>We define the Divisia index below.

As an example, consider the production structure described above, but assume that there are two types of labor: unskilled labor  $n_u$  and skilled labor  $n_s$ , which trade at prices  $w_u$  and  $w_s$ . Suppose that skilled and unskilled labor combine and generate the labor aggregate  $n = G(n_u, n_s)$ . The aggregator function  $G$  is constant returns to scale. Using the same arguments as above for the Solow growth accounting procedure, we can write aggregate labor growth as a cost-share-weighted sum of the skilled and unskilled labor growth rates

$$\hat{n} = \omega_u \hat{n}_u + \omega_s \hat{n}_s,$$

where  $\omega_u = w_u n_u / (w_u n_u + w_s n_s)$  and  $\omega_s = w_s n_s / (w_u n_u + w_s n_s)$ . Notice that the aggregator function is time invariant, i.e., the productivity of skilled and unskilled labor does not change over time. Essentially, this is an identification assumption: given our assumptions we can only make statements about aggregate productivity, not about factor-specific productivity. We will return to this issue below. In general, if we have prices and quantities for a collection of commodities  $\{(p_i, q_i) : i = 1, \dots, m\}$  we assume that there is a constant returns-to-scale aggregator function  $\bar{q} = Q(q_1, \dots, q_m)$ , and define the growth rate of the aggregate quantity index as

$$\hat{\bar{q}} = \sum_{i=1}^m \frac{p_i q_i}{\bar{p} \bar{q}} \hat{q}_i \quad \text{with} \quad \bar{p} \bar{q} = \sum_{i=1}^m p_i q_i$$

and  $\bar{p}$  is the implicit aggregate price index. The expression for the growth rate of aggregate output is also the definition of the Divisia quantity index for this particular collection of commodities.

The level of aggregation depends on the focus of the research. Recent research on the effects of IT has tried to establish how much of output growth can be attributed to IT capital accumulation and if the spread of IT has affected TFP growth in various industries differentially. For this purpose, researchers have constructed separate aggregates for IT related capital, such as computing and communications equipment and other capital goods. In this context, Divisia indexes have the nice property that they aggregate consistently. Therefore, we can first construct industry TFP growth from industry output, capital, and labor growth, then use the industry data to construct aggregate output, capital, and labor growth, and finally obtain aggregate TFP growth, which is also a weighted sum of industry productivity growth rates (see Jorgenson et al. [1987]).

### *Price, Quantity, and Quality*

Until now we have worked according to the assumption that it is easy to obtain prices and quantities for any particular commodity. Yet the commodity structure of an industrial economy is not static: existing commodities are improved upon or replaced by new commodities. Very often the distinction

between improvement and replacement is just a matter of degree, and it is more useful to think of products as having certain quality properties that are relevant to the purpose for which the commodity is used, be it in consumption or production. For example, the average car today is very different from the same car 20 years ago in terms of its performance characteristics, its maintenance requirements, etc. One way to measure the car production in the economy would simply be to count the number of units produced, but this method clearly does not reflect the superior quality of today's car relative to yesterday's car, and it would lead one to underestimate output growth and thereby productivity growth. The appropriate procedure is then to adjust a car for its quality content, i.e., a car is weighted according to its characteristics. Not accounting for quality change in the production of cars would lead one to underestimate output and productivity growth.

When commodities differ according to quality, we have to construct quality-adjusted price measures. In order to see if a broadly defined commodity has become expensive over time, we do not compare the price of two similar commodities at different points in time, but we compare the quality-adjusted prices. Only an increase in the quality-adjusted price represents a true price increase. The use of quality-adjusted prices, or hedonic prices, was pioneered by Griliches (1961). Gordon's (1990) work on durable goods shows that the relative price of durable goods declines at a substantially faster rate once one accounts for quality change.

The counterpart of this observation is that, using Gordon's (1990) price deflator, the quantity of durable goods produced increases at a faster rate. For the case of investment goods, disregarding quality change leads one not only to underestimate output growth, but also to underestimate input growth because investment is used to construct capital stocks. The effect on measured productivity growth can be ambiguous since we underestimate both output and input growth. Obviously, adjusting for quality change is more important for new products in innovative industries such as IT. Recently this approach has been successfully applied to the construction of computer price indexes in the United States (see Cole et al. [1986]). This application was successful because there was a well-defined and easily measured set of characteristics describing the performance of computers.

When it is difficult to apply hedonic pricing—e.g., when it is impractical or conceptually hard to distinguish products' characteristics—there can be other ways to make quality adjustments. In a recent innovative paper by Bils and Klenow (1999), one such method is developed and put to work. Loosely speaking, the alternative to brute-force measurement of quality components of products proposed by Bils and Klenow is to use theory. Consider, for instance, vacuum cleaners. Most households own one. However, there are many brands and qualities of vacuum cleaners, and by looking at detailed household data one can find out, on average, to what extent additional household income

translates into a more expensive vacuum cleaner. After using the cross section to find out how income translates into quality, Bils and Klenow (1999) turn to the time series and use aggregate changes in household income to predict the added quality component in vacuum cleaner purchases over time. This method is applied to a broad set of products, and the results can be summarized in a downward revision of the growth of the official Bureau of Labor Statistics price index by over 2 percentage points per annum (with a corresponding upward revision in real output growth).

The problems of quality adjustment are well recognized but hard to resolve. With the explosion of new IT-related products, quality mismeasurements are likely to be more severe. Fortunately, IT advances are likely to ease data collection in the future, but the brute-force method surely needs to be complemented with alternative methods, such as that of Bils and Klenow (1999).

In the service sector, a failure to account for changes in quality may explain the poor productivity performance in a variety of industries. A prominent example in the United States is the banking sector, where until recently bank output was extrapolated based on bank employment. As heavy users of IT, the financial industries have substituted equipment capital for labor. Given the measurement procedure, the capital-labor substitution had the unfortunate consequence of lowering measured output while maintaining or increasing the use of inputs. An incorrect measure of output thus results in apparent productivity declines. Recent revisions define bank output as an employment-weighted sum of the number of different transactions performed (see Moulton [2000]). However, this still does not correct for changes in the quality of transactions, such as convenience, reliability, and speed. One might expect that future IT developments will allow for further improvements along these quality dimensions.

Another sector whose contribution to the aggregate economy has increased and where quality aspects are very important is the provision of health services. For this sector one would have to construct medical diagnosis price indexes that would account for the accuracy of the diagnosis and the inconvenience to the patient, as well as treatment price indexes that would account for the success rate, intrusiveness, side effects, etc. of the treatment (see Shapiro, Shapiro, and Wilcox [1999]).

Finally, to our knowledge, all productivity accounting exercises assume that the quality of different types of labor remains constant over time. That is, the overall quality of the aggregate labor force may increase because the economy employs more skilled than unskilled labor, but the quality of skilled and unskilled labor is assumed to remain the same. We return to this issue in the next section.

### *Missing Inputs and Outputs*

Closely related to the measurement of quality is the problem of missing inputs and outputs, which can bias measured rates of productivity growth. This problem is evident in the treatment of expenditures on Research and Development (R&D) and software and in the construction of capital stock series from investment and depreciation.

Progress can be made toward solving the problem of missing inputs and outputs. The recent National Income and Product Account (NIPA) revision in the United States now includes one previously missing capital input, namely computer software (see Moulton, Parker, and Seskin [1999]). Before the NIPA revision, software was not treated as an investment good, but as an intermediate good; it therefore did not add to final demand. The inclusion of software investment has contributed about 0.2 percentage points to total U.S. GDP growth from the early 1990s on (see Seskin [1999]).<sup>3</sup> Jorgenson and Stiroh (2000) find that software investment contributes about 5 percent to output growth and that software capital makes up about one-ninth of total capital accumulation. It is not clear if R&D spending should be treated the same way as spending on software. Since R&D spending generates knowledge, similar to “organizational” capital acquired by firms when they learn how to use new IT, one could interpret this knowledge capital as a missing input. On the other hand, these inputs—knowledge and organizational capital—are not traded commodities so their accumulation might as well be captured as productivity improvements.

Related to the question of missing inputs and outputs are Kiley’s (1999) and Whelan’s (2000) discussions of capital stock measurement. Research has shown that the perpetual inventory model with geometric depreciation is a reasonable approximation to observed depreciation patterns for durable goods. If the depreciation rate,  $\delta$ , of a class of durable goods is constant over time, then the net increase of the capital stock,  $k$ , is investment,  $x$ , minus depreciation,  $\delta k$ :

$$\dot{k} = x - \delta k.$$

Kiley (1999) argues that for high rates of capital accumulation, such as those observed for IT over the last 20 years, observed investment expenditures do not capture all resource costs associated with capital accumulation. Resource costs that are incurred in the process of new capital formation and are in addition to the observed investment expenditures are called “adjustment costs.” Adjustment costs can affect productivity measurement in two ways. On the

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<sup>3</sup>The 1999 NIA revisions increased real GDP by about 0.4 percentage points for the period 1992–1998. Revised price index numbers contributed about 0.1 percentage points. The remaining increase was mainly due to the revised treatment of software expenditures, but also reflects the effects of the revised output measurement in the banking sector (Seskin 1999).



one hand, the presence of adjustment costs could mean that standard measures of output underestimate true output because they are net of adjustment costs. On the other hand, we could say that standard procedures overestimate true capital accumulation because the marginal product of investment in the production of capital goods is not constant at one, but declining. Whelan (2000) argues that for computers, current procedures overestimate depreciation rates because they confuse physical depreciation—which lowers the effective capital stock—with economic depreciation, which does not affect the effective capital stock.<sup>4</sup>

Finally, we want to raise the perennial favorite issue of market versus nonmarket transactions, or how to value household production. One of the presumed improvements generated by the Internet is the additional convenience it provides to consumers: the Net makes product search and price comparisons easier, provides access to certain services, and reduces overall the time households have to spend on transactions. While one can interpret this problem as one of missing inputs and outputs, to us it appears to be a quality measurement problem. From the point of view of the household, transactions have certain characteristics, and a commodity or service obtained through the Net has different characteristics than the same commodity or service obtained in a store. Very little work has been done to date to assess the value of these changes in characteristics.

### *Input Cost Shares*

For the Solow growth accounting, we identify an input's output elasticity with the input's revenue share. We therefore need measures of the prices or rental rates of all inputs. This measurement is apparently not a problem for the calculation of aggregate productivity growth, for we have data on payments to labor and can treat payments to capital as the residual. There is an issue,

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<sup>4</sup> Usually the depreciation rate for a particular type of capital good is estimated from a cross section of quality-adjusted used capital goods prices. Older capital goods are less efficient due to depreciation, and this is reflected in their lower prices. Assuming geometric depreciation, the slope of the age-price line for the different vintages of used capital goods reflects the depreciation rate. Suppose in addition not only that capital goods depreciate, but that their lifetime is finite because at some age it is no longer profitable to operate a capital good (economic depreciation). In this case the slope of the age-price line also incorporates the effects of a declining remaining service life for the capital good. For capital goods with long service lives this effect is not very important, but for computers, which currently have quite short service lives, this effect may dominate the physical depreciation.

Whelan (2000) suggests that for computer equipment, current procedures identify all of the slope of the price-age line with physical depreciation, even though most of it is due to a finite service life. If this is true, then this procedure may underestimate the computer capital stock during the early phase of computer capital accumulation because it depreciates computer capital too fast. On the other hand, this procedure also assumes that capital is around for a much longer time period than the actual service life of capital, that is, it overestimates the capital stock in the later phase of computer capital accumulation. One would expect that after some time, these two effects would balance and the measured capital stock would be about right.

however, about how to allocate proprietor's income; part of it is payment for labor services and part represents capital income, but this issue appears to be minor. Our problem is not completely solved, however, since we still have to construct aggregate capital and labor series. If we define aggregate capital and labor as an equally weighted sum of the different types of capital and labor in the economy, we are done. These measures of capital and labor, however, are not the theoretically preferred Divisia indexes as discussed above, and for the construction of a Divisia index we need to know the amount of the payment made to each component of the index, not just the sum of all payments. This requirement creates a problem for the construction of capital aggregates: Because capital is usually owned by producers, the services of capital are not traded on spot markets, and we therefore have no observations on rental rates for different types of capital. The usual procedure is to make an assumption on the rate of return on capital and then calculate the rental rate of capital implied by an asset pricing equation (see Jorgenson, Gollop, and Fraumeni [1987]). The asset pricing relationships are derived under the assumption that there is no uncertainty, which is not an innocuous assumption if one believes that the economy can experience a technological revolution. During a revolutionary period, one would expect that first, overall uncertainty would increase, and second, that not all types of capital would be equally affected by the increased uncertainty.

### *Solow's Assumptions*

Let us now consider the two theoretical assumptions underlying Solow growth accounting: production is constant returns to scale and producers are competitive. In the context of business cycles analysis, it has been argued that Solow growth accounting systematically mismeasures true changes in productivity because the underlying assumptions do not hold, namely that there are increasing returns to scale and that producers do not equate price to marginal cost (see Hall [1988]). Extensive research in this area has not completely resolved all issues, but it is apparent that constant returns to scale and competition are reasonable approximations (Basu and Fernald 1999). A remaining problem for short-run productivity accounting appears to be a missing input: unobserved factor utilization, which is essentially a theoretical construct and is very difficult to measure. We do not expect this problem to affect medium- to long-term growth accounting since theory suggests that there is no trend growth to this particular activity.

We usually attribute changes in TFP to technological improvements, but clearly TFP also reflects the effects of government regulations, market structures, firm organization, prevailing work rules, etc. In a nice case study, Schmitz (1998) describes how in the 1980s changing competitive pressures on the U.S. and Canadian iron-ore mining industry induced mines to change their work practices in a way that increased their productivity without actually

changing their technology. Standard Solow growth accounting registers the change in TFP, but it does not explain why it occurs. It is probably also true that productivity changes of this variety will result in one-time improvements, and cannot account for sustained productivity growth. Nevertheless, an explanation of this observation would be useful because many discussions of IT suggest that it makes the environment more competitive and induces firms to respond with technological and organizational improvements. A possible explanation might be based on a framework where (1) managers, workers, and capital owners somehow share the surplus from operating a firm, (2) the relative surplus shares depend on the relative bargaining strengths of the different parties, and (3) changes in competitive pressures have a differential impact on the parties' bargaining positions. This framework would represent a radical departure from the standard Solow growth accounting assumptions.

### **Recent Evidence on IT and Productivity Growth**

We now review the most recent work on IT and aggregate productivity growth using standard Solow growth accounting. The papers of Jorgenson and Stiroh (2000), Oliner and Sichel (2000), Whelan (2000), and Kiley (1999) focus on the contribution of IT capital to aggregate output growth and changes in aggregate productivity growth rates during the 1990s. There are some differences in the studies' particular definitions of IT capital, but the studies share the conclusion that in the 1990s the contribution of IT capital accumulation to output growth increased and productivity growth increased. Hall (1999, 2000) proposes a method for measuring unobserved capital accumulation associated with the diffusion of IT and studies the implications for TFP growth.

#### ***Aggregate TFP***

Jorgenson and Stiroh (2000) identify IT capital with computer hardware and software and with communications equipment. They find that from 1973–1990 to 1995–1998, the contribution of IT to aggregate growth doubles and productivity growth triples. For the earlier time period, IT investment accounted for one-tenth of output growth, and IT capital accumulation made up one-fifth of total capital accumulation and about one-tenth of total output growth. In the more recent period, IT investment accounts for about one-fifth of output growth, and IT capital accumulation makes up two-fifths of total capital accumulation and about one-fifth of total output growth. At the same time, productivity growth increases from an annual rate of 0.3 percent to 1 percent, a rate that is about as high as the golden era of the 1950s and 1960s. Oliner and Sichel (2000), using the same definition of IT capital and a somewhat narrower definition of output, find a similar increase in productivity growth and contribution of IT capital accumulation to output growth. Both studies

find the increase in productivity growth rates to be limited to the post-1995 period.

Whelan (2000) identifies IT with computing equipment and argues that standard measures of depreciation overestimate the physical depreciation rates of computing equipment. His estimates of computing equipment stocks in 1998 exceed standard values by almost 50 percent, which would indicate an enormous measurement error. The implied faster growth rates and higher revenue shares for computing equipment double the contribution of IT capital accumulation to output growth. Since aggregate output growth is not affected by the redefinition of depreciation rates, the higher contribution of IT capital accumulation is offset by a corresponding decline in the contribution of other capital and overall TFP growth.

In sum, the most recent studies find important productivity improvements for the very last part of the 1990s, but the productivity slowdown still appears to be a mystery. It is possible that the productivity slowdown may simply be indicative of structural change and that an increasing share of the economy is badly mismeasured. This hypothesis is discussed in some detail in Hornstein and Krusell (1996), although the main conclusion from that work—and any other work we are aware of—is that there is suggestive but not much hard evidence at this point that would allow us to reassess the 1973–1995 period. Structural change can have important implications in economies with a number of adjustment costs in the form of learning, reorganization, etc., and we have noted the mismeasured quality problem in our discussion of methods.

In this context, Kiley (1999) also identifies IT with computing equipment and performs a growth accounting exercise that allows for adjustment costs to capital accumulation.<sup>5</sup> He finds that in the 1970s and 1980s high IT capital accumulation rates actually reduced observed net-output growth. Unlike other studies, which use standard Solow growth accounting, he finds that aggregate productivity growth has remained constant from the 1970s to the 1990s. Adjustment costs are a theoretical concept used to motivate why short-run movements in investment are less volatile than predicted by the standard growth model; it is very difficult to obtain direct evidence on them. Since adjustment costs are used to study short-run dynamics, they are usually normalized such that they are zero when the investment-capital stock ratio is at its long-run average. The available evidence on adjustment costs seems to relate to local deviations from long-run averages. Obviously, for a new product like IT, the investment-capital stock ratio will be very different from its long-run value, which means that adjustment costs might be substantial and can have a

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<sup>5</sup> Solow growth accounting is based on standard economic theory, as represented by the growth model, and it does not include adjustments costs. The introduction of adjustment costs forces Kiley (1999) to deviate from the usual nonparametric Solow growth accounting procedure: He has to specify a functional form for the adjustment cost function.

measurable impact on net-output growth. On the other hand, we do not know if the local properties of adjustment costs apply when investment-capital stock ratios are far from their long-run averages.

Finally, Hall (1999, 2000)—or eHall, according to his latest paper—starts out with the assumption that in the 1990s the spread of IT was associated with the accumulation of a new type of capital, e-capital for short, and that e-capital is not measured by standard National Income and Product Accounting. This assumption reflects the observation that the market value of private corporations relative to the replacement cost of their physical capital increased from a factor of one at the beginning of the 1990s to a factor of three at the end of the 1990s. eHall extends the standard growth accounting framework and assumes that measured output is produced with physical capital, e-capital, skilled labor, and unskilled labor and that new e-capital is accumulated through the employment of skilled labor.<sup>6</sup> Using data on the market value of firms in addition to the usual series on quantities and factor rental rates employed in growth accounting, he constructs a series for e-capital. He finds that with e-capital, the contribution of other inputs and TFP to output growth is substantially reduced: without e-capital, TFP accounts for two-fifths of total output growth; with e-capital the combined contribution of e-capital and TFP accounts for three-fourths of total output growth, and most of it is due to e-capital. eHall's approach has the undesirable property that large stock market reevaluations imply the creation/destruction of large amounts of e-capital, since equity makes up a large portion of the market value of firms. This property does not fit well with our understanding of capital as a durable good. We can account for large equity market reevaluations if we assume that a substantial fraction of a firm's assets are indeed not reproducible, but that market values reflect current and future production opportunities. This is an important point to consider in an environment where new technologies change the way we see the future.

### *Disaggregated TFP*

Finally, we may want to know where technical change takes place. Is it concentrated in particular industries, or do we see a general increase in TFP for all industries? Is industry TFP growth related to the use of IT? Evidence on these points is mixed.

Jorgenson and Stiroh (2000) report TFP growth rates for a range of two-digit industries. They find that TFP growth varies widely: the best-performing industries include Trade, Electronic and Electric Equipment, Agriculture, Industry Machinery and Equipment, Transport and Warehouse; the worst-

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<sup>6</sup> eHall also relates the interaction of e-capital and skilled and unskilled labor to the idea of skill-biased technical change. We discuss this issue in the sections on multifactor productivity growth below.

performing industries with negative TFP growth are Services and Finance, Insurance, and Real Estate (FIRE). Two observations are applicable. First, the results concerning the relative ranking of industries and the fact that large parts of the economy (FIRE, Services) show negative TFP growth rates are similar to those of previous studies, i.e., accounting for IT has apparently not had an impact.<sup>7</sup> Second, the impact of IT on particular industries appears to be mixed. Given the advantages IT provides to inventory control and production planning, industries such as Trade and Transportation and Warehousing should have benefited from the diffusion of IT. On the other hand, although a substantial fraction of IT investment is going to Services and FIRE, the productivity performance of these industries has not improved at all. Above, we have suggested that for these industries IT diffusion may simply worsen the output measurement problem.

More specifically related to the production of computing equipment is Oliner and Sichel (2000), who use changes in the relative price of computers and semiconductors to evaluate the contribution of the sector producing computing equipment to aggregate TFP growth.<sup>8</sup> They find that despite the relatively small revenue share of the computing equipment sector, that sector accounts for about half of total TFP growth.

### *Microstudies*

We have noted that it is difficult to find any clear relationship between the utilization of IT and the resulting TFP growth at the industry level. However, Brynjolfsson and Hitt (2000a) argue that more evidence on the impact of IT applications on productivity is available for firm level data. Brynjolfsson and Hitt (2000b) estimate the impact of computing equipment on TFP growth at the firm level using a variation of Solow growth accounting. Essentially they argue that TFP growth at the firm level is positively correlated with the growth of computer capital in the firm. They also suggest that the benefits from investment in computer capital are delayed, which can be interpreted as being due to needing to learn to use IT or to the accumulation of IT-related organizational capital.

Bresnahan, Brynjolfsson, and Hitt (1999) study the interaction of IT capital accumulation, firm-specific human capital accumulation, and organizational change at the firm level. They use survey data on firms to construct an index of human capital (average education levels, skill levels as perceived by management, and occupational mix), an index of human capital investment (training and screening activities), and an index of how “decentralized” the

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<sup>7</sup> Unfortunately, Jorgenson and Stiroh have not yet calculated industry TFP numbers for post-1995.

<sup>8</sup> See also our discussion of Greenwood, Hercowitz, and Krusell (1997) in the next section.

firm's organizational structure is (measures of team orientation). They find that their measures of IT capital, human capital, and work organization are all positively correlated. In particular, (1) firms that have a better educated work force and a more decentralized work organization tend to use more IT capital, and (2) firms that use more IT capital tend to spend more on training their work force.

Finally, Brynjolfsson and Yang (1999) study the relation between the stock of computer capital in a firm and the market value of that firm. They argue that one dollar of computer capital in the firm raises the market value of a firm by more than one dollar. They suggest that this markup reflects other "unmeasured" capital which is complementary to computer capital. In this context they point out that when a firm implements a new information management system, the biggest cost component is consulting, training, and software development, not hardware expenditures.<sup>9</sup>

## 2. FACTOR-SPECIFIC PRODUCTIVITY

At times of significant technological change, the relative importance of different inputs, or factors of production, may change substantially because of specific technological innovations. For example, during the last 30 years we have witnessed striking changes in the relative prices of new equipment capital and in the premiums paid to highly educated workers (skilled workers for short). These changes likely reflect factor-specific technology movements, that is, technological advances that have enabled some factors to enjoy large increases in marginal productivity while others have seen none or have decreased. In other words, factor-specific productivity measurements may capture the economic signs of a technological revolution even when TFP measurements show tranquility. The increased productivity of one factor may lead to changes in the provision of factors—by changing the amount of hours worked of different kinds of labor or by causing changes in the accumulation of physical and human capital—in such a way that TFP does not change much.

This hypothesis has been described and compared to past technology revolutions, such as the introduction of electricity in the beginning of the 20th century, in Greenwood and Yorukoglu (1997). In this article, we only discuss this possibility on a broad level; future work will explore it in more detail. We point out the advantage of these multidimensional productivity measures, and we underline their shortcomings. We also present some recent examples of empirical work aimed at factor-specific productivity (FSP) measurement.

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<sup>9</sup>The recent reclassification of software expenditures as investment should ameliorate this problem in the NIPA.

### Introducing Factor-Specific Productivity

Solowian productivity accounting shows how the productivity of all inputs changes while it imposes a minimal amount of theoretical structure. Factor-specific productivity accounting imposes more theoretical structure than the Solowian method does, but also allows us to evaluate productivity changes for individual inputs. Factor-specific productivity accounting recognizes that TFP growth may not be exogenous, but in fact can depend on the relative use of different inputs. This recognition has important consequences for policy evaluation. For example, whether or not government taxes or subsidizes the accumulation of equipment capital affects capital stock accumulation, which in turn may affect measured TFP growth. In order to evaluate the effect of a tax or subsidy on equipment investment, one would need to know more about the *nature* of the productivity improvements. In particular, it may be that technological change interacts asymmetrically with different inputs and that the effect of capital accumulation on TFP growth depends on the nature of these interactions. We leave the discussion of policy and other counterfactual experiments to a future paper. Here, we will show some useful ways of allowing technological change to interact differently with different inputs: we will characterize productivity change multidimensionally.

To illustrate the difference between TFP growth and factor-specific productivity growth, consider the basic neoclassical production structure with output a function of capital and labor (see Section 1 above). Now impose the additional assumption that output is a *time-invariant* function of *efficiency units* of each input

$$y = F(A_k k, A_n n),$$

where  $k$  is the number of machines and  $A_k$  is a machine-specific productivity factor that changes over time (and similarly for labor). The factor-specific productivities are assumed to be exogenous. The marginal change in output is  $\dot{y} = F_1(\dot{A}_k k + \dot{k} A_k) + F_2(\dot{A}_n n + \dot{n} A_n)$ . Assuming constant returns to scale and perfect competition we can write the growth rate of output as

$$\hat{y} = (1 - \alpha_n)(\hat{A}_k + \hat{k}) + \alpha_n(\hat{A}_n + \hat{n}),$$

where  $\alpha_n$  is the labor income share, and the components of TFP growth are

$$\hat{z} = (1 - \alpha_n)\hat{A}_k + \alpha_n\hat{A}_n.$$

Since, with the exception of a Cobb-Douglas production function, the labor income share depends on the input ratio, TFP growth will depend on inputs. If the elasticity of substitution between inputs was greater than one, the labor income share would decrease with an increase in the stock of capital. In this case, we would expect that a subsidy to capital increases TFP growth if and only if  $\hat{A}_k > \hat{A}_n$ . In addition, TFP growth is not a goal in itself. Rather, a government's objective might be a higher output growth rate, in which case the relative importance of  $A_k$  and  $A_n$  clearly matters again.



The disadvantage of factor-specific productivity accounting is that it imposes substantially more structure than the assumption of constant returns to scale and marginal-product pricing, as is sufficient for Solow's TFP accounting.<sup>10</sup> As we will discuss below, much more structure is typically needed in order to draw inference about factor-specific productivity. The example above assumes that the production technology is invariant over time with the inputs measured in "efficiency units," such that technological change can take only the form of increases in the efficiency factors.<sup>11</sup> The quantitative results depend on the form of the  $F$  function (on the elasticity of factor substitution especially).

Finally, we would like to address the potential quantitative importance of considering FSP measures. One potential objection to FSP is based on the observation that over the last century, aggregate labor and capital shares have been remarkably stable in the United States. These stable factor shares suggest that the aggregate production function for the United States is well approximated by the Cobb-Douglas function with constant factor shares and unit elasticity of substitution. But with unit elasticity FSP and TFP accounting are equivalent. There are several other observations, however, that indicate substantial variation of factor income shares. First, stable shares are mainly observed for the very broadest aggregates: labor versus capital. For breakdowns of the labor input—into different skill (educational) groups—shares have had strong trends and swings around trend. For the capital income share, there is information that for our object of interest—new equipment/IT-related capital—the cost share has increased dramatically. Second, if one looks at a cross section of countries, especially including countries at a lower level of development, then one sees that there is variation in the labor share with development; at the very least, countries do not seem to have the same labor shares. Third, and on a related point, some developed countries have had much larger swings in the aggregate shares than what has been observed in the United States; one example is the dramatic increase of profit shares in France in the 1980s.

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<sup>10</sup> There is a sense in which factor-specific productivity (FSP) accounting imposes less structure than TFP accounting. In the example above we back out FSP for capital, given a functional form for production. But FSP essentially represents a change in quality, and a more structured procedure would try to obtain measures of quality, as discussed above for TFP.

<sup>11</sup> There are alternative, tractable structural approaches to how technology changes over time. For example, one could specify a CES function with elasticities changing exogenously over time. More structurally still, Cordoba (2000) describes the sequential adoption of output technologies with higher and higher capital shares. He then shows, with closed-form solutions, that this form of "structural change" implies increases in the capital-output ratio while allowing the interest rate to remain constant; these properties seem to well approximate the development path of many countries.

We now turn to factor-specific productivity measurement for the four factors mentioned most often: capital equipment and structures and skilled and unskilled labor.

### Investment-Specific Technological Change

The recent decades of technological change and the current focus on IT are often described as examples of how technology is “embodied” in new equipment. The idea is that productivity improvements occur in the sector producing equipment investment, and these productivity improvements are transmitted to the rest of the economy through new equipment investment. Today’s higher productivity in the investment-goods producing sector then effectively enhances the production possibilities for consumption in the future, through increases in the capital stock. The embodiment question has a long history; see, for example, Solow (1959) and Jorgenson (1966), as well as a recent discussion and evaluation in Hercowitz (1998). Greenwood, Hercowitz, and Krusell (1997) argue that for the postwar United States, especially after the 1970s, most productivity growth was of the embodied variety.<sup>12</sup>

In its most basic version, capital-embodied technological change represents changes in factor-specific productivity: currently produced new capital goods are relatively more productive than previously produced capital goods. On the other hand, once we measure capital in terms of efficiency units, we can interpret capital-embodied technological change in terms of product-specific changes in TFP, namely the productivity of the economy’s investment goods sector relative to the consumption goods sector. We follow this second interpretation, but we discuss capital-embodied technological change in the current section on changes in FSP, as opposed to in the previous section on changes in TFP, because we impose considerably more theoretical structure when we derive measures of capital-embodied technological changes.

We first provide a general discussion of TFP accounting in a simple two-sector model of the economy and how it relates to the usual measures of aggregate TFP accounting. We follow this route in order to show how the assumptions used by Greenwood et al. (1997) allow them to interpret their results in terms of aggregate productivity in a one-sector economy. Finally, we present Greenwood et al.’s (1997) results on the relative contributions of sectoral TFP growth to aggregate growth.

Goods—consumption  $c$  and new capital  $x$ —are produced using the factors capital and labor as inputs to constant-returns-to-scale technologies

$$c = z_c F_c(k_c, n_c) \text{ and } x = z_x F_x(k_x, n_x);$$

<sup>12</sup>This finding relates to the observations by Jorgenson and Stiroh (2000) and Oliner and Sichel (2000) on sectoral TFP growth discussed in the previous section.

total factor inputs can be freely allocated across sectors,

$$k_c + k_x = k \text{ and } n_c + n_x = n;$$

and investment is measured in efficiency units. The technologies may differ across sectors because of different factor substitution properties ( $F_c$  may differ from  $F_x$ ), and technological improvements may occur at different rates ( $z_c$  may grow at a different rate than does  $z_x$ ). We normalize productivity relative to the consumption goods sector,  $z_c = z$  and  $z_x = qz$ , and  $q$  is the relative productivity advantage of producing new capital goods. The evolution of the capital stock is described by

$$\dot{k}(t) = x(t) - \delta k(t).$$

One could now proceed and calculate sector-specific TFP growth as described in the previous section. Greenwood et al. (1997) choose an alternative route and use this setup to calculate and interpret TFP growth within an aggregate growth accounting framework.

In the first section of the present article, we postulated—in accordance with Solow’s assumptions—a measure  $y$  of aggregate output as equaling an aggregate production function of capital, labor, and time. It was not made explicit in that framework what output was made up of. In the one-sector neoclassical growth model, aggregate output is by definition equal to the sum of consumption and investment,  $y = c + x$ , but what is aggregate output in a multisector economy, such as the two-sector model just described? Rather than starting with an aggregate output concept, we will first summarize the production possibilities in the two-sector economy described above by the transformation function  $G(c, x, k, n, t) = 0$ . The function  $G$  tells us what combinations of consumption and investment goods  $c$  and  $x$  the economy can produce, given its total factor inputs  $k$  and  $n$ . Since production is constant-returns-to-scale, the transformation function is homogeneous of degree one in outputs and inputs.

Following our discussion of Divisia indices in Section 1, we can define an aggregate output index and a measure of aggregate TFP growth based on this output measure:

$$\hat{y}^D \equiv s_c \hat{c} + (1 - s_c) \hat{x} \text{ and } \hat{z}^D \equiv \hat{y}^D - \alpha \hat{k} - (1 - \alpha) \hat{n}.$$

The growth rate of the Divisia index of aggregate output is a weighted average of the output growth rates in the two sectors, where the weights are the revenue shares of consumption and investment,  $s_c = p_c c / (p_c c + p_x x)$ .<sup>13</sup> The growth rate of aggregate TFP is then defined analogously to the one-sector economy as the difference between the aggregate output growth rate and the weighted average of the aggregate input growth rates, where the weights are the aggregate income shares of capital and labor,  $\alpha = p_k k / (p_k k + p_n n)$ .

<sup>13</sup> See our definition of Divisia indices in the section “Aggregation,” above.

Divisia indices allow us to perform aggregate productivity accounting, but there is no particular theoretical justification suggesting that a Divisia index is the unique aggregator function for the economy.<sup>14</sup> In fact, one can show that for multi-sector models there does not exist an output aggregator; that is, in general no function exists that relates some measure of aggregate output to measures of aggregate inputs (Hall 1973). However, let us now assume that  $G$  is separable so that it is possible to find an output aggregator:

$$G(c, x, k, n, t) = H(c, x, t) - F(k, n, t).$$

Here, we interpret  $F$  as the aggregate production function and  $H$  as the aggregate output function, and both functions are homogeneous of degree one. In particular, aggregate output is defined as  $y = H(c, x, t) - F(k, n, t)$ . Notice that we must in general allow both of these functions to depend on time in order to allow technological change of a general kind.

Now this setup can be specialized further to illustrate different kinds of technological change: rather than allowing the variable  $t$  to have a general influence on  $H$  and  $F$ , consider instead  $F(zk, zl)$  and  $H(c, x/q)$ , where  $z$  and  $q$  are time-dependent processes. That is, technological change is expressed only through  $z$  and  $q$ , with  $z$  representing neutral technological change and  $q$  investment-specific technological change.<sup>15</sup> Can we obtain measures for the two types of technological change for this aggregate specification of the economy? We might want to proceed as in the case of the Solow residual, and define the productivity growth rates based on the equations which relate output growth to input or expenditure growth rates

$$\hat{y} = \alpha \hat{k} + (1 - \alpha) \hat{n} + \hat{z} = s_c \hat{c} + (1 - s_c) (\hat{x} - \hat{q}).$$

But here we face a problem: Although our theory suggests that there exists an output aggregate, we do not have a measure of that output aggregate. In order to construct the measure of aggregate output, we need to know the functional form of  $H$  and  $F$  and the values of the productivity levels  $z$  and  $q$ . One way to proceed is to assume that there is no investment-specific technological change, that is,  $q$  is constant. With this assumption we have identified the aggregate output index. In particular, the growth rate of aggregate output is equal to the Divisia index growth rate  $\hat{y}^D$  defined above. On the other hand, we have defined our problem away: There no longer is any investment-specific technical change.<sup>16</sup>

<sup>14</sup> As stated in the first section, Divisia indices have certain nice properties in terms of aggregation (they are revenue-weighted sectorial indices, and this property applies to output, input, and productivity indices), but this does not mean that they are in any sense the "true" aggregators for an economy.

<sup>15</sup> This is a slightly more general version of the model Greenwood et al. (1997) analyze (they use specific functional forms for  $H$  and  $F$ ), but cast in a one-sector form.

<sup>16</sup> An interesting question is, Is this model potentially consistent with the falling relative price of investment? In principle the answer is "yes" because a falling relative price can be obtained

Since Greenwood et al. (1997) want to study the role of investment-specific technological change, they have to make other assumptions in order to identify  $z$  and  $q$ . They assume that the factor substitution properties in the two sectors of the economy are the same, that is,  $F_c = F_x = F$ . With this restriction one can show that  $H(c, x/q) = c + x/q$ , and that  $1/q$  is the price of investment goods relative to consumption goods. Greenwood et al. (1997) can recover  $H$  by deflating nominal GDP with the consumption goods deflator; that is, they define aggregate output in terms of consumption goods,  $y^{GHK} = [p_c c + p_x x] / p_c = c + x/q$ . This is an unusual definition of aggregate output—it does not coincide with the Divisia measure—but it is justified within the confines of the model. In fact, it is rather natural given that consumption is the ultimate source of welfare in the model.

Suppose we next calculate aggregate TFP based on this definition of aggregate output; we would then obtain

$$\hat{z}^{GHK} = \hat{y}^{GHK} - \alpha \hat{k} - (1 - \alpha) \hat{n} = \hat{z}.$$

Greenwood et al.'s (1997) definition of TFP growth indeed recovers exogenous productivity changes that are not contaminated with the endogenous response of the economy to these productivity changes. On the other hand, their definition of aggregate TFP actually recovers productivity in the consumption goods sector and not in the “aggregate economy.” Given the assumptions they make, what does the aggregate TFP index based on the Divisia output index recover? Using the definition of  $\hat{z}^D$ , we can show that

$$\hat{z}^D = s_c \hat{z} + (1 - s_c) (\hat{z} + \hat{q}).$$

That is, the Divisia-based residual is a revenue share-weighted aggregation of the sector-specific residuals. Moreover, the relative importance of  $\hat{q}$  for  $\hat{z}^D$  is measured by  $(1 - s_c) \hat{q} / ([\hat{z} + (1 - s_c) \hat{q}])$ . Note that the displayed Divisia measure of aggregate TFP growth mixes the exogenous sectoral productivity growth rates with the economy's endogenous response to these growth rates as reflected in the consumption and investment share.<sup>17</sup>

When Greenwood et al. (1997) implement their approach for the U.S. economy, they use Robert Gordon's (1990) quality adjustments to construct the quality-adjusted inverse relative price of new investment goods  $1/q$ . With the quality-adjusted investment series they construct the capital stock, and with Solowian growth accounting methods for their consumption-based output measure they construct a series for  $z$ . Their method implies a growth rate of investment-specific technology of around 3 percent per annum, with growth in neutral technology of around 1 percent per annum. Moreover, consistent

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by appropriate assumptions on  $H$ . As the economy grows, the isoquants may significantly change shape so as to produce a continuous relative price change. Although this perspective seems rather academic, it is a logical possibility.

<sup>17</sup> In “Introducing Factor-Specific Productivity” we discussed why this might be undesirable.

with the hypothesis of an equipment-led technology revolution, the growth rate of the  $q$  series increased, already beginning in the mid-1970s, by about half a percentage point. This finding is also consistent with McHugh and Lane's (1987) finding, based on cross-section evidence, that adjacent vintages show significantly smaller productivity differences prior to the mid-1970s. Of course, neutral technology slowed down considerably at around the same time—the TFP version of the productivity slowdown.<sup>18</sup>

Building on this measurement, Greenwood et al. (1997) attribute, in terms of the model and as an entirely structural exercise, a substantial part of long-term output growth to investment-specific technological change (growth in  $q$ ) rather than neutral technological change (growth in  $z$ ).

### **How Technology Affects Skilled and Unskilled Labor**

U.S. data over the last couple of decades reveal substantial changes in the returns to education, the skilled wage premium. Moreover, typical wage regressions show large increases in residual variance: wage variance that cannot be attributed to observed characteristics such as age, experience, education, race, or gender. Katz and Murphy (1992) and earlier observers speak of “skill-biased technical change” as the explanatory factor behind these wage developments. Alternative explanations have been proposed, such as a decrease in union activity and increased foreign competition for unskilled labor. Bound and Johnson (1992), however, conclude that the lion's share of the changes in relative wages reflect relative changes in factor-specific productivity. In a recent paper, Krusell, Ohanian, Ríos-Rull, and Violante (2000) provide a more structural explanation of the wage premium. They argue that it is not factor-specific technological progress that increases the relative productivity of skilled labor, but rather the rapid accumulation of equipment capital together with a skilled labor-capital complementarity that determines the wage premium.

#### *Skill-Biased Technological Change*

We will next discuss how factor-specific productivity measurements have been used to rationalize changes in the wage premium. Consider a production function with capital and the two types of labor of the following kind:

$$y = F [k, G (A_s n_s, A_u n_u)],$$

where  $G$  is a CES function with substitution elasticity parameter  $\nu$  and we have abstracted from capital-specific productivity (alternatively, capital

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<sup>18</sup> A very similar exercise is conducted in Gort, Greenwood, and Rupert (1999), where quality-adjusted data are used not only for equipment but also for structures, thus identifying both a  $q_e$  and a  $q_s$  series.

embodies technological change and  $k$  is measured in efficiency units, as in the previous section on investment-specific technological change). As above, we assume that  $F$  and  $G$  are time-invariant, so that any technological change comes through  $(A_s, A_u)$ . When the two types of labor are paid their marginal products, the production structure implies that

$$\log \frac{w_s}{w_u} = \frac{\nu - 1}{\nu} \cdot \log \frac{A_s}{A_u} - \frac{1}{\nu} \cdot \log \frac{n_s}{n_u}.$$

Katz and Murphy (1992) use this structure to interpret their leading finding that in a regression of (the log of) relative wages on (the log of) relative factor supplies and a time trend, using 1963–1987 aggregate U.S. annual data, one obtains:

$$\log \frac{w_s}{w_u} = 0.033 \cdot t - 0.71 \cdot \log \frac{n_s}{n_u}.$$

Katz and Murphy (1992) conclude from this wage regression that (1) the input elasticity  $\nu$  is about  $\sqrt{2}$ ; and (2) the productivity of skilled labor relative to that of unskilled labor increased on average by almost 12 percent per year over the period.<sup>19</sup> More interestingly for our purposes, the wage premium first rose during the 1960s, fell over the early 1970s, and finally rose sharply beginning in the late 1970s. The latter increase continued unabated through the end of the 1990s. What do these relative swings tell us about technology?

We first observe that a large range of different data sets (time series as well as cross-section) and methods also yield an input elasticity of  $\sqrt{2}$ . This suggests that assuming a stable production function with  $\nu = \sqrt{2}$  is reasonable, and we can thus back out the entire sequence of factor-specific technology ratios using the same methodology as in the example with investment-specific technological change analyzed in Greenwood et al. (1997). For this data set, one observes that (1) the overall increase of the wage premium is due to a rise of the relative productivity of skilled labor  $A_s/A_u$ , (2) the fall of the wage premium in the early 1970s is due to the significant increase of the relative supply of skilled labor  $n_s/n_u$ , and (3) the relative productivity of skilled labor started to rise sharply in the late 1970s.

The approach just described allows us to recover factor-specific productivities, conditional on assumptions about the relative factor substitutabilities. In particular, it assumes that skilled and unskilled labor are equally substitutable with capital. Going back to a well-known paper by Griliches (1969), it has long been argued that most production technologies exhibit “capital-skill complementarity.” That is, capital and skilled labor are more complementary than are capital and unskilled labor.

<sup>19</sup> In the wage regression, the coefficient on the log of relative factor supplies represents  $1/\nu$ , that is  $\nu = 1/0.71$ . Furthermore, if the relative productivity of skilled labor grows at the rate  $(1 + \gamma)$ ,  $(A_s/A_u)_t = (1 + \gamma)(A_s/A_u)_{t-1}$ , then in the wage regression the coefficient on time represents  $\nu - 1/\nu \log(1 + \gamma)$ , that is  $\gamma \approx .033 \cdot \nu/\nu - 1$ .

*Capital-Skill Complementarity*

Krusell et al. (2000) argue that the higher wage premium is actually due to capital accumulation since skilled labor is relatively more complementary with capital than is unskilled labor.<sup>20</sup> They capture the differential complementarity between capital and skilled and unskilled labor using the following nested CES production technology

$$y = F [A_u n_u, G(k, A_s n_s)],$$

where  $F$  and  $G$  are CES functions. This structure, unlike the one studied in the previous section, allows capital-skill complementarity. If the factor elasticity between capital and skilled labor is denoted  $\mu$ , and that between unskilled labor and either skilled labor or capital is denoted  $\nu$ , then we have capital-skill complementarity if  $\mu < \nu$ . Capital-skill complementarity means that the relative wage will change when the capital stock changes, even if labor inputs *and* labor-specific productivity levels do not change. Krusell et al. (2000) show that with an estimate of  $\mu$  in line with the findings from the labor demand literature (see, for example, Hamermesh [1993]), a  $\nu$  around  $\sqrt{2}$ , and a measure of quality-adjusted capital, the relative wage movements in the data can be quite closely tracked without *any* change in the relative labor productivity  $A_s/A_u$ .<sup>21</sup> When Krusell et al. (2000) relax the assumption of constant relative labor productivity, they find that the relative productivity of skilled labor grows at a modest 3 percent per year.

Notice how the results of Krusell et al. (2000) stand in sharp contrast to the conclusion based on Katz and Murphy's (1992) work. When relative wage changes are driven by changes in relative labor productivities alone, a different capital accumulation behavior would have no effect on wages. On the other hand, from the perspective of Krusell et al. (2000), there would have been no rapid increase in the skill premium in recent years had it not been for the faster growth rate of capital. In sum, it appears plausible that equipment-specific technological change, possibly accompanied by some additional, independent skill-biased technological change unrelated to equipment, lies behind the large movements in relative wages of the last 30 years. That is, relative wage data can be usefully employed to understand the nature and evolution of aggregate technology in the economy.

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<sup>20</sup> Similar points, but in different theoretical structures, have been made in Greenwood and Yorukoglu (1997) and Caselli (1999).

<sup>21</sup> Krusell et al. (2000) emphasize the relative complementarities between equipment capital and skilled and unskilled labor. The quality-adjusted equipment capital stock is again based on the work of Gordon (1990) and subsequent updates, especially for IT technology.



### *Factor-Specific Productivity and Relative Factor Endowments*

Our discussion of factor-specific productivity so far has assumed that it evolves exogenously. In a recent study Caselli and Coleman (2000) apply the methods of Krusell et al. (2000) to a cross section of countries. Some of their results seem to suggest that countries choose among a menu of skilled-unskilled labor productivities and that these choices depend on the countries' relative factor endowments.

Caselli and Coleman (2000) obtain measures of capital and skilled- and unskilled-labor input measures for a large cross section of countries. The authors then assume marginal-product pricing and estimate a nested CES technology, which is common in form across countries. Given the estimated CES parameters, they back out a set of factor-specific productivity levels, one for each country. Although the results are preliminary as of this moment, three interesting conclusions appear from our perspective. First, capital-skill complementarity receives support. Second, countries appear to have very different mixes in factor-specific productivity levels. In particular, there seems to be a negative correlation between  $A_s$  and  $A_u$  in the cross section: Countries with high skilled-labor productivities tend to have low unskilled-labor productivities and vice versa.<sup>22</sup> This correlation suggests the existence of a "productivity possibility frontier," but the results also indicate that the choices along the  $(A_s, A_u)$  frontier still leave much to be explained: many countries are significantly inside the frontier and thus are operating inefficiently. Third, countries with relatively more skilled labor tend to have relatively high skilled labor productivities and vice versa. This tendency suggests that a country's technology choice depends on its factor endowments, a point which has been made by Acemoglu (see, for example, Acemoglu [2000] and Acemoglu and Zilibotti [1998]).

### **3. A UNIFIED VIEW OF THE LAST QUARTER CENTURY?**

What emerges from the sections on TFP and FSP measurement is a view of technological change in the United States that is based on major improvements in equipment production, with major effects on both aggregate and factor-specific productivities. Several questions arise, however, regarding the effects of TFP and FSP change. The first of these relates to the productivity slowdown. Among the most significant productivity movements over the entire century is the large slowdown in TFP starting around 1973. Can the asserted improvements in equipment-producing technologies be made consistent

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<sup>22</sup> It is an open question whether these findings are robust to better measurement of capital; with appropriate quality adjustments, large differences can be observed in capital stocks, and the capital-skill complementarity hypothesis then has implications for the factor-specific productivity measurements.

with the productivity slowdown? Some recent papers advance the hypothesis that learning problems associated with the use of the new equipment may have been responsible for the aggregate slowdown.<sup>23</sup> However, empirical assessments of learning costs in implementing new technology are inherently difficult (see, for example, the recent arguments in Atkeson and Kehoe [2000] and Hornstein [1999]) and we are far from being able to reach a conclusion regarding this hypothesis. Nevertheless, the possibility remains an interesting one.

Second, changes in technology are unlikely to occur only in the United States; insights about the efficiency of different production methods, new blueprints, and capital travel relatively easily across borders. Does international data support the above productivity analysis? The European data tell a different story about labor markets than the U.S. data. Whereas unemployment stayed low in the United States, it increased dramatically in Europe, and European relative wages did not move nearly as much as U.S. relative wages. However, the unemployment response in Europe occurred concurrently with the relative wage response in the United States, so a common underlying explanation should not be ruled out.

In particular, it seems quite plausible that differences in labor market institutions, and one common shock, can yield quite different responses in two economies. Our hypothesis, thus, is that more heavily regulated and unionized labor markets can make skill-biased technological change lead to increases in the rate of unemployment instead of increases in the skill wage. This hypothesis has been explored theoretically in Ljungqvist and Sargent (1998), Marimon and Zilibotti (1999), and recently in Hornstein, Krusell, and Violante (2000).<sup>24</sup> As labor market theory with frictions—allowing a nontrivial role for unemployment—has not advanced as far quantitatively as has neoclassical theory, it is too early yet for a firm evaluation of this hypothesis. As for data on equipment relative prices, we do not know of European data comparable to the U.S. data by Gordon (1990) on the more recent revisions for some equipment categories in the NIPA. Improvements in equipment price measurement should, in our view, be placed high on the agenda in the United States and even higher in Europe.

A unified view of the macroeconomic productivity and labor market performances during the last quarter century in the western world is a very interesting one that ought to be explored in much further detail. It can be viewed as a “third industrial revolution,” placing advanced equipment and IT on center stage. We believe that careful reassessments of input and output measurements, together with theory developments aimed at structural evaluation of the main hypothesis, would be most productive.

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<sup>23</sup> See, for example, Hornstein and Krusell (1996) and Greenwood and Yorukoglu (1997).

<sup>24</sup> Related work, focusing more on wages than on unemployment, is found in Violante (1999) and Aghion, Howitt, and Violante (1999).

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## REFERENCES

- Acemoglu, Daron. "Technical Change, Inequality, and the Labor Market," *Journal of Economic Literature* (forthcoming).
- \_\_\_\_\_, and Fabrizio Zilibotti. "Productivity Differences," *Quarterly Journal of Economics* (forthcoming).
- Aghion, Philippe, Peter Howitt, and Giovanni Violante. "Technology, Knowledge, and Inequality." Working Paper. University of California, Berkeley, 1999.
- Atkeson, Andrew and Patrick J. Kehoe. "The Transition to a New Economy Following the Second Industrial Revolution," Federal Reserve Bank of Minneapolis Working Paper 606, September 2000.
- Basu, Susanto, and John G. Fernald. "Why Is Productivity Procyclical? Why Do We Care?" International Finance Discussion Working Paper 638. Board of Governors of the Federal Reserve System, June 1999.
- Bils, Mark, and Peter J. Klenow. "Quantifying Quality Growth." Mimeo, 1999.
- Bound, John, and George Johnson. "Changes in the Structure of Wages in the 1980s: An Evaluation of Alternative Explanations," *American Economic Review*, vol. 82 (June 1992), pp. 371–92.
- Bresnahan, Timothy F., Erik Brynjolfsson, and Lorin M. Hitt. "Information Technology, Workplace Organization and the Demand for Skilled Labor: Firm-level Evidence," *Quarterly Journal of Economics* (forthcoming).
- Brynjolfsson, Erik, and Lorin M. Hitt. "Computing Productivity: Firm-Level Evidence," Working Paper, 2000b.
- \_\_\_\_\_. "Beyond Computation: Information Technology, Organizational Transformation and Business Performance," *Journal of Economic Perspectives*, vol. 14 (Fall 2000a), pp. 23–48.
- Brynjolfsson, Erik, and Shunhyu Yang. "The Intangible Costs and Benefits of Computer Investments: Evidence from the Financial Markets." Proceedings of the International Conference on Information Systems, Atlanta, Georgia, December 1997 (revised April 1999).
- Caselli, Francesco. "Technological Revolutions," *American Economic Review*, vol. 89 (March 1999), pp. 78–102.
- \_\_\_\_\_, and John Coleman. "The World Technology Frontier," Working Paper, University of Chicago, 2000.

- Cole, Roseanne, Y. C. Chen, Joan A. Barquin-Stelleman, Ellen Dulberger, Nurhan Helvacian, and James H. Hodge. "Quality-Adjusted Price Indexes for Computer Processors and Selected Peripheral Equipment," *Survey of Current Business*, vol. 66 (January 1986), pp. 41–50.
- Cordoba, Juan Carlos. "Transient Growth and Structural Change." Mimeo, University of Rochester, 2000.
- Gordon, Robert J. *The Measurement of Durable Goods Prices*. Chicago, IL: University of Chicago Press, 1990.
- Gort, Michael, Jeremy Greenwood, and Peter Rupert. "Measuring the Rate of Technological Progress in Structures," *Review of Economic Dynamics*, vol. 2 (January 1999), pp. 207–30.
- Greenwood, Jeremy, and Mehmet Yorukoglu. *Carnegie-Rochester Conference on Public Policy XLVI*, 1997 [1974], pp. 49–95.
- \_\_\_\_\_, Zvi Hercowitz, and Per Krusell. "Long-run Implications of Investment-Specific Technological Change," *American Economic Review*, vol. 87 (June 1997), pp. 342–62.
- Griliches, Zvi. "Capital-Skill Complementarity," *Review of Economics and Statistics*, vol. 51 (November 1969), pp. 465–68.
- \_\_\_\_\_. "Hedonic Price Indexes for Automobiles: An Econometric Analysis of Quality Change," in *The Price Statistics of the Federal Government*. New York: National Bureau of Economic Research, 1961, pp. 137–96.
- Hall, Robert E. "e-Capital: The Link between the Stock Market and the Labor Market in the 1990s," Working Paper, 2000.
- \_\_\_\_\_. "The Stock Market and Capital Accumulation," NBER Working Paper 7180, 1999.
- \_\_\_\_\_. "The Relation between Price and Marginal Cost in U.S. Industry," *Journal of Political Economy*, vol. 96 (Oct. 1988), pp. 921–47.
- \_\_\_\_\_. "The Specification of Technology with Several Kinds of Output," *The Journal of Political Economy*, vol. 81 (July-August 1973), pp. 878–92.
- Hamermesh, Daniel S. *Labor Demand*. Princeton, NJ: Princeton University Press, 1993.
- Hercowitz, Zvi. "The 'Embodiment' Controversy: A Review Essay," *Journal of Monetary Economics*, vol. 41 (February 1998), pp. 217–24.
- Hornstein, Andreas. "Growth Accounting with Technological Revolutions," Federal Reserve Bank of Richmond *Economic Quarterly*, vol. 85 (Summer 1999), pp. 1–22.

- \_\_\_\_\_, and Per Krusell. "Can Technology Improvements Cause Productivity Slowdowns?" in Ben S. Bernanke and Julio J. Rotemberg, eds., *Macroeconomics Annual 1996*. Cambridge, Mass.: MIT Press, 1996, pp. 209–59.
- \_\_\_\_\_, and Giovanni Violante. "Technology, Policy, and the Inequality-Unemployment Tradeoff." Mimeo, 2000.
- Hulten, Charles R. "Divisia Index Numbers," *Econometrica*, vol. 41 (November 1973), pp. 1017–26.
- Jorgenson, Dale W. "The Embodiment Hypothesis," *Journal of Political Economy*, vol. 74 (February 1966), pp. 1–17.
- \_\_\_\_\_, Frank Gollop, and Barbara Fraumeni. *Productivity and U.S. Economic Growth*. Cambridge, Mass.: Harvard University Press, 1987.
- Jorgenson, Dale W., and Kevin J. Stiroh. "Raising the Speed Limit: U.S. Economic Growth in the Information Age," *Brookings Papers on Economic Activity* (forthcoming).
- Katz, Lawrence, and Kevin Murphy. "Changes in Relative Wages: Supply and Demand Factors," *Quarterly Journal of Economics*, vol. 106 (February 1992), pp. 35–78.
- Kiley, Michael T. "Computers and Growth with Costs of Adjustment: Will the Future Look Like the Past?" Finance and Economics Discussion Working Paper 36. Board of Governors of the Federal Reserve System, July 1999.
- Krusell, Per, Lee Ohanian, José-Víctor Ríos-Rull, and Giovanni Violante. "Capital-Skill Complementarity and Inequality: A Macroeconomic Analysis," *Econometrica*, vol. 68 (September 2000), pp. 1029–53.
- Ljungqvist, Lars, and Thomas J. Sargent. "The European Unemployment Dilemma," *Journal of Political Economy*, vol. 106 (June 1998), pp. 514–50.
- Marimon, Ramon, and Fabrizio Zilibotti. "Unemployment vs. Mismatch of Talents: Reconsidering Unemployment Benefits," *Economic Journal*, vol. 109 (April 1999), pp. 266–91.
- McHugh, Richard, and Julia Lane. "The Role of Embodied Technical Change in the Decline of Labor Productivity," *Southern Economic Journal*, vol. 53 (April 1987), pp. 915–24.
- Moulton, Brent R. "Measurement of Banking Services in the U.S. National Income and Product Accounts: Recent Changes and Outstanding Issues." Presented at a meeting of the BEA Advisory Committee, May 5, 2000.

- \_\_\_\_\_, Robert P. Parker, and Eugene Seskin. "A Preview of the 1999 Comprehensive Revision of the National Income and Product Accounts: Definitional and Classificational Changes," *Survey of Current Business*, vol. 79 (October 1999), pp. 7–20.
- Oliner, Stephen D., and Daniel E. Sichel. "The Resurgence of Growth in the Late 1990s: Is Information Technology the Story?" Finance and Economics Discussion Working Paper 20. Board of Governors of the Federal Reserve System, March 2000.
- Schmitz, James A., Jr. "Reorganizing Work to Increase Productivity: The Dramatic Recovery of the United States and Canadian Iron-ore Industries." Mimeo, Federal Reserve Bank of Minneapolis, 1998.
- Seskin, Eugene P. "Improved Estimates of the National Income and Product Accounts for 1959–98: Results of the Comprehensive Revision," *Survey of Current Business*, vol. 79 (August 1999), pp. 15–43.
- Shapiro, Irving, Matthew D. Shapiro, and David W. Wilcox. "Quality Improvement in Health Care: A Framework for Price and Output Measurement," *American Economic Review*, vol. 89 (May 1999), pp. 333–37.
- Solow, Robert M. "Investment and Technological Progress," in Kenneth J. Arrow, Samuel Karlin, and Patrick Suppes, eds., *Mathematical Methods in the Social Sciences 1959*. Stanford, CA: Stanford University Press, 1960, pp. 89–104.
- \_\_\_\_\_. "Technical Change and the Aggregate Production Function," *Review of Economics and Statistics*, vol. 39 (August 1957), pp. 312–20.
- Violante, Giovanni. "Technological Acceleration, Skill Transferability and the Rise in Residual Inequality." Mimeo, University College London, 1999.
- Whelan, Karl. "Computers, Obsolescence, and Productivity," Finance and Economics Discussion Working Paper 6. Board of Governors of the Federal Reserve System, January 2000.