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What Drives Productivity Growth?

- Neoclassical and “new growth” theories offer alternative explanations for productivity and output growth.
- In the neoclassical view, exogenous technical progress drives long-run productivity growth since broadly defined capital suffers from diminishing returns. In contrast, the new growth models yield long-run growth endogenously, either by avoiding diminishing returns to capital or by explaining technical progress internally.
- Despite their differences, both views help to explain the recent rise in U.S. productivity growth. The methodological tools developed by neoclassical economists provide a means to measure the rate of technical progress, while the models of the new growth economists can provide an internal explanation for technical progress.

In 1995, the U.S. economy started to experience a strong resurgence in labor productivity growth. After growing only 1.3 percent per year from 1973 to 1995, labor productivity growth jumped to 2.5 percent from 1995 to 1999 (see chart).[1] This striking revival has hardly gone unnoticed, with academics, policymakers, and the financial press hotly debating competing explanations. Some commentators emphasize rapid capital accumulation and the recent investment boom, others point to deeper factors like fundamental technological change in high-tech industries, and still others argue that cyclical forces provide the primary explanation.[2]

This debate about the forces driving the U.S. economy mirrors a larger debate between the neoclassical and new growth theories regarding the sources of economic growth. Economists have long disagreed about this vital question, and the recent U.S. productivity revival presents an opportune backdrop to review this debate.

In the neoclassical view, broadly defined capital accumulation drives growth in the short run, but capital eventually succumbs to diminishing returns, so long-run productivity growth is entirely due to exogenous technical progress. The new growth theory, however, moves beyond this unsatisfying conclusion, arguing that productivity growth can continue indefinitely without the elixir of exogenous, and entirely unexplained, technical progress. Either by avoiding

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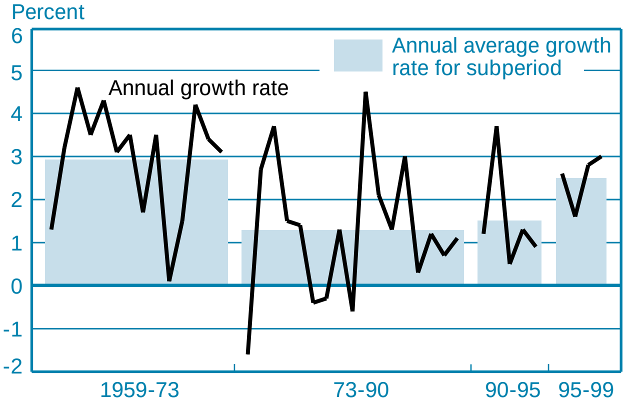
diminishing returns to capital or by explaining technical change internally, this framework offers an economic explanation for sustained productivity and output growth.

Despite these divergent conclusions, the neoclassical and new growth frameworks both contribute to our understanding of the growth process. Using traditional neoclassical methods, for example, Jorgenson and Stiroh (2000) and Oliner and Sichel (2000) show that a combination of accelerating technical progress in high-tech industries and the resultant investment in information technology (IT) are driving recent productivity gains in the United States. This type of neoclassical analysis clearly illustrates *what* happened to the U.S. economy. It cannot, however, explain *why* technical progress accelerated in high-tech industries; this is a job left to the new growth theorists. In this sense, each theory makes a significant contribution to our understanding of productivity growth. The sophisticated methodological tools developed by neoclassical economists enable us to measure the rate of technical change, while the sophisticated models of the new growth theorists provide an internal explanation for the sources of technical change. In the next section, I compare these alternative views and discuss the useful role of each.

One important theme, common to both views, is that investment is a fundamental part of the growth process. Investment, moreover, may be defined broadly to include any expenditure that provides productive payoffs in the future; therefore, measures of human capital and research and development (R&D) expenditures are now routinely included in productivity analyses. Indeed, even the concept of tangible capital is not static—the U.S. national accounts now treat software expenditures as an investment good since software code is a durable asset that contributes to production over several years.

U.S. Labor Productivity Growth, 1959-99



Source: U.S. Department of Labor, Bureau of Labor Statistics.

Note: Both series refer to annual nonfarm business productivity.

In addition to this broadening of the investment concept, an important part of the measurement process is the recognition of the enormous heterogeneity of investment. For example, the productive impact of investment in information technology may be quite different from that of investment in structures. By disaggregating investment and accounting for these differences, economists can accurately gauge the productive impact of input accumulation and thus isolate and gauge the extent of technical change. In this article, I outline several major conceptual and methodological issues related to measuring production inputs and technical progress correctly.

The differences between neoclassical and new growth theories also have a direct bearing on several specific topics that have recently generated considerable interest. Later in this article, I address two relevant issues. In particular, I present a resolution to the computer productivity paradox and review the renewed embodiment controversy. These topics are important in their own right, and they illuminate the ongoing debate over the sources of productivity and output growth.

Productivity Growth from the Neoclassical and New Growth Perspectives

Economic growth theory has enjoyed a revival in recent years, with questions about the sources of productivity growth high on the list of scholars, policymakers, and the business press. The academic growth literature has bifurcated, however, into arguments for two competing views—a neoclassical and a new growth view.[3] This section presents stylized models from each perspective and discusses the strengths and weaknesses of each.

Broadly defined investment—which includes expenditures on tangible assets, education, training, and other human capital accumulation, as well as research and development—plays a pivotal role in both frameworks, although investment's precise impact on productivity growth differs. Benefits from investment may accrue only internally to the economic agent that actually makes the investment, or the benefits may spill over more broadly to others in the economy. As a preview of the discussion, the idea that broadly defined capital generates primarily internal and diminishing returns is the hallmark of the neoclassical view, differentiating it from the new growth theory's focus on external and constant (or increasing) returns. This leads to contrasting views of the investment-productivity nexus and the potential for long-run growth.

The World of Neoclassical Growth

The standard neoclassical growth model is well known and will be reviewed here only briefly. Seminal papers by Solow (1956, 1957) formalized the neoclassical model, integrated theory with national account data, and formed the basis for much of applied growth analysis.

The Basic Neoclassical Model

The link between output, Y, and capital services, K, labor input, L, and labor-augmenting (Harrod-neutral) technical progress, T, is given by the familiar aggregate production function

$$Y_t = f(K_t, T_t \cdot L_t), \tag{1}$$

where the neoclassical production function is typically assumed to have constant returns to scale, positive and diminishing returns with respect to each input, and marginal products of each input that approach zero (infinity) as each input goes to infinity (zero).

Investment enters through the capital accumulation equation, which governs the relationship between investment in tangible assets, I, and capital stock, S, via the perpetual inventory relationship

$$S_t = (1-\delta) \cdot S_{t-1} + I_t, \tag{2}$$

where δ is depreciation and I_t can either be determined endogenously by profit-maximizing firms or assumed to be some fixed proportion of output.

Note that the production function includes a measure of capital services, K, while the perpetual inventory equation defines the capital stock, S. These two capital concepts are closely linked but differ according to compositional changes in aggregate investment. In the simplest neoclassical world with one investment good, the two concepts are identical, but in a world with many heterogeneous types of investment goods, they differ. For example, a shift in investment toward high-tech equipment with large marginal products leads capital services to grow more quickly than capital stock. This important distinction is discussed in detail later in this article.

The striking implication of the neoclassical model is that, in the long run, per capita output and productivity growth are driven entirely by growth in exogenous technical progress and they are independent of other structural parameters like the savings rate.[4] If the savings rate and investment share increase, for example, the long-run level of productivity rises but the long-run growth rate eventually reflects only technical progress. In this sense, the neoclassical growth model is not really a model of long-run growth at all since productivity growth is due to exogenous and entirely unexplained technical progress. Nonetheless, the neoclassical model has proved to be a useful tool for understanding the proximate factors that contribute to output and productivity growth.[5]

Solow (1957) provides an explicit methodology for measuring the rate of technical progress under the neoclassical assumptions of competitive factor markets and input exhaustion when technology is Hicks-neutral and output is modeled as $Y_t = A_t \cdot f(K_t, L_t)$. In this case, the rate of Hicks-neutral technical progress equals the famous Solow residual, or total factor productivity (TFP) growth. This is defined as the difference between output growth and the share-weighted growth rates of primary inputs (capital and labor) as

$$\Delta lnA = \Delta lnY - v_K \Delta lnK - v_L \Delta lnL, \tag{3}$$

where Δ represents a first difference, v_K is capital's share of national income, v_L is labor's share of national income, the standard neoclassical assumptions imply $v_K + v_L = 1$, and time subscripts are dropped for ease of exposition.[6]

Under the same assumptions, one can identify the sources of average labor productivity (ALP) growth, defined as output per hour worked, Y/H. Transforming equation 3 yields

$$\begin{aligned} \Delta lny &= \Delta lnY - \Delta lnH \\ &= v_K \Delta lnk + v_L(\Delta lnL - \Delta lnH) + \Delta lnA, \end{aligned} \tag{4}$$

where lowercase letters are per hour worked.

Growth in ALP, Δlny, depends on three factors. The first is capital deepening, Δlnk, which captures the increase in capital services per hour. The second is the growth in labor quality, which measures substitution toward workers with higher marginal products and is defined as the difference between the growth of labor input and the growth of hours worked $(\Delta lnL - \Delta lnH)$. The third is the growth in TFP, ΔlnA, defined in equation 3, which captures the impact of technical change and other factors that raise output growth beyond the measured contribution of inputs.

If the neoclassical assumptions fail to hold, however, the Solow residual will not measure only technical change. Other factors that affect the Solow residual include distortions from imperfect competition, externalities and production spillovers, omitted inputs, cyclical fluctuations, nonconstant returns to scale, and reallocation effects. If there are increasing returns to scale but no technical change, for example, input shares will not equal output elasticities and one would estimate a positive Solow residual even though there is no technical change. While this may confound the interpretation of the Solow residual as a pure technology measure, it remains a useful indicator of the underlying technological forces. Basu and Fernald (1997), for example, report a high correlation between a traditional Solow residual and a more sophisticated index of technology that controls for market imperfections. Moreover, they argue that the Solow residual is an important welfare measure, even when it is not a measure of pure technical change.

Applications of the Neoclassical Model

Jorgenson and Stiroh (2000) use equations 2-4 in a traditional growth accounting analysis to study the sources of U.S. economic growth. They conclude that investment in tangible assets has been the dominant source of growth over the past four decades, while the contribution of technical progress as measured by the Solow residual has been relatively modest.

From 1959 to 1998, output grew 3.63 percent per year, reflecting 1.59 percent annual growth in hours and 2.04 percent growth in labor productivity (Table 1). Labor productivity growth reflects the contributions of capital deepening (1.10 percentage points per year), labor quality (0.32 percentage point per year), and TFP growth (0.63 percentage point per year). Thus, accumulation of tangible assets and human capital (measured as labor quality gains) has been an important part of U.S. output and productivity growth over the past four decades.

For the late 1990s, Jorgenson and Stiroh (2000) find that both an acceleration of TFP and rapid capital accumulation contributed to the recent U.S. productivity revival. For the 1995-98 period, estimated TFP growth of 0.99 percent per year was nearly three times as fast as it was during the 1973-95 period. Although the neoclassical model cannot really explain why TFP accelerated, it is nonetheless an important result since faster technical progress drives long-run productivity growth. Indeed, faster TFP growth is now incorporated into the rapid medium-run growth projections made by the Congressional Budget Office (2000).

Gauging the relative importance of capital deepening and technology has also been an important part of the debate surrounding the performance of the Asian newly industrialized countries (NICs). Krugman (1994), Young (1995), and Collins and Bosworth (1996) use this type of traditional neoclassical analysis to evaluate the potential for long-run growth in the NICs. All three conclude that broadly defined capital accumulation, as opposed to exogenous technical progress (measured as TFP growth), was the primary engine of growth for the NICs, and thus they are pessimistic about future growth prospects. Again, it is the neoclassical implication—that only technical change drives long-run productivity growth—that makes this distinction so important. These findings have led to a sharp debate over the relative importance of capital accumulation and TFP growth as sources of growth in these economies.[7]

These two applications of neoclassical growth accounting help to explain the proximate factors driving growth in the United States and in the NICs, although the conclusions must be kept in the proper perspective. As stressed by Hulten (1979), this methodology yields a valid measure of the rate of technical change if neoclassical assumptions hold, but also tends to understate the economic importance of it. For example, in a simple neoclassical model, faster technical change induces higher output, saving, investment, and capital accumulation, so part of historical capital accumulation itself is due to technical change in a deeper sense. It must be stressed, however, that the goal of growth accounting is to quantify the contribution of accumulated inputs correctly so that the rate of technical progress can be accurately measured. Modern growth accounting is more about measuring technical change than explaining it.

Table 1

Sources of U.S. Output and Productivity Growth, 1959-98

	1959-98	1959-73	1973-90	1990-95	1995-98
Growth in output (Y)	3.63	4.33	3.13	2.74	4.73
Growth in hours (H)	1.59	1.38	1.69	1.37	2.36
Growth in average labor productivity (Y/H)	2.04	2.95	1.44	1.37	2.37
Contribution of capital deepening	1.10	1.49	0.91	0.64	1.13
Contribution of labor quality	0.32	0.45	0.20	0.37	0.25
Contribution of aggregate total factor productivity	0.63	1.01	0.33	0.36	0.99

Source: Jorgenson and Stiroh (2000).

Notes: Decomposition of labor productivity growth is based on equation 4 in the text. All values are average annual percentages.

Moving beyond the Neoclassical Model

The appealing simplicity and intuition of the neoclassical framework have made it the backbone of applied work on productivity and economic growth.[8] Despite this popularity, however, several shortcomings make the standard neoclassical model not entirely satisfactory. First, early studies attributed the vast majority of labor productivity growth to exogenous forces.[9] Then, in the 1970s and 1980s, the neoclassical model failed to offer a persuasive explanation for important U.S. productivity trends like the post-1973 productivity slowdown. Second, since capital accumulation is subject to diminishing returns, steady-state growth in per capita variables inevitably grinds to a halt without exogenous technical progress. Finally, the international data did not seem to fit with the basic neoclassical model in terms of observed differences in income, capital shares and rates of return, and convergence properties.[10] These shortcomings led to several lines of subsequent research on the relationship between investment and productivity growth.

One approach, originated by Jorgenson and Griliches (1967) and summarized in Jorgenson (1996), remained firmly embedded in the neoclassical tradition and sought to develop better measures of investment, capital, labor, and other omitted inputs in order to reduce the magnitude of the unexplained residual. This approach did not seek to explain the origins of technical progress but rather to reduce its importance as an empirical explanation of growth. I return to the details of this work later. The second direction was the endogenous growth literature, to which I now turn.

The World of Endogenous Growth

The endogenous or new growth theory was developed to move beyond the neoclassical model by providing an endogenous mechanism for long-run productivity growth, either by removing the diminishing returns to capital or by explaining technical change as the result of specific actions. This literature is quite varied, and alternative explanations focus on many factors like different production structures, the dynamics of competition, innovation, increasing returns, and production spillovers. The following discussion describes a representative endogenous growth model.[11]

A Simple Endogenous Growth Model

A primary motivation for developing endogenous growth models was the desire to avoid the neoclassical implication that only exogenous technical progress drives long-run productivity growth. Indeed, one can simply assume a constant marginal product of capital as in the so-called "AK" models in which output is a linear function of capital, $y_t = Ak_t$.[12] In this case, long-run productivity growth can continue, and any change in the level of technology or savings rate leads to a long-run change in productivity growth.

Romer (1986), in a classic paper that sparked the new growth theory, provided a mechanism and corresponding economic explanation for why capital might not suffer from diminishing returns. In particular, Romer focused on the possibility of external effects as research and development efforts by one firm spill over and affect the stock of knowledge available to all firms. Firms face constant returns to scale to all private inputs, but the level of technology, A, varies, depending on the aggregate stock of some privately provided input

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$$(5) \qquad Y_i = A(R) \cdot f(K_i, L_i, R_i),$$

where an i subscript represents firm-specific variables, R is the aggregate stock of knowledge, and time subscripts are dropped.[13]

The exact nature of the spillover is not particularly important for the aggregate properties of the model, and economists have identified several alternative channels. For instance, Arrow (1962) emphasizes "learning-by-doing," in which investment in tangible assets generates spillovers as aggregate capital increases; past gross investment proxies for experience and determines *A(.)*.[14] Alternatively, Romer (1986) essentially models *A(.)* as a function of the stock of R&D, Lucas (1988) models *A(.)* as dependent on the stock of human capital, and Coe and Helpman (1995) argue that *A(.)* also depends on the R&D stock of international trading partners. The key point is that there may be constant (or increasing) returns to accumulated inputs at the aggregate level, and thus the generation of long-run endogenous growth.[15]

The existence of production spillovers raises a significant empirical question that has generated a vast literature. If investment of any type—tangible assets, human capital, or R&D—generates benefits to the economy that are not internalized by private agents, then this suggests that there are multiple long-run growth paths and that there are specific policy implications. Since investment may be too low from society's point of view, spillovers open a role for government intervention such as investment tax credits or research and development grants. R&D spillovers, in particular, have attracted considerable attention in the new growth literature, and I review the microeconomic evidence on them later.

Macro Evidence of Endogenous Growth

One aggregate implication of early endogenous growth models is a "scale effect," in which productivity growth increases with the size of the economy. Larger economies devote more resources to R&D and knowledge production is available to all, so technology should grow more rapidly. In addition, this suggests that government policy, in the form of taxes or subsidies that increase resources allocated to knowledge production or investment, can raise long-run growth.

In a pair of influential studies, however, Jones (1995a, 1995b) strongly rejects this scale effect and finds little relationship between policy variables and long-run growth. There is no obvious relationship between the number of scientists and engineers employed in R&D activities and U.S. TFP growth (Jones 1995a), nor has there been persistent acceleration in growth in countries belonging to the Organization for Economic Cooperation and Development, even as investment shares rose dramatically (Jones 1995b). Over a very long horizon, however, the evidence of a scale effect is somewhat stronger; Kremer (1993) argues that productivity and population growth are highly correlated with initial population levels, as scale effects imply.

This influential critique has led to several alternatives to remove the link between scale and growth found in endogenous growth models.[16] Jones (1995a), for example, presents a model of "semi-endogenous" growth, in which long-run growth still reflects firms' R&D choices, but is independent of government policies such as investment tax credits or R&D subsidies. Scale or policy variables affect the levels of output and productivity but not long-run growth rates. The key factor determining long-run growth in this semi-endogenous growth model remains the degree of external returns in the R&D process, which delivers endogenous growth and provides the critical distinction from the neoclassical model.

In more recent work at the macro level, Jones and Williams (1998) formalize the macroeconomic impact of increasing overall returns due to various external effects related to R&D. They calibrate their model and estimate that optimal investment in R&D is two to four times actual investment in the United States. This work suggests an important role for R&D but remains consistent with the empirical refutation of the macro R&D models in Jones (1995a, 1995b).

Expanding the Investment Definition

I now turn to several broad measurement issues that directly affect how these types of models are implemented and evaluated. Over the years, sophisticated tools have been developed to measure inputs properly, and the definition of investment has been expanded beyond tangible assets. By quantifying substitution between heterogeneous tangible assets and explicitly recognizing investment in human capital, research and development, and public infrastructure, economists have made considerable methodological advances in the understanding of productivity growth. These improvements are now well-accepted and are part of the toolkits of most applied productivity analysts; for example, the official U.S. TFP estimates of the Bureau of Labor Statistics (2000a) account for asset substitution, human capital, and R&D.

These advances are also relevant to the debate between the neoclassical and new growth views. From the neoclassical view, improved measurement of inputs allows technical progress to be more accurately assessed. From the new growth view, constant returns may be more realistic for broader definitions of capital. The degree of economy-wide returns to accumulated inputs—diminishing returns in the neoclassical world and constant (or increasing) returns in the new growth world—remains the fundamental difference between the two views of economic growth, and this is conceptually independent of how broadly capital is defined or measured. Simply including additional inputs like human capital or R&D capital is not enough to generate endogenous growth if broadly defined capital still faces diminishing returns.

Finally, many of these methodological advances have been implemented within neoclassical growth accounting analyses. As mentioned above, the primary goal of these studies is to develop better measures of inputs and a more accurate estimate of technical progress. It is not, as is often assumed, to show that there is no technical progress. Careful growth accounting analyses purge the transitory impact of investment and input accumulation to leave behind a more precise estimate of the growth rate of technical progress.

Heterogeneous Tangible Assets

An important insight, first implemented by Jorgenson and Griliches (1967), is that one must account for the vast heterogeneity of capital inputs. A dollar spent on new computer equipment, for example, provides more productive services per period than a dollar spent on a new building. By explicitly recognizing these types of differences, one can estimate a "capital service flow" that is appropriate for the production function in equation 1.

Aggregate capital service flows are estimated by using asset-specific "user costs" or "rental prices" to weight each heterogeneous asset and to account for substitution between them. As firms respond to changing relative prices—for example, by substituting toward high-tech equipment and away from structures—a larger portion of investment is in assets with relatively high marginal products, and the capital service flow rises.[17] The difference between capital service flows and capital stock is called "capital quality" by some authors and reflects the changing composition of investment toward assets with higher marginal products.[18]

Jorgenson and Stiroh (2000) provide estimates of this decomposition between capital stock and capital quality. As shown in Table 2, capital stock accumulation has been the dominant force behind the growth in capital services in the United States, accounting for 1.32 of the 1.77 percentage point growth contribution of capital for the 1959-98 period. For the most recent period, the contribution of capital quality has increased markedly as firms steadily responded to changing relative prices and substituted toward high-tech equipment. Gordon (1999a) examines a longer time period, dating back to 1870, and concludes that quality adjustments of capital and labor inputs have been important sources of long-run growth in the United States.

The evidence shows that one must use a capital services methodology to quantify the role of capital accumulation correctly and to isolate technical progress. Failure to account for ongoing substitution understates the contribution of input accumulation and overstates the TFP residual from equation 3. Thus, this type of careful measurement of capital services is critical to obtaining accurate measures of technical progress and understanding long-run growth.

Human Capital

A second important extension of the capital concept is the explicit inclusion of the contribution of changes in labor quality. Economists have long recognized the importance of investments in human beings; and expenditures on education, job training, labor migration, and health care all increase the quality of human labor, enhance productivity, and are rightly called investments.[19]

Griliches (1960), Denison (1962), and Jorgenson and Griliches (1967) pioneered the use of wage data to weight heterogeneous workers and construct constant-quality indexes

Table 2

Growth Contribution of Capital and Labor Inputs, 1959-98

	1959-98	1959-73	1973-90	1990-95	1995-98
Contribution of capital services (*K*)	1.77	2.07	1.62	1.20	2.17
Contribution of capital stock	1.32	1.66	1.22	0.77	1.23
Contribution of capital quality	0.45	0.40	0.41	0.43	0.95
Contribution of labor input (*L*)	1.23	1.25	1.17	1.18	1.57
Contribution of labor hours	0.92	0.80	0.97	0.81	1.32
Contribution of labor quality	0.32	0.45	0.20	0.37	0.25

Source: Jorgenson and Stiroh (2000).

Notes: Growth contribution of capital quality equals the difference between the contribution of capital services and capital stock. Growth contribution of labor quality equals the difference between the contribution of labor input and labor hours. See the text for details. All values are average annual percentages.

of labor input. Similar to the treatment of capital, this approach captures substitution between different types of labor and results in a flow of labor inputs appropriate for the production function analysis of equation 1. In contrast, a simple sum of hours worked by heterogeneous workers ignores this type of compositional change.[20]

Using the framework in equations 3 and 4 and again defining labor quality as the difference in the growth of labor input and unweighted hours, Jorgenson and Stiroh (2000) estimate that labor quality growth accounted for nearly 15 percent of labor productivity growth for the 1959-98 period (Tables 1 and 2). Similarly, the Bureau of Labor Statistics (1999b) attributes one-third of U.S. nonfarm labor productivity growth from 1990 to 1997 to labor composition effects. Again, failure to account for these quality changes overstates historical TFP growth.

Looking at the impact of human capital from a different perspective, Mankiw, Romer, and Weil (1992) include investment in human capital in an augmented Solow growth model to examine cross-country differences in growth. Employing a Cobb-Douglas specification for aggregate output, they explicitly model human capital as a determinant of output as

$$(6) \qquad Y = K^{\alpha} H^{\beta} (AL)^{1-\alpha-\beta},$$

where H is the stock of human capital.[21]

Mankiw, Romer, and Weil (1992) use educational attainment to proxy for human capital accumulation. They find that this extended neoclassical model fits the data well in terms of the growth convergence predictions and the estimated output elasticities. The authors conclude that the augmented Solow model in its neoclassical form is consistent with the international evidence. In contrast, Lucas (1988) incorporates human capital in a growth model but explicitly includes an external spillover effect in the spirit of new growth theory.

Although these studies differ in their approach and questions—Jorgenson and Stiroh (2000) show labor quality to be an important contributor to U.S. productivity growth, and Mankiw, Romer, and Weil (1992) find human capital to be a good predictor of cross-country income differences—both emphasize the importance of accounting for human capital accumulation. By correctly identifying and measuring accumulated inputs, this extension of the neoclassical model allows for a better understanding of the growth process.

Research and Development

Knowledge creation through explicit research and development activities is a third extension of the capital accumulation process that deserves special attention. R&D, broadly defined as investment in new knowledge that improves the production process, has been the focus of considerable research activity. There is still some debate, however, over whether R&D is best viewed as a neoclassical factor of production or if it is best viewed as a source of spillovers as in the endogenous growth models.

It is straightforward to think of R&D as just another form of capital in which firms choose to invest. In this sense, R&D is not fundamentally different from investment in tangible capital. Griliches (1973, 1979), for example, argues that it is reasonable to view the primary impact of R&D investment in a neoclassical sense since returns accrue internally. Firms presumably invest in R&D to improve their own production processes and to raise profits, so any spillover effects are secondary and unintended consequences.

While it is conceptually straightforward to treat R&D as a neoclassical factor of production with diminishing returns, Griliches (1995), Hall (1996), and Jorgenson (1996) all emphasize the practical difficulty in measuring the growth contribution of R&D because of thorny measurement problems and a lack of adequate data. Hall (1996) points out that R&D is often associated with product improvements, and the measured impact of R&D therefore depends critically on how price deflators are constructed and how output is deflated. In addition, one must estimate an appropriate depreciation rate to calculate the productive stock of R&D capital.

Despite these problems, many studies have attempted to measure the direct impact of R&D.[22] As an example of the typical approach, Griliches (1995) presents a skeletal model of R&D that is a straightforward extension of the neoclassical framework:

$$(7) \qquad lnY = a(t) + \beta lnX + \gamma lnR + \varepsilon,$$

where X is a vector of standard inputs, such as capital and labor, and R is a measure of cumulative research effort.

Studies of this type typically have found that R&D capital contributes significantly to cross-sectional variation in productivity. It is important to emphasize that equation 7 examines the relationship between firm or industry productivity and its own R&D stock. In the equation, R&D is treated as a conventional neoclassical capital input with internal rewards.

Others, however, argue that R&D capital is fundamentally different from tangible and human capital. Knowledge capital appears to be noncompetitive since many producers can use the same idea simultaneously, and the returns may be hard to appropriate due to potential production spillovers. This difference is what makes R&D capital an important part of the endogenous growth models discussed earlier.[23] As emphasized by Romer (1994) and Basu (1996), the distinction between internal and external benefits drives the difference in returns to capital that delineates the role of research and development in the neoclassical and the new growth theories.

There seems to be some confusion, however, about what constitutes a true production spillover and what is really a more conventional measurement problem. Griliches (1995, p. 66) defines a production (knowledge) spillover as "ideas borrowed by research teams of industry *i* from the research results of industry *j*." This is quite distinct from situations in which transaction prices do not fully reflect the marginal benefit of the innovation (for example, see Bresnahan [1986], Bartelsman, Caballero, and Lyons [1994], and Keller [1998]). Similarly, Hall (1996) discusses how competition may lead to lower prices for goods of innovative firms. Rather than measuring spillovers in Griliches' sense, these gains to innovation reflect the inaccuracy of prices that do not adequately capture changes in the quality dimension.[24] While there are daunting practical difficulties, if all attributes and quality characteristics could be correctly priced, then increased quality or variety of intermediate inputs would not be measured as productivity spillovers.

The distinction between internal and external benefits drives the difference in returns to capital that delineates the role of research and development in the neoclassical and the new growth theories.

If true productivity gains do spill over to other firms, however, one channel for endogenous growth is opened. The microeconomic evidence suggests that R&D spillovers may exist,[25] but a wide variation in results and conceptual difficulties suggest that some caution is warranted. Griliches (1995), for example, points out that the impact of R&D in industry analyses is not greater than in firm analyses (as the presence of spillovers implies) and warns, "in spite of a number of serious and promising attempts to do so, it has proven very difficult to estimate the indirect contribution of R&D via spillovers to other firms, industries and countries" (p. 83). Given the poor quality of the data and methodological problems discussed earlier, it is difficult to draw definitive conclusions from these studies.

Public Infrastructure

A final extension of the investment concept worth noting is public infrastructure investment. In a series of influential and controversial studies, Aschauer (1989a, 1989b, 1990) argues that core infrastructure investment is an important source of productivity growth and that the sluggish productivity performance of the 1970s can be largely attributed to a slowdown in public investment. These claims led to a wide-ranging debate about policy implications and possible methodological problems such as potential biases from common trends, omitted variables, and potential reverse causality.[26]

Independent of any methodological concerns, the primary impact of government capital is conceptually the same as that of tangible capital and depends on proper measurement.[27] In a standard neoclassical growth accounting framework with only private inputs, any impact from government capital would be mismeasured as TFP growth. In this sense, government capital is just another accumulated input that is often missed and thus contributes to an overstatement of true technical change. As long as diminishing returns to all capital exist, the neoclassical implications hold.

Alternatively, Barro (1990) suggests that government services generate constant returns to broadly defined capital and lead to endogenous growth. In this view, government capital differs from private capital, and the real question is whether long-run constant returns to scale exist across broadly defined capital.[28]

The recent results of Fernald (1999) shed some light on this question. He shows that investment in roads contributed substantially to productivity prior to 1973, but he also suggests that new investment in roads offers a normal or even zero return at the margin. That is, the original interstate highway system improved productivity, but a second one would not. While not an exact test, this seems more consistent with the neoclassical view of diminishing returns of capital than with the endogenous growth view.

Recent Productivity Controversies

I now move to a discussion of two current and important issues relating to investment, productivity, and growth. Both are concerned with understanding the sources of productivity growth and draw on the neoclassical and endogenous growth theories described above. In particular, I offer a resolution to the computer productivity paradox and review the renewed embodiment controversy.

The Computer Productivity Paradox

Over the past few decades, investment in high-tech equipment, particularly computers, exploded, but aggregate productivity growth remained sluggish through the mid-1990s. This apparent contradiction—the so-called computer productivity paradox of the 1980s and early 1990s—disappointed many observers and initiated a broad research effort at both the macro and micro levels. More recently, however, productivity growth has accelerated sharply (see chart); I argue that this pattern is entirely consistent with neoclassical explanations of capital accumulation and technical progress.[29]

The defining characteristic of the information technology revolution is the enormous improvement in the quality of computers, peripherals, software, and communications equipment. As epitomized by Moore's Law—the doubling of the power of a computer chip every eighteen months—each generation of new computers easily outperforms models considered state-of-the-art just a few years earlier. The constant-quality deflators employed by the U.S. Bureau of Economic Analysis translate these massive quality improvements into increased real investment and real output and show annual price declines of 18 percent over the past four decades.[30]

How does this IT phenomenon fit within the neoclassical framework? To address this question, it is critical to distinguish between the *use* and the *production* of IT.[31] Information technology is both an output from the IT-producing industries and an input to the IT-using industries, so there are two effects. The massive quality improvements in IT contribute to faster productivity growth in the IT-producing industries and faster input accumulation in the IT-using industries. Thus, the neoclassical model predicts rapid capital deepening and ALP growth in IT-using industries, and technical progress and TFP growth in the IT-producing industries. This fundamental distinction is apparent in Solow (1957), but often has been overlooked in discussions of the computer productivity paradox.

IT Use, Capital Deepening, and Productivity Growth

Consider the productivity of firms and industries that invest in and use information technology. Following the neoclassical framework in equation 4, strong IT investment contributes directly to ALP growth through traditional capital deepening effects. In the case of IT, this reflects rapid growth in capital services and, until recently, a small income share. Over the past four decades, however, U.S. firms have continued to respond to large price declines by investing heavily, particularly in computer hardware, and rapidly accumulating IT.

As long as relative prices continued to fall, it was inevitable that IT inputs would eventually make a large contribution to growth. Indeed, recent estimates by Jorgenson and Stiroh (2000), Oliner and Sichel (2000), and Whelan (2000) indicate substantial increases in the growth contributions from computers and other IT capital. Jorgenson and Stiroh (2000), as reported in Table 3, estimate that the contribution of computer hardware increased from 0.19 percentage point per year for the 1990-95 period to 0.46 percentage point for 1995-98; Oliner and Sichel (2000) report an increase from 0.25 for 1990-95 to 0.63 for 1996-99.[32] Both agree that IT capital accumulation has been an important part of the acceleration in U.S. productivity since 1995.

Table 3
Growth Contribution of Information Technology and Other Assets, 1959-98

	1959-98	1959-73	1973-90	1990-95	1995-98
Contribution of capital services (K)	1.77	2.07	1.62	1.20	2.17
Other capital	1.45	1.89	1.27	0.80	1.42
Computer hardware	0.18	0.09	0.20	0.19	0.46
Computer software	0.08	0.03	0.07	0.15	0.19
Communications equipment	0.07	0.06	0.08	0.06	0.10

Source: Jorgenson and Stiroh (2000).

Notes: A growth contribution is defined as the share-weighted real growth rate of the asset as in equation 3 in the text. All values are average annual percentages.

This historical record on IT capital accumulation appears entirely consistent with the neoclassical model. Massive input substitution and rapid capital accumulation during the 1990s have led to an aggregate growth contribution that is now quite large. Prior to that, the contribution was modest because the stock of IT was small. Only in the late 1990s, after a major information technology investment boom, were there enough information technology inputs to have a substantial impact on growth and labor productivity at the aggregate level.

Despite the straightforward relationship and mounting aggregate evidence, the empirical evidence on computers and ALP growth across industries has been mixed. Gera, Gu, and Lee (1999), McGuckin, Steitwieser, and Doms (1998), McGuckin and Stiroh (1998), and Steindel (1992) find a positive impact, while Berndt and Morrison (1995) report a negative impact. Morrison (1997) finds overinvestment in high-tech assets for much of the 1980s. The microeconomic evidence for firms is somewhat stronger. For example, Brynjolfsson and Hitt (1993, 1995, 1996), Lehr and Lichtenberg (1999), and Lichtenberg (1995) typically estimate returns to computers that exceed other forms of capital.

Only in the late 1990s, after a major information technology investment boom, were there enough information technology inputs to have a substantial impact on growth and labor productivity at the aggregate level.

On the surface, exceptionally high returns to IT suggest effects found in some endogenous growth models. The findings of large gross returns, however, are also quite consistent with the neoclassical model—computers must have high marginal products because they obsolesce and lose value so rapidly. Computers have a low acquisition price, but rapid obsolescence makes them expensive to use and a high return is needed as compensation. This is exactly the type of asset heterogeneity for which the user-cost methodology was designed. In addition, Brynjolfsson and Yang (1997) suggest that much of the "excess returns" to computers actually represent returns to previously unspecified inputs such as software investment, training, and organizational change that accompany computer investment.

Note that the neoclassical framework predicts no TFP growth from IT use since all output contributions are due to capital accumulation. Computers increase measured TFP only if there are nontraditional effects like increasing returns, production spillovers, or network externalities, or if inputs are measured incorrectly. The nontraditional effects, if present, would move the IT revolution into the world of new growth theory. The evidence, however, is not very strong. Siegel and Griliches (1992) and Siegel (1997) estimate a positive impact of computer investment on TFP growth across U.S. industries, while Berndt and Morrison (1995) and Stiroh (1998a) do not. Working with aggregate data, Gordon (2000) finds no evidence of computer-related spillovers in the late 1990s. In sum, there does not appear to be compelling evidence for nontraditional effects from IT that lead outside of the neoclassical model.

IT Production and Technical Progress

Now consider the productivity of firms and industries that produce IT assets. These sectors are experiencing fundamental technical progress—the ability to produce more output in the form of faster processors, expanded storage capacity, and increased capabilities from the same inputs—that should be measured directly as industry TFP and lead to higher ALP growth (equations 3 and 4). This affects both industry and aggregate productivity.

The data are quite clear that fundamental technical progress, measured as TFP growth, is a driving force in the production of these new high-tech assets. The Bureau of Labor Statistics (1999b), Jorgenson and Stiroh (2000), Oliner and Sichel (2000), and Stiroh (1998a) all report strong industry TFP growth in the high-tech producing industries. Moreover, much of the acceleration in aggregate U.S. productivity growth after 1995 can be traced to accelerations in the pace of technical progress—measured as faster relative price declines in these high-tech industries.[33]

This notion that technical progress in specific industries drives aggregate productivity is hardly new and is consistent with the broad neoclassical framework. As early as Domar (1961), economists recognized that aggregate TFP growth reflects technical progress among component industries. Accelerating technical progress in key industries can then drive aggregate productivity through both a direct TFP contribution and induced capital accumulation as relative prices change.

Alternative Explanations

The preceding discussion still leaves open the question of why even ALP growth remains sluggish in some computer-intensive sectors like finance, insurance, real estate, and services. Since computers are highly concentrated in service sectors, where output and productivity are notoriously hard to measure, Diewert and Fox (1999), Griliches (1994), Maclean (1997), and McGuckin and Stiroh (1998) suggest that measurement error plays a role in the remaining computer productivity paradox for certain IT-using industries.

A second common explanation is that computers are still relatively new and it may just be a matter of time until they fundamentally change the production process and usher in a period of faster productivity growth throughout the economy. David (1989, 1990) draws a parallel between the slow productivity benefits from electricity and those from computers. Triplett (1999a), however, cautions against such analogies, arguing convincingly that the massive declines in computer prices, and hence the diffusion patterns, are unprecedented. Moreover, computers are no longer really a new investment—the first commercial purchase of a UNIVAC mainframe computer was in 1954, and computer investment has been a separate entity in the U.S. national accounts since 1958.[34] This critical mass and delay hypothesis is beginning to lose credibility as an explanation for low productivity in certain computer-intensive industries.

Technical change in the production of information technology assets lowers the relative price, induces massive high-tech investment, and is ultimately responsible for the recent productivity revival.

A final explanation is simply that computers are not that productive in some industries. Anecdotes abound of failed systems, lengthy periods of downtime, unwanted and unnecessary “features,” and time-consuming upgrades—all of which can reduce the productivity of computer investment.[35]

IT and the New Economy

Despite some lingering questions, the computer productivity paradox appears to be over. Aggregate productivity growth is strong, and IT-producing industries are showing rapid TFP growth. Moreover, the IT revolution and the “new economy” appear to be largely a neoclassical story of relative price declines and input substitution. Technical change in the production of information technology assets lowers the relative price, induces massive high-tech investment, and is ultimately responsible for the recent productivity revival.

These benefits, however, accrue primarily to the producers and users of IT, with little evidence of large spillovers from computers. That is, we see TFP growth in IT-producing industries and capital deepening elsewhere. Of course, the neoclassical model provides no explanation for why technical progress may have accelerated in high-tech industries in recent years. Perhaps models of endogenous innovation and competition can provide an answer.

The Renewed Embodiment Controversy

The discussion so far has focused on the modern neoclassical framework and new growth models as explanations of productivity growth. An alternative perspective, however, argues that technological progress is “embodied” in new machinery and equipment, as opposed to being a more pervasive force that affects the production of all goods and services. In challenging papers, Greenwood, Hercowitz, and Krusell (1997) and Hercowitz (1998) recently brought this debate back to center stage and reopened the embodiment controversy.

This debate is important since it helps us to understand the precise roles of technology and investment in the growth process. By better understanding these issues, such as whether technology is driving the recent investment boom, one may be able to implement more effective policies. Moreover, there are clear implications associated with how real aggregate output should be measured that directly affect how the economy is viewed. For example, Greenwood et al. (1997) disagree with the current practice of adjusting the output of investment goods, such as computers, for quality improvements. As noted in the previous section, gains in the production of computers have been a major part of the productivity revival of the 1990s and excluding them would substantially change our perception of the U.S. economy.

The embodiment idea goes back at least to Solow (1960), who suggests that technical change is embodied in new investment goods, which are needed to realize the benefits of technical progress. In response, Jorgenson (1966) shows this to be no different conceptually from the neoclassical view of disembodied technical change with the calculation of investment price deflators responsible for apparent differences. If new vintages of capital have different productive characteristics, the appropriate constant-quality deflators attribute output and productivity growth to input accumulation and not to technical progress. Hulten (1992) shows how failure to account for improved characteristics of recent vintages of investment goods suppresses capital enhancements into the traditional TFP residual.

There seems to be general agreement that different vintages of capital inputs need to be adjusted for quality change in order to understand and quantify the sources of growth. A second conclusion of Jorgenson (1966), however, is that investment as an output must also be measured in quality-adjusted units; Hulten (2000) discusses potential measurement errors when investment is not measured in such units. While this methodology has been integrated into the U.S. national accounts—where constant-quality deflators are used for investment goods like computer hardware and software to calculate real GDP—it plays a central role in the renewed embodiment debate.

> *An alternative perspective [to the neoclassical and new growth models] argues that technological progress is “embodied” in new machinery and equipment.*

Greenwood et al. (1997) and Hercowitz (1998) argue explicitly against adjusting investment output for quality change, preferring to measure real investment output in units of consumption. As motivating evidence, Greenwood et al. report that the relative price of equipment in the United States has fallen 3 percent per year in the postwar era, while the equipment-to-GDP ratio increased dramatically. They calibrate a balanced growth path and attribute 60 percent of postwar productivity growth to “investment-specific technological change” that is conceptually distinct from capital accumulation and disembodied (Hicks-neutral) technological change. A clear implication, they argue, is that constant-quality price indexes are appropriate only for deflating investment inputs, not for deflating investment as an output.[36]

It is essential, in my view, that both investment outputs and capital inputs be measured consistently in quality-adjusted units, as currently employed in the U.S. national accounts. The key point is that improved production characteristics of new investment cohorts are themselves produced and rightly considered output. Although a rigorous theoretical model is beyond the scope of this article, it is useful to sketch out a defense of this position.

Consider a simple two-sector, neoclassical model like the one outlined in the earlier discussion of the computer productivity paradox. One sector produces computers and one sector uses computers; both use neoclassical production functions. Can this explain the motivating evidence cited by Greenwood et al.? The answer is clearly yes. Disembodied technical change in the computer-producing industry (measured as industry-level TFP) reduces the marginal cost of producing computers and lowers prices. Profit-maximizing firms elsewhere in the economy respond to the relative price change, substitute between inputs, and rapidly accumulate computers. Thus, one would observe falling relative prices and rising investment shares in a traditional neoclassical world with purely disembodied technical change in one sector.

Greenwood et al. appear to need investment-specific technical change since they focus on a one-sector model in which consumption, equipment investment, and construction equipment are produced from the same aggregate production function. This effectively imposes perfect substitutability between investment and consumption goods and requires investment-specific technical change to explain relative price changes. In a multisector neoclassical model like the one proposed by Domar (1961) and implemented by Jorgenson et al. (1987), investment-specific technical change is not needed since disembodied technical progress can proceed at different rates in different industries and generate the observed relative price changes.[37]

What does this say about the appropriate deflation of investment goods? In this example, the answer clearly depends on what one believes the computer-producing sector actually produces. High-tech industries expend considerable resources in the form of investment, R&D, and labor to produce better, faster, and more powerful products. Indeed, the hedonic literature on computers is based on the idea that the computer-producing industry creates computing power measured as a bundle of productive characteristics, rather than as computer boxes or units.[38] If computing power measured in quality-adjusted efficiency units is the appropriate measure of industry output, and I believe it is, then internal accounting consistency requires that aggregate output also be measured in quality-adjusted units.

Finally, and perhaps more fundamentally, the neoclassical model at its most basic level is a model of production and not of welfare. This too implies that output must be a measure of produced characteristics in terms of quality-adjusted units, rather than consumption forgone. The embodiment approach, in contrast, confounds the link between the sources of growth (labor, capital, and technology) and the uses of growth (consumption and investment goods) that constitute separate views of production and welfare.

Conclusion

This article provides a broad overview of the link between investment and productivity in two alternative views—the neoclassical and new growth models. Although the models emphasize different aspects of productivity growth, they both contribute to our understanding of the growth process.

The key distinction between the neoclassical and new growth theories concerns the aggregate returns to capital and the implications for long-run productivity growth. In the neoclassical world, capital (broadly defined to include all accumulated inputs) suffers from diminishing returns, and productivity growth is ultimately determined by exogenous technical progress. In the world of endogenous growth, there can be constant returns to capital that generate long-run growth in per capita variables. Although both views attempt to explain growth, they focus on different aspects and need not be mutually exclusive. Neoclassical economists developed sophisticated measurement tools to identify technical progress accurately by removing the transitory impact of input accumulation; new growth theorists developed sophisticated growth models to explain the evolution of technology as a result of the actions of economic agents. Both contributions are important.

Attempts to understand recent changes in the U.S. economy illustrate this complementarity. Aggregate productivity growth has accelerated in the past few years due to a combination of accelerating technical progress in high-tech industries and corresponding investment and capital deepening. This type of neoclassical analysis clearly explains *what* happened to the U.S. economy. To explain *why* it happened, we need to focus on the incentives and actions of the firms that actually invest, innovate, and create the new capital and knowledge that are driving the U.S. economy. This is the domain of the endogenous growth framework. Thus, both approaches make important contributions to our understanding of the economic growth process.

Endnotes

1. Labor productivity is defined as real output per hour worked. These estimates are for the U.S. nonfarm business sector from the Bureau of Labor Statistics (2000b) and are consistent with the revised GDP data after the benchmark revision in October 1999.

2. See, for example, Jorgenson and Stiroh (2000), Oliner and Sichel (2000), Gordon (1999b, 2000), and Parry (2000).

3. See Jorgenson (1996) for a discussion of the growth theory revival, Barro and Sala-i-Martin (1995) for a thorough analysis of the neoclassical framework, and Aghion and Howitt (1998) for a detailed review of different strands of new growth theory. The terms "new growth" and "endogenous growth" are used interchangeably throughout this article.

4. The Solow model assumes labor is fully employed so per capita income and labor productivity growth coincide.

5. The neoclassical model has also been used extensively to examine cross-country differences in the growth and level of output. This vast body of literature is not discussed here; see Barro and Sala-i-Martin (1995) for references and Mankiw (1995) for a summary of the strengths and weaknesses of the neoclassical model in this context.

6. Under the neoclassical assumptions, an input's elasticity equals its share of nominal output since the marginal product of an input equals its factor price, for example, the wage rate for labor and the rental price for capital.

7. Hsieh (1997, 1999), Rodrick (1997), and Young (1998b) provide recent views on this controversy.

8. Stiroh (1998b) reports that the long-run projection models used by various U.S. government agencies—for example, the Social Security Administration, the Congressional Budget Office, the Office of Management and Budget, and the General Accounting Office—are all firmly embedded in this neoclassical tradition.

9. Solow (1957), for example, estimates that nearly 90 percent of per capita income growth is due to technical progress.

10. See Mankiw (1995), particularly pp. 280-9.

11. My working definition follows Segerstrom (1998), who defines endogenous growth models as those in which "the rates of technological change and economic growth are endogenously determined based on the optimizing behavior of firms and consumers" (p. 1292). Hulten (2000) identifies noncompetitive markets, increasing returns to scale, externalities, and endogenous innovation as the key aspects of the new growth theory.

12. Technically, long-run growth in per capita variables exists under constant returns to all accumulated inputs. Note that in the simplest AK model like this one, A represents a constant level of technology, in contrast to the general production functions in the text.

13. These simplifications follow Romer (1994), who summarizes the evolution of endogenous growth models. One alternative mechanism is to allow for increasing returns at the level of individual firms. However, this approach is inconsistent with perfect competition. See Aghion and Howitt (1998) for a discussion. In addition, there are aggregation concerns when moving from a firm to an aggregate production function.

14. Note that Arrow (1962) does not explicitly derive a model of endogenous growth. In his model, growth eventually stops if population is held constant.

15. Barro (1990) achieves endogenous growth in a model with constant returns to capital and government services together, but diminishing returns to private capital alone. DeLong and Summers (1991, 1992, 1993), although not modeling endogenous growth, argue that equipment investment yields large external benefits in the spirit of Arrow (1962).

16. See, for example, Jones (1995a), Kortum (1997), Segerstrom (1998), and Young (1998a). Jones (1999) reviews.

17. An asset's rental price reflects the opportunity cost of buying the asset, depreciation, and any capital gains or losses on the asset. High-tech equipment experiences more rapid depreciation and smaller capital gains than structures, so equipment must have a correspondingly higher marginal product and service price. See Hall and Jorgenson (1967) for the original derivation and Jorgenson and Stiroh (2000) for a recent application and details.

18. Note that capital quality in this framework does not reflect increased productive power from a particular asset. These gains, such as the enhanced performance of more recent vintages of computers, are handled by the investment deflator, which translates nominal investment into larger quantities of real investment. I provide details later in this article.

Endnotes (Continued)

19. Mincer (1958, 1974), Shultz (1961), and Becker (1962) are early examples; Griliches (1996) provides a summary of the early work on human capital. As early as 1961, the similarities between investments in tangible capital and human capital such as tax incentives, depreciation, pricing imperfections, and the primarily internal benefits of human capital investments were discussed by Schultz (1961, pp. 13-5).

20. This methodology provides an index of aggregate human capital that changes as the composition of the labor force changes. The key assumption is that the quality of a particular type of labor—for example, a person of a given age, education, experience—is constant over time. Ho and Jorgenson (1999) provide methodological details.

21. Note that Mankiw, Romer, and Weil (1992) explicitly assume there are diminishing returns to accumulated inputs, $\alpha + \beta < 1$, which places the model squarely in the neoclassical tradition.

22. Good et al. (1996), Griliches (1994, 1995), and Hall (1996) provide detailed surveys of the empirical literature.

23. Hall (1996) offers a number of reasons why R&D might lead to production spillovers such as reverse engineering, migration of scientists and engineers, and free dissemination of public R&D. Grossman (1996, particularly pp. 86-8) emphasizes the differences between R&D capital and tangible capital.

24. See Griliches (1992) for a discussion of this distinction.

25. Good et al. (1996) state that “most of these recent studies point in the direction that there is some effect of R&D spillovers on the productivity growth of the receiving industry or economies” (p. 39). Griliches (1992) states that “in spite of many difficulties, there has been a significant number of reasonably well-done studies all pointing in the same direction: R&D spillovers are present, their magnitude may be quite large, and social rates of return remain significantly above private rates” (p. S43).

26. The conference proceedings in Munnell (1990) explore this issue. Aaron (1990) is a good example of important critiques of the Aschauer findings. Gramlich (1994) and Binder and Smith (1996) provide more recent reviews.

27. Measurement problems may be more severe for government capital because there are no markets for many types of such capital, which makes estimation of user costs difficult.

28. One obvious difference between private and public investment is the financing mechanism. For example, the typical argument for government infrastructure investment is a traditional public-good argument that prevents returns from being recouped by the investor, which can lead to underprovision of the good. Gramlich (1990) discusses this in detail.

29. Brynjolfsson and Yang (1996) summarize earlier empirical work, Sichel (1997) provides a broad analysis of the impact of computers, and Triplett (1999a) presents a detailed critique of common explanations for the productivity paradox. Ultimately, one would like to answer a difficult counterfactual question—how fast would labor productivity have grown in the absence of computers?—but this is very difficult indeed. For example, the explosion of computing power occurred roughly contemporaneously with the well-known productivity slowdown, and one must distinguish the productivity impact of computers from the host of factors examined in that context. See Federal Reserve Bank of Boston (1980), Baily and Gordon (1988), Baily and Schultze (1990), and Wolff (1996) for a few examples of the extensive literature on the productivity slowdown.

30. There is strong agreement that adjusting the output of computers for quality change is appropriate, but there are dissenting views. Denison (1989) argues specifically against constant-quality price indexes for computers.

31. See Baily and Gordon (1988), Stiroh (1998a), Gordon (2000), Jorgenson and Stiroh (2000), and Oliner and Sichel (2000) for details on this fundamental distinction. This discussion is also relevant to the discussion of the renewed embodiment controversy below.

32. These empirical differences primarily reflect the time periods and output concepts. See Oliner and Sichel (2000) for details.

33. As an important caveat, Triplett (1996) shows that one must incorporate quality adjustments for all inputs to correctly allocate TFP across sectors to specific high-tech industries. His results suggest that falling prices of computers are in large part due to enormous technical progress in the production of semiconductors, a crucial intermediate input to computer production. See Oliner and Sichel (2000) for recent estimates.

34. Gordon (1989) provides a history of the early evolution of computers.

Endnotes (Continued)

35. Gordon (2000) summarizes this pessimistic view. Kiley (1999) presents a formal model of how computer investment could lower productivity due to large adjustment costs.

36. Reported relative price changes are based on Gordon (1990) and extended forward. This is a puzzling appeal to evidence, however, since the goal of Gordon’s monumental effort was to develop better output price measures and he explicitly states, “both input price and output price indexes treat quality change consistently” (p. 52). Moreover, this approach assumes no quality change in consumption goods, so measured relative price changes are more accurately thought of as the relative rate of technical change between these two.

37. In their introduction, Greenwood et al. (1997) seem to agree; they view their motivating facts as evidence of “significant technological change in the production of new equipment” (p. 342). Although they do calibrate a simple two-sector model, it is not fully integrated with their empirical work on the sources of growth and they reject it as an unreasonable explanation of balanced growth rates.

38. See Triplett (1989) for a survey.

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