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INVESTMENT AND PRODUCTIVITY GROWTH A SURVEY FROM THE NEOCLASSICAL AND NEW GROWTH PERSPECTIVES

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INVESTMENT AND PRODUCTIVITY GROWTH A SURVEY FROM THE NEOCLASSICAL AND NEW GROWTH PERSPECTIVES

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ABSTRACT

This paper reviews the wide literature on investment and productivity with the debate between the neoclassical and the new growth theories providing a context for discussion. Both schools of thought regard investment, broadly defined to include purchases of tangible assets, human capital expenditures, research and development efforts, etc., as the fundamental source of improved productivity and economic growth, but the two views diverge on the exact transmission mechanism. Most importantly, the neoclassical framework focuses on internal returns to investors who appropriate the benefits of new investment, while new growth models emphasize external effects as productivity gains spill over to others. This crucial dichotomy leads to differences regarding the role of investment as a source of growth, policy prescriptions, and implications for long-run gains in productivity and living standards. The paper then reviews several empirical and conceptual issues relating to investment and productivity and outlines areas for future research.

1. INTRODUCTION

Economists have long recognized that investment is a crucial source of productivity and economic growth. By providing workers with more capital and thus improving labour productivity, tangible investment expands output and raises living standards. The fundamental importance of investment has led to an enormous amount of research, both theoretical and empirical, that examines the relationship between investment, productivity, and economic growth.

The purpose of this paper is to provide a broad survey of the recent literature that links investment to productivity, a link that depends critically on an understanding of the economic growth process. The pioneering work of Ramsey, Harrod, Domar, Solow, and others first laid a framework that focused on private investment in tangible assets and the resulting accumulation of physical capital in a neoclassical framework. Recent contributors have used this neoclassical model as a starting point, but extending the analysis in ways that have irrevocably altered our perspective on the importance of investment as a source of productivity.

One important innovation was the expansion of the investment and capital concepts by Aschauer, Becker, Griliches, Jorgenson, Mincer, Schultz, and others beyond private investment in tangible assets to include investment-driven substitution between heterogeneous assets, human capital accumulation, research and development expenditures, and investment in public infrastructure. While emphasizing a broader view of investment, this literature has typically remained in the neoclassical tradition where the benefits of investment are internal in the form of enhanced productivity or higher wages. A second major innovation was the move away from the neoclassical model to examine alternative productivity channels in the “new growth” theory of Arrow, Grossman, Helpman, Lucas, Romer, and others. This view attaches greater significance to certain types of investment that create externalities and generate an additional productivity boost through production spillovers or the associated diffusion of technology.

The first part of this paper sketches the role of investment in determining productivity in these two frameworks. While there is staunch support for both, the evidence suggests that a traditional neoclassical focus on input accumulation and internal returns remains the best explanation for improvements in labour productivity. For example, the strong performance of the newly industrialized Asian economies is primarily due to their rapid accumulation of physical and human capital, with a relatively small role for technological progress. Likewise, massive substitution towards high-tech capital goods is raising the relative productivity of firms and industries that are able to invest and restructure their activities, with little evidence that productivity gains spill over to others.

Investment and input accumulation are not the whole story, however, with roughly one-fifth of U.S. post-war growth remaining unexplained in a complete quality-adjusted, neoclassical model. This leaves an obvious need for an explanation of technological progress and alternative sources of productivity. New growth theory can fill this gap. Thus, these two frameworks can be viewed as complements rather than substitutes, with neoclassical input accumulation explaining the majority of growth and the new growth theory providing a conceptual foundation for the remainder of productivity growth that falls outside of the neoclassical framework.

The second part of the paper reviews a wide range of current issues relating to investment and productivity. Topics examined include international evidence on investment spillovers from equipment investment, potential research and development spillovers, the “computer productivity paradox,” the impact of investment on labour market outcomes, the renewed embodiment controversy, and recent microeconomic evidence from large longitudinal databases. By outlining some of the important policy implications of the current research and summarizing relevant questions that remain unanswered, this section highlights specific areas for future research on the relationship between investment and productivity.

The paper is organized as follows. Section 2 briefly outlines the traditional role that investment plays in the neoclassical model of growth, including broader concepts of investment and capital, and contrasts this model with the new models of endogenous growth. Section 3 looks at current issues relating to investment and productivity. Section 4 concludes the paper and discusses topics that are most suitable for future research.

2. INVESTMENT, PRODUCTIVITY, AND GROWTH

Economic growth theory has recently enjoyed a revival, with insights from both the classic and recent contributions providing an appropriate point of departure for a discussion of investment and productivity. The growth literature has recently bifurcated, however, with arguments put forward for both a neoclassical model of growth and an alternative, new growth view.[1] Although investment plays a central role in both, conceptual differences lead to contrasting views of the investment-productivity nexus.

Economists often think of investment as the purchase of tangible assets that contribute to current and future production as capital is accumulated. Indeed, this concept was featured in the early analysis of Cobb and Douglas (1928), Tinbergen (1942), Solow (1956, 1957), and others that first used an "aggregate production function" to describe the relationship between an economy's output and primary inputs, e.g. tangible capital and labour. This perspective has changed, however, with Mankiw (1995) concluding: "…there is an increasing consensus that the role of capital in economic growth should be more broadly interpreted" (p. 308). If capital is interpreted more broadly, then investment must also be defined more broadly to include the purchase of any asset or service that generates future production returns. Jorgenson (1996) summarizes this view with a concise definition:

> "Investment is the commitment of current resources in the expectation of future returns and can take a multiplicity of forms…the distinctive feature of investment as a source of economic growth is that the returns can be internalized by the investor" (p. 57).

This broader definition includes investment in tangible assets, as well as education, training, other human capital accumulation, or research and development, since these actions are specifically undertaken by the firm or worker to increase their own future benefits, which ultimately contribute to output, productivity, and growth. As a preview of the subsequent discussion, the idea that investment, broadly defined, primarily generates internal returns is a hallmark of the neoclassical model of investment, productivity, and growth that differentiates it from the new growth theory.

The Neoclassical Model

The standard neoclassical growth model is well known and will be reviewed here only briefly. The seminal papers of Solow (1956, 1957) formalized the neoclassical model, integrated the aggregate production function with national income data, and form the basis for much of applied growth analysis. The role of investment in this framework can be summarized by two familiar equations. The relationship between output, Y, and capital input, K, labour input, L, and “Hicks-neutral” technology,[2] A, can be described with an aggregate production function:

(1) $Y = A*f(K,L)$,

and the capital accumulation equation, which governs the relationship between investment in tangible assets, I, and capital stock, is the well-known perpetual inventory relationship:

(2) $\Delta K_t = I_t - K_{t-1}*\delta$,

where Δ represents a discrete change, d is depreciation, and I_t can either be determined endogenously by profit-maximizing firms or assumed to be some fixed proportion of output, say sY_t. The question of whether the production function should include a measure of capital stock, as described by Equation (2), or the flow of capital services is discussed below.

Under the neoclassical assumptions of competitive factor markets and constant returns to scale where all inputs are paid their marginal products, the standard growth accounting decomposition relates output growth to the share-weighted growth rates of primary inputs and total factor productivity, i.e. the famous “Solow residual,” $\Delta \ln A$,

(3) $\Delta \ln Y = v_K \Delta \ln K + v_L \Delta \ln L + \Delta \ln A$,

where v_K is capital’s share of national income, v_L is labour’s share of national income, and the neoclassical assumptions imply $v_K + v_L = 1$.

Equations (2) and (3) show the direct link between investment in tangible assets and economic growth as the accumulation of capital contributes to growth in proportion to capital’s share of national income. One can then derive the neoclassical relationship between investment and labour productivity growth, defined as output per hour worked, by transforming Equation (3) as:

$$(4) \qquad \Delta \ln y = v_K \Delta \ln k + v_L (\Delta \ln L - \Delta \ln H) + \Delta \ln A,$$

where lower-case letters are per hour worked. Growth in average labour productivity (ALP), given by $\Delta \ln y$, depends directly on the rate of per hour capital accumulation (capital deepening), $\Delta \ln k$, growth in labour quality, measured as the difference between the growth of labour input and the growth of hours worked, $(\Delta \ln L - \Delta \ln H)$, and the growth in total factor productivity (TFP), $\Delta \ln A$.[3]

The appealing simplicity and intuition of this neoclassical framework has made it the backbone of applied and theoretical work on productivity and economic growth.[4] Despite its popularity, however, the neoclassical model leads to several troubling results. First, TFP growth is entirely exogenous to the model, i.e. technology is typically described by some *ad hoc* function such as $A_t = A_0 e^{gt}$, where g is an unexplained parameter of the economy. Since capital accumulation is subject to diminishing returns, without exogenous technical progress there could be no steady growth in per capita income. Moreover, despite being totally unexplained, early empirical research found TFP growth to be the dominant source of per capita income and labour productivity growth. Indeed, Solow (1957) originally attributed nearly 90 percent of U.S. per capita output growth to exogenous technical progress, leaving many economists unsatisfied. Finally, the international data did not seem to fit with the basic neoclassical model in terms of capital shares and convergence properties.[5]

These shortcomings set the stage for several lines of subsequent research on the relationship between investment and productivity growth. One school of thought, originated by Jorgenson and Griliches (1967) and summarized in Jorgenson (1990, 1996), remained firmly embedded in the neoclassical tradition and sought to develop better measures of investment, capital, labour, and other omitted inputs in order to reduce the importance of the unexplained residual. That is, if all inputs are correctly measured, then exogenous technical progress will be a less important source of growth. A second school moved beyond the neoclassical model and sought to provide an endogenous mechanism for the evolution of technical progress, which was left unexplained in earlier work. By explicitly modelling the dynamics of competition, innovation, and production spillovers, this research culminated in models of endogenous growth in the new growth theory.

Expanding the Investment Concept

The neoclassical model described above can easily be extended beyond investment in tangible assets to account for any accumulated input that contributes to production. This includes investment-driven substitution between heterogeneous tangible assets, investment in human capital through education and worker training, research and development efforts, and public infrastructure expenditure.

Heterogeneous Tangible Assets

In the context of Equation (1), K should measure the service flow of capital inputs, which includes the services from many heterogeneous assets, ranging from long-lived structures to short-lived equipment. By recognizing that tangible assets have different acquisition prices, service lives, depreciation rates, tax treatments, and ultimately marginal products, Jorgenson and Griliches (1967) formally incorporated the heterogeneity of inputs by creating constant quality indices of capital and labour inputs. In contrast, Solow (1957) originally used a simpler measure of aggregate capital stock as in Equation (2).[6]

A constant quality index of capital input is estimated using an asset-specific “user cost of capital” to aggregate heterogeneous capital stocks, rather than acquisition prices. By weighting assets by their user cost, which equals the marginal product in equilibrium, the index of capital input incorporates important differences in the productive contribution of heterogeneous investments as the composition of investment and capital changes. It should be emphasized that “quality” change in this framework represents changes in the composition of assets and not higher productivity from any particular asset. Quality change of that type, e.g. the improved performance of more recent computers, is handled by the investment deflator and is discussed below in the section on the computer productivity paradox.

As derived in Hall and Jorgenson (1967) and elaborated in Jorgenson and Yun (1991), the user cost of capital, $P_{k,t}$, measures the annualized cost of using a piece of capital for one period, from $t\text{-}1$ to t, which equals the opportunity cost of purchasing the asset plus depreciation of the asset less any capital gains, all adjusted for tax considerations. The user cost can be estimated with a capital service price equation:

$$(5) \qquad P_{k,t} = \frac{1 - ITC - Z * t}{1 - t} * (i * P_{a,t-1} + d * P_{a,t} - p_t * P_{a,t-1}),$$

where *ITC* is the investment tax credit, *Z* is the present discounted value of capital consumption allowances, t is the statutory tax rate, *i* is the nominal rate of return, $P_{a,t}$ is the acquisition price of capital or investment, d is the rate of geometric depreciation, and p_t is the revaluation rate of asset prices, all for each individual asset.

Jorgenson and Stiroh (2000), for example, include 57 types of private investment assets and emphasize the massive substitution towards computer equipment in response to the falling acquisition price and high marginal product of these assets. Brown and Hellerstein (1997) evaluate patterns of U.S. tangible investment from 1960 to 1996 and conclude that relative price changes, particularly for information technology investments, have lead real business investment as a share of GDP to reach a 40-year high.

Table 1
The Sources of U.S. Economic Growth and the Role of Computers 1959–98

	1959–73	1973–90	1990–98
Output growth	4.32	3.13	3.44
Contribution of capital inputs (*K*)	1.41	1.15	1.07
Non-computers and software (K_n)	1.31	0.92	0.68
Computers and software (K_c)	0.10	0.24	0.39
Contribution of consumers' durables services (*D*)	0.62	0.47	0.35
Non-computers and software(D_n)	0.62	0.45	0.25
Computers and software (D_c)	0.00	0.02	0.10
Contribution of labour input (*L*)	1.25	1.17	1.32
Aggregate total factor productivity	1.05	0.34	0.70

Contribution of inputs are real growth rates weighted by average, nominal shares.
All values are average, annual percentages.
Source: Jorgenson and Stiroh (2000).

Jorgenson and Stiroh (1995, 1999, 2000) apply this capital service methodology to the U.S. economy and conclude that investment in tangible assets was the dominant source of growth in the post-war period. These results, reported in Table 1 and taken from Jorgenson and Stiroh (2000), show that output grew 3.6 percent per year from 1959 to 1998, with capital inputs, including consumers' durables, accounting for 48 percent of the total growth, while labour inputs accounted for 34 percent and the TFP residual held the remaining 18 percent. Gordon (1999) presents a longer historical perspective, dating back to 1870; he compares alternative measures of inputs for the U.S. economy, and concludes that quality adjustment of labour and capital input accounts were important sources of long-run growth. Thus, to correctly estimate the contribution of capital to growth, one must utilize a capital services concept and incorporate substitution between heterogeneous assets.

Human Capital

Economists have recognized the importance of investments in human beings at least since the early work of Mincer (1958, 1974), Shultz (1961), and Becker (1962).[7] Expenditures on education, job-training, labour migration, and health care are all expenditures that increase the quality of human labour, enhance productivity, and are rightly called investments. As early as 1961, the similarities between investments in tangible capital and in human capital, e.g. tax incentives, depreciation, pricing imperfections, and the primarily internal benefits of human capital investments, were discussed by Schultz (1961, pp. 13–5). In more recent treatments, Heckman, Lochner, and Taber (1998) and Lord and Rangazas (1998) examine the impact of tax policy on skill and human capital investment.

Jorgenson and Griliches (1967) formally incorporated heterogeneous labour inputs into an aggregate growth analysis by weighting labour hours with relative wages to account for differences in human capital and productivity. Similar to the measurement of capital, this approach incorporates substitution between different types of labour and results in a constant quality index of labour input that is suitable for the production function analysis of Equation (1). Accumulation of human capital is an important source of growth and is now routinely included in growth analyses. The U.S. Bureau of Labor Statistics (1999b), for example, reports that one-third of U.S. non-farm labour productivity growth from

1990 to 1997 was due to changes in the composition of labour, i.e. improved labour quality.

In an important paper supporting the broad neoclassical model, Mankiw, Romer, and Weil (1992) formally include investment in human capital in an augmented Solow growth model. Employing a Cobb-Douglas specification for aggregate output, they explicitly model human capital as a determinant of output:

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

where *H* is the stock of human capital and *A* is labour-augmenting technical change.

Mankiw, Romer, and Weil (1992) use a measure of education attainment as a proxy for human capital accumulation and conclude that the model fits the data well in terms of the growth convergence predictions and the estimated output elasticities. They conclude that the augmented Solow model is consistent with the international evidence.[8] More recently, Hall and Jones (1999) use a similar model to compare levels of output across a wide range of countries and find that human capital differences explain some, but by no means all, of the wide variation in per capita output levels. Ho and Jorgenson (1999) simulate the impact of higher investment in education on U.S. economic performance.

From a microeconomic perspective, Black and Lynch (1996) find that human capital is an important determinant of cross-sectional differences in establishment productivity, e.g. a 10 percent increase in average education leads to an 8.5 percent increase in manufacturing productivity and a 12.7 percent increase in non-manufacturing productivity. Again, this research supports the neoclassical view as investment in human capital leads to benefits for the economic agent that makes the investment.

Research and Development

A second type of investment that can be incorporated into the neoclassical model is investment in research and development (R&D), defined broadly as expenditures on new knowledge that improves the production process. The growth impact of R&D has received considerable attention, particularly within the context of spillovers, but the primary impact of R&D investment is internal (Griliches 1973, 1979). Aghion and Howitt (1998), important contributors to the new growth theory, recognize this by noting that "technological knowledge is itself a kind of capital good…and it can be accumulated through R&D (p. 26)." Since firms presumably undertake R&D investment to improve their own production process and raise profits, many endogenous growth models explicitly treat spillover effects as secondary, unintended consequences. It is precisely this distinction between internal and external benefits that delineates the role of R&D in the neoclassical and the new growth theories.

While it is conceptually straightforward to treat R&D as a neoclassical factor of production, serious practical difficulties prevent the R&D contribution from being easily estimated. Griliches (1995), Hall (1996), and Jorgenson (1996) all emphasize the difficulty of measuring the contribution of R&D to growth 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. As a concrete example, Griliches (1994) shows that including the U.S. computer industry, which has a quality-adjusted price deflator, in a cross-sectional analysis has an enormous impact on the estimated gross rate of return to R&D. In addition, one must estimate an appropriate depreciation rate to calculate the productive stock of R&D capital.

Despite these problems, many studies have tried to measure the impact of R&D.[9] Griliches (1995) presents a "skeletal model" of R&D that is a straightforward extension of Equation (1):

$$(7) \qquad \ln Y = a(t) + \beta \ln \mathrm{X} + \gamma \ln R + u,$$

where X is a vector of standard inputs, e.g. capital and labour, and R is a measure of the cumulative research effort.[10] Alternatively, Equation (7) can be rewritten in terms of growth rates.

A consensus has emerged around the fact that R&D capital contributes significantly to cross-sectional variation in productivity: Hall (1996) reports an elasticity of 0.10 to 0.15 using data through 1977, and Griliches (1995) reports an estimated elasticity of output with respect to R&D capital of between 0.06 and 0.10. It is important to note, however, that Equation (7) depicts the relationship between a firm's or industry's productivity and its *own* R&D stock. The impact of R&D spillovers is addressed below.

Public Infrastructure

The neoclassical view described above focuses on private investment by optimizing firms and individuals as the primary source of growth. In a series of influential and controversial papers, however, Aschauer (1989a, 1989b, 1990) argued that core infrastructure was an important source of productivity growth and that the productivity slowdown observed after 1973 can be largely attributed to a slowdown in public investment. These claims led to a wide-ranging debate that addressed the policy implications and pointed out important econometric issues including potential biases from common trends, omitted variables, and potential reverse causality.[11]
In the canonical specification, Aschauer (1989a) includes a flow of productive services from government capital, G, into the neoclassical model as:

(8) $Y = A^*f(K,L,G)$,

and concludes that "a core infrastructure of streets, highways, airports, mass transit, sewer, water systems, etc. has most explanatory power for productivity" (p. 177).

Even if one ignores the econometric and methodological criticism, this does not necessarily mean that economy-wide productivity and growth can be easily improved through public investment. For example, Aschauer (1989b) raises the issue of crowding out of private investment by public investment; Nazmi and Ramirez (1997) empirically find strong crowding out effects for Mexico. Moreover, empirical estimates of the productivity impact of infrastructure investment are inconclusive.

Morrison and Schwartz (1996) find a significant productivity impact of infrastructure across U.S. states, but they also report evidence suggesting that the net return, after accounting for the social cost of infrastructure investment, may be close to zero. Vijverberg, Vijverberg, and Gamble (1997) compare three alternative econometric approaches — a production function, a cost function, and a profit function — that are all based on an augmented production function similar to Equation (8), and report tremendous variation in results across models and specifications. They draw no firm conclusions about the impact of public investment on private productivity. Nadiri and Mamuneas (1994) find that highway investment contributes to productivity and output growth at both the sectoral and the aggregate level in the United States, although the output elasticity of private capital is four times as large as that of highway capital in all industries. Finally, Cassou and Lansing (1998) present a general equilibrium model with an optimizing government and conclude that even if public investment is not optimal, as in the United States, there is little impact on the long-run growth of labour productivity.

The obvious difference between private and public investment is the financing mechanism. As emphasized above, private investment provides returns to private agents that can be internalized and thus there is no role for government intervention. The argument for government-financed infrastructure, however, is a traditional public good argument that prevents all of the returns from being recouped by a private investor, which can lead to underprovision of the good. Gramlich (1990) addresses various types of infrastructure investments and explores the rationale for their public provision.

In an international comparison, Hulten (1996) utilizes a similar framework to examine the productivity impact of both the quantity and the quality of public investment for 42 countries from 1970 to 1990. Cross-sectional regressions that control for private tangible and human capital suggest that “infrastructure effectiveness” has an impact on growth more than seven times greater than the impact of public investment. Sanchez-Robles (1998) also focuses on alternative measures of public infrastructure, i.e. an index of “physical units of infrastructure,” and finds a significant correlation with output growth. This suggests that there is no simple way for a government to improve productivity through infrastructure investment. Considerable care must be taken to determine the most effective type of investment and its social costs cannot be ignored.

An Important Caveat

The common theme in all of the preceding studies is that investment (broadly defined as the sacrifice of present consumption for future consumption) is the important determinant of both long-run productivity growth and cross-sectional variation in productivity. An important caveat, however, is that many of these studies examine only a subset of these investment variables and there is only so much variation in productivity to explain. For example, the well-known productivity slowdown has been attributed by various authors to a shortfall of public infrastructure investment, a shortfall of R&D investment, and a shortfall of equipment investment. All cannot be responsible for the entire slowdown.[12]

To correctly identify the productivity impact of any single input, one must include all the relevant factors of production. As an example, Morrison and Siegel (1997) include R&D investment, high-tech capital investment, and human capital investment in a single analysis, and find all to be significant determinants of productivity growth in U.S. manufacturing, with R&D having the strongest impact. Future empirical research work must include many broad types of investment and capital in any productivity analysis. Only by accounting for the quantity and quality of all inputs can one correctly estimate the marginal importance of each type of investment.

The New Growth Theory

An important motivation for the endogenous growth literature was the desire to avoid the neoclassical implication that diminishing returns to capital make exogenous technical progress the only source of long-run growth in per capita income. Endogenous growth models tried to explain how private economic agents make decisions that drive long-run growth through spillovers, increasing returns, and other non-traditional effects. Aghion and Howitt (1998) provide a detailed summary of the endogenous growth theory.

The early work on endogenous growth began with Arrow (1962), Shell (1966), and others, and was revisited in important research by Romer (1986, 1990), Lucas (1988), and Grossman and Helpman (1991). Arrow, Romer, and Lucas all present models where firms face constant returns to scale to private inputs, but the level of technology, *A* in Equation (1), depends on the aggregate stock of some privately provided input. Arrow (1962) emphasizes “learning-by-doing” where investment in tangible assets generates spillovers as aggregate capital increases. That is, Arrow (1962) uses past gross investment to index experience and his learning-by-doing model can be written in simplified form as:[13]

(9) $Y_i = A(K)*f(K_i,L_i)$,

where the *i* subscript represents firm-specific variables and *K* is the aggregate capital stock. Romer (1986) essentially made *A(.)* 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. Barro (1990) presents an alternative specification of endogenous growth in a model with constant returns to scale for capital and government services, but diminishing returns to capital alone.

This type of investment spillover, whether from tangible capital, human capital, or R&D expenditures, is the fundamental distinction between the neoclassical model and the new growth theory. Simply including additional inputs, e.g. public infrastructure or human capital, is not enough to generate endogenous growth if these other assets are accumulated like traditional tangible assets, if all returns are internalized, and if individual firms face diminishing or constant returns. Lucas (1988), for example, explicitly states "I want to consider an external effect. Specifically, let the average level of skill or human capital…also contribute to the productivity of all factors" (p. 18), while Romer (1986) emphasizes "investment in knowledge suggests a natural externality. The creation of new knowledge by one firm is assumed to have a positive external effect on the production possibilities of other firms because knowledge cannot be perfectly patented or kept secret" (p. 1003). Coe and Helpman (1995) state "when a country has free access to all inputs available in the world economy, its productivity depends on the world's R&D experience" (p. 862). This has a natural interpretation as a production spillover since gains do not depend on own resource expenditures.

Basu (1996), commenting on Jorgenson (1996) and describing the neoclassical framework, concludes:

> In his (Jorgenson's) framework, "technology" is just knowledge (a shorthand for R&D) and other forms of human capital. On the other hand, the New Growth theory, which also treats knowledge as a form of capital, believes that knowledge is special, in the sense that investors cannot fully internalize the benefits from accumulating knowledge. The New Growth theory thus has large spillovers to knowledge accumulation (p. 79).

The existence of spillovers is a significant empirical question that has generated a vast literature for obvious reasons. If investment of any type — tangible assets, human capital, or R&D — generates benefits to the economy that cannot be internalized by private agents, then it means that there are different growth paths and policy implications. Since investment may be too low from society's point of view, spillovers open a role for government intervention. The empirical evidence on spillovers from different types of investment is reviewed below.

A class of models that deserves special mention in a discussion of investment and productivity relates to "general purpose technologies" (GPTs). Originated by Bresnahan and Trajtenberg (1995), this research characterizes a GPT innovation "by the potential for pervasive use in a wide range of sectors and by their technological dynamism" (p. 84). The authors argue that investing in and adopting GPT innovations like the steam engine, electricity, and semi-conductors, brings productivity gains to a wide range of industries and applications. Helpman (1998) provides a review and a collection of recent papers.

GPTs fall into the class of endogeous growth models because they explicitly include two types of investment-related spillovers. First, there are "innovational complementarities," which raise the productivity of R&D in sectors that use the GPT. For example, the computer chip may allow a financial service firm to innovate in more profitable and productive ways. Second, there are horizontal externalities since many sectors reap the benefits of the GPT, but coordination problems lead to underprovision of the GPT. These externalities can lead the market to provide a sub-optimal amount of the GPT. By exploring how a certain innovation diffuses through the economy, this research provides an important theoretical framework for the empirical search of production spillovers. This interesting explanation for well-known phenomena like the computer revolution deserves continued attention and further research.

As a final point to improve clarity, it should be noted that the term "endogenous" is used by both neoclassical and new growth advocates, but its interpretation is subtly different. Jorgenson (1996) and Jorgenson and Yip (1999), for example, use the word "endogenous" to refer to all growth that can be attributed to the accumulation of measurable inputs, i.e. all growth except the unexplained Solow residual. New growth theorists, on the other hand, use "endogenous" when explaining the evolution of the residual. That is, Jorgenson, Griliches, etc. developed sophisticated measurement tools to reduce the magnitude of the residual, while Arrow, Romer, Lucas, etc. developed sophisticated growth models to explain the creation of the standard residual as a result of specific actions of economic agents.

Although both views are attempting to explain growth, they are focusing on different aspects, which has led to some confusion in the debate. More important, the two explanations need not be mutually exclusive since even a complete quality-adjusted model of the U.S. economy leaves a large role for the unexplained residual. Thus, there are important explanatory roles for both. The neoclassical and new growth views can be combined by using neoclassical explanations to focus on broadly defined capital accumulation, conditional on the level of technology, while the new growth explanations can provide insight into the evolution of technology and the source of the residual.[14]

3. CURRENT ISSUES AND RESULTS

This section reviews several areas of current research and debate relating to investment, productivity, and growth. While significant advances have been made in all of these areas, many unanswered questions remain and there is ample room for future research.

International Comparisons

Despite large practical and conceptual difficulties, many authors have examined international differences in investment and productivity. Van Ark (1996) provides a recent survey of methodologies, in which he describes many of the difficulties involved in comparing productivity across countries, e.g. conversion to common currencies, capital stock and quality differences, variation in the productivity impact of education, etc., and reviews available international data sets. This section briefly reviews several recent empirical papers that provide estimates of investment and productivity performance across countries and sectors. It does not, however, examine the large literature on cross-sectional growth regressions in any detail.

As a first step, it is useful to compare relative investment trends. Kirova and Lipsey (1997, 1998) provide estimates of various measures of capital formation for 13 countries (Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, the Netherlands, Norway, Sweden, the United Kingdom, and the United States) and conclude that nominal values of traditional investment in tangible assets give a misleading perspective on capital accumulation. Consistent with the broader interpretation of capital described above, they calculate a broadly defined version of investment by including consumer durables, education, research and development, and military capital formation. As shown in Table 2, Kirova and Lipsey (1997) report that, after taking into account price differences, the United States led with $20,061 in broadly defined real capital formation per worker from 1990 to 1994, followed by Canada with $19,670, Belgium with $17,447, and Japan with $16,723. Billings (1996) focuses on tangible capital, concludes that the U.S. lags in terms of commercial structures, and points to differences in capital cost recovery methods as a possible explanation of the observed variation.

Table 2
International Comparison of Investment per Worker
1970–94

	1970–74	1975–79	1980–84	1985–89	1990–94
			Conventional Capital Formation		
Belgium	1,999.9	3,364.4	4,435.1	6,021.2	9,156.2
Canada	2,147.5	3,610.1	5,914.9	8,332.5	10,450.1
Denmark	2,149.8	3,114.9	3,599.2	5,379.1	5,767.4
Finland	2,333.4	3,394.6	5,225.5	7,264.3	7,704.5
France	2,394.0	3,648.4	5,452.7	7,460.3	9,809.7
Germany	2,277.0	3,415.1	5,109.1	6,400.9	8,589.6
Italy	2,087.5	3,092.2	4,808.4	6,382.9	8,285.7
Japan	2,109.8	3,419.6	5,327.4	7,947.1	11,733.3
Netherlands	2,546.6	3,801.3	4,832.8	6,110.1	7,057.7
Norway	2,515.9	4,443.6	6,131.4	7,815.5	8,446.2
Sweden	1,956.2	2,771.1	3,850.9	5,625.6	6,693.5
United Kingdom	1,332.1	1,997.1	2,918.2	4,522.5	5,659.5
United States	2,695.9	3,971.2	5,755.0	7,637.5	9,717.1
Simple Mean	2,195.8	3,388.0	4,873.9	6,684.6	8,390.0
			Broadly Defined Capital Formation		
Belgium	3,477.5	6,044.0	8,766.1	11,953.7	17,447.1
Canada	3,926.0	6,435.8	10,356.1	15,066.4	19,669.6
Denmark	3,373.2	5,215.0	6,556.2	9,368.6	11,430.7
Finland	3,275.1	5,009.0	7,886.4	11,576.8	13,895.9
France	3,549.2	5,678.9	8,835.1	12,345.9	16,414.1
Germany	3,462.7	5,632.7	8,431.1	11,197.3	15,317.7
Italy	3,029.8	4,567.0	7,627.2	10,878.4	14,905.8
Japan	2,725.4	4,570.3	7,287.6	11,199.4	16,723.5
Netherlands	4,227.7	6,900.6	8,742.0	10,900.3	12,716.5
Norway	3,723.1	6,383.3	8,992.2	12,051.6	14,080.9
Sweden	3,298.2	4,866.7	6,692.9	9,869.9	12,418.5
United Kingdom	2,317.1	3,630.9	5,722.1	8,500.2	11,281.1
United States	5,277.6	7,441.5	10,625.8	14,951.8	20,061.4
Simple Mean	3,512.5	5,567.4	8,193.9	11,527.7	15,104.8

Conventional capital formation is defined as business and non-government construction and purchases of plant, equipment, and owner-occupied housing.
Broadly defined capital formation includes investment in education, research and development, consumer durables, and military capital.
All values are converted to a common currency using purchasing power parities for capital goods.
Source: Kirova and Lipsey (1997), Tables B-1 and B-6.

Table 3
International Comparison of Average Labour Productivity
1950–94

	Average Growth Rate			**Relative Productivity Level**			
	1950–73	**1973–87**	**1987–94**	**1950**	**1973**	**1987**	**1994**
Australia	2.6	1.8	1.0	71.5	69.9	76.6	76.6
Austria	5.9	2.7	1.5	31.7	63.8	79.0	81.6
Belgium	4.5	3.0	2.2	46.5	68.1	88.6	96.3
Canada	2.9	1.7	1.0	75.3	78.9	85.9	85.7
Denmark	4.1	1.7	2.1	46.2	62.5	67.6	73.0
Finland	5.2	2.2	2.8	31.9	55.3	64.3	72.8
France	5.0	3.1	1.7	44.4	73.4	95.8	100.7
Germany	6.0	2.5	3.2	33.8	69.2	84.0	98.0
Greece	6.4	2.4	1.8	18.7	42.0	50.3	53.0
Ireland	4.3	3.6	5.1	29.9	42.5	59.3	78.6
Italy	5.8	2.5	2.6	32.9	64.3	77.8	86.9
Japan	7.7	3.0	2.6	15.2	44.8	57.9	64.6
Netherlands	4.8	2.6	1.5	49.3	77.4	94.7	98.0
Norway	4.2	3.4	2.6	40.4	56.3	76.4	85.4
Portugal	6.0	1.7	2.0	18.0	36.9	39.9	42.8
Spain	6.4	2.9	4.1	19.8	44.4	56.5	69.8
Sweden	4.1	1.6	1.0	53.7	73.4	78.1	78.3
Switzerland	3.3	1.2	2.6	67.7	75.9	76.5	85.4
United Kingdom	3.1	2.4	1.9	60.5	65.8	78.6	83.5
United States	2.7	1.1	1.0	100.0	100.0	100.0	100.0
Simple Mean	4.8	2.4	2.2	42.9	62.9	74.3	80.8

Average labour productivity is defined as real gross domestic product per hour worked.
Productivity levels are relative to the United States in each year.
Mean of relative productivity levels excludes the United States.
Source: van Ark (1996), Table 1.

In terms of productivity comparisons, van Ark (1996) provides recent estimates of relative labour productivity, both in levels and growth rates, for the OECD countries. Results from that study are reported in Table 3 and show several familiar trends: a sustained productivity slowdown after 1973 across most industrialized countries, increasing variation in productivity growth since 1987, and a relative productivity advantage through 1987 for the

United States. However, France has overtaken the United States in terms of economy-wide labour productivity levels (real GDP per worker) in 1994.

Building on the same underlying data, Pilat (1996) examines differences in productivity levels and growth rates across manufacturing and service industries in OECD countries and emphasizes differences in physical capital, human capital, and R&D as an explanation. Also at a disaggregated level, the U.S. Bureau of Labor Statistics (1998) provides estimates of manufacturing productivity in 10 countries from 1979 to 1997. These growth rates, reproduced in Table 4, are typically larger than the economy-wide numbers of van Ark (1996) and show the growing divergence between the manufacturing and service sectors. An important topic for future research is to understand whether this reflects data deficiencies, mismeasurement, or a real productivity phenomenon.

Table 4
Labour Productivity Growth in Manufacturing
1979–97

	Average Growth Rate		
	1979–85	**1985–90**	**1990–97**
Belgium	6.1	2.3	2.7
Canada	2.3	1.2	2.0
France	3.0	3.4	3.5
Germany	2.0	2.2	3.2
Italy	4.9	2.6	3.4
Japan	3.5	4.3	3.2
Norway	2.4	1.4	0.9
Sweden	3.0	1.8	5.0
United Kingdom	4.4	4.6	2.7
United States	3.1	2.2	3.7
Simple Mean	3.5	2.6	3.0

Average labour productivity is defined as real value added in manufacturing per hour worked.
Source: U.S. Bureau of Labor Statistics (1998), Table B.

Table 5
Sources of Growth for the G-7 Countries
1960–95

	1960–73	1973–89	1989–95
		Canada	
Output per Capita	3.20	2.45	–0.37
Input per Capita	1.70	2.21	0.21
Total Factor Productivity	1.51	0.23	–0.59
		France	
Output per Capita	4.26	2.04	0.92
Input per Capita	2.15	0.74	1.37
Total Factor Productivity	2.11	1.31	–0.45
		Germany	
Output per Capita	3.74	2.15	1.66
Input per Capita	1.24	1.25	1.78
Total Factor Productivity	2.50	0.90	–0.11
		Italy	
Output per Capita	4.62	2.69	1.40
Input per Capita	0.79	2.42	1.49
Total Factor Productivity	3.82	0.27	–0.10
		Japan	
Output per Capita	8.77	2.71	1.81
Input per Capita	2.42	2.15	1.63
Total Factor Productivity	6.35	0.56	0.18
		United Kingdom	
Output per Capita	2.74	1.75	0.42
Input per Capita	0.98	1.10	1.77
Total Factor Productivity	1.76	0.65	–1.35
		United States	
Output per Capita	2.89	1.90	0.97
Input per Capita	1.53	1.45	0.68
Total Factor Productivity	1.36	0.45	0.29

All values are average, annual growth rates.
Input per capita includes the contribution to growth of capital stock, capital quality, labour hours, and labour quality.
Source: Jorgenson and Yip (1999), Table 3.

Dougherty and Jorgenson (1996, 1997) use the expanded neoclassical framework described above to explain differences in labour productivity among the G-7 countries (Canada, France, Germany, Italy, Japan, the United States, and the United Kingdom) during the period 1960–89. They conclude that investment and capital accumulation, broadly defined, are the most important sources of growth for all countries except France. Jorgenson and Yip (1999) update this work through 1995 and reach similar conclusions. These results, reported in Table 5, show that measured growth in input per capita was the dominant source of per capita output, with only the United States and Japan showing a positive contribution from TFP growth in the 1990s. In contrast, Klenow and Rodriguez-Clare (1997) use a cross-sectional regression analysis and report that TFP growth accounts for nearly half of output growth for 98 countries. While these studies examine different samples (i.e. Jorgenson and Yip include only a subset of rich countries), it would be useful to sort out the methodological differences that lead to such large empirical discrepancies.

Although data limitations typically force these studies to focus on developed countries, there has been interesting work recently on the newly industrialized Asian economies. Krugman (1994), Young (1995), and Collins and Bosworth (1996) use a neoclassical approach to evaluate the potential for long-run growth in the newly industrial countries (NICs) of Asia. All three studies conclude that broadly defined capital accumulation, as opposed to exogenous technical progress (measured as TFP growth), has been the primary source of growth, and are thus pessimistic about future growth prospects. These claims have lead to a sharp debate about the relative importance of capital accumulation and total factor productivity growth as sources of success in these economies. Hsieh (1997), Rodrick (1997), and Young (1998b) provide recent views on this controversy.

Equipment Investment Spillovers

The possibility that investment generates external productivity effects dates back at least to Arrow (1962), who formalized the idea by making productivity-enhancing experience a function of the cumulative capital stock. Wolff (1991) explores this idea and lists five channels that could link investment and technological progress: 1) investment is needed to put new inventions into practice, as in Solow (1960); 2) investment leads to organizational changes; 3) learning-by-doing, as in Arrow (1962); 4) technology offers a higher rate of return, which stimulates investment;

and 5) positive feedback effects through aggregate demand growth. Wolff (1991, Table 3) finds a statistical relationship between TFP growth and growth in the capital/labour ratio for 7 countries from 1870 to 1979, although the relationship does not appear particularly robust. Moreover, this type of finding is subject to a Jorgenson/Griliches-style critique about using capital stock and labour hours rather than constant-quality indices of capital and labour input when estimating TFP growth.

In a series of provocative papers, DeLong and Summers (1991, 1992, 1993) search for productivity spillovers from equipment investment. After examining a wide variety of sample periods, specifications, statistical tests, and country samples, DeLong and Summers (1991) conclude that the social return to equipment is large and far exceeds the private return. DeLong and Summers (1992) extend this work to more countries, a later time period, and additional statistical tests, and reach the same conclusion, even when examining subsets of relatively rich economies. While they do not model the link between investment and productivity spillovers directly, they suggest that producer experience generates production process efficiency gains, and that reverse engineering and organizational learning accompany investment in new equipment.

These results have clear implications about government intervention as a means to stimulate growth, and DeLong and Summers do not shrink from this position. In their first paper, they state that “If the results stand up to scrutiny…the gains from raising equipment investment through tax or other incentives dwarf losses from any non-neutralities” (DeLong and Summers 1991, p. 485). In their second paper, they go farther and conclude that “governments must avoid anti-equipment incentive policies” (DeLong and Summers 1992, p. 195). While the authors explicitly recognize the importance of market signals and are keenly aware of the difficulties of economic engineering, they clearly support a role for government intervention to promote equipment investment.

These findings, however, have generated considerable controversy and it is not clear that the results do in fact stand up to scrutiny. In the formal paper discussion, Abel (1992) questions whether the evidence is strong enough to dismiss the neoclassical view of no spillovers, while the “General Discussion” raised many important issues about causality, omitted variable bias, and interpretation as an externality. Auerbach, Hassett, and Oliner (1994) formalize some of these objections and point out that since equipment depreciates faster than structures, it requires a higher marginal product even in the standard neoclassical model.

In a strong defense of the neoclassical model, they find "returns to equipment and structures that are fully consistent with the Solow model" and conclude that "evidence of excess returns to equipment investment is tenuous" (Auerbach, Hassett, and Oliver 1994, p. 790).

Beyond the empirical issue of whether a strong, causal relationship does in fact exist, a second line of criticism questions the implications for government policies. In the "General Discussion," for example, Robert Gordon questioned whether alternative government incentives, e.g. education or public infrastructure, might not be preferable from society's point of view. Temple and Voth (1998) expand on this idea in a model where human capital accumulation drives industrialization, productivity growth, and equipment investment. DeLong and Summers themselves acknowledge many of these criticisms, but the critiques cannot be easily dismissed.

While this issue is still very much in debate, the evidence to date suggests that investment in equipment primarily affects growth and productivity through the traditional, neoclassical channels. That is, investment leads to capital deepening and labour productivity, but does not generate total factor productivity. More research is needed before a convincing case can be made for the existence of equipment investment spillovers and the accompanying government intervention. Until then, the simpler explanation seems more appropriate.

R&D Investment Spillovers

Knowledge creation is an important source of productivity and economic growth, and research and development (R&D) investment generates new knowledge. While creation of new knowledge requires expenditure and is thus rightly viewed as a form of investment, there is a sense that knowledge capital differs from tangible capital in fundamental ways. Knowledge appears to be non-rival, i.e. many producers can simultaneously use the same idea, and the returns are difficult to appropriate, i.e. spillovers may be present. As emphasized by Romer (1994), Basu (1996), and others, it is these external effects that are so important in the new growth theory. Hall (1996) lists a number of reasons why R&D might lead to spillovers, e.g. reverse engineering, migration of scientists and engineers, and free dissemination of public R&D. Grossman (1996), particularly on pp. 86–8, emphasizes the differences between R&D capital and tangible capital.

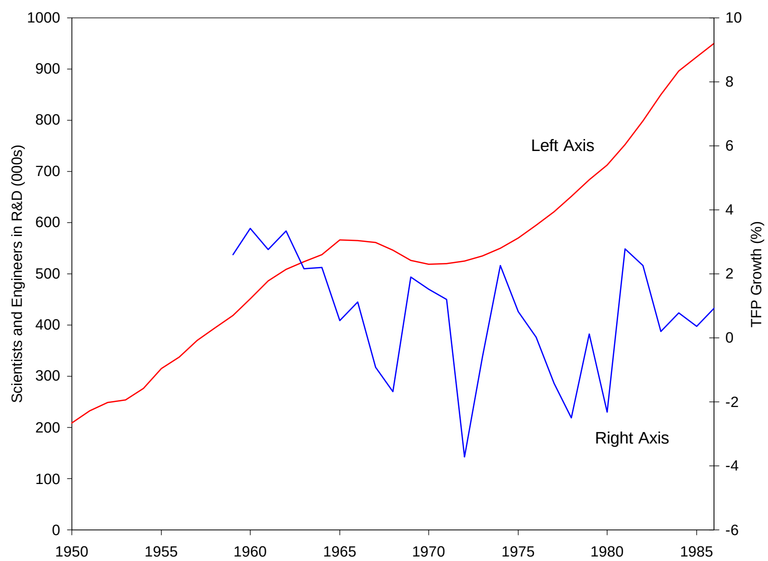
As a brief aside, Hall (1996) also discusses how competition may lead to lower prices for goods of innovative firms, but Griliches (1995) distinguishes this type of pricing problem when the transaction price does not fully reflect the marginal benefit of the innovation from pure knowledge spillovers. While measurement problems are surely important, particularly with regard to new goods and services, it is the true knowledge spillovers, defined by Griliches as "ideas borrowed by research teams of industry *i* from the research results of industry *j*" (p. 66), that may make knowledge capital fundamentally different.

The empirical literature on R&D spillovers is enormous and there are many excellent reviews.[15] Rather than repeating this effort, the present section discusses spillovers from R&D investment as a source of productivity growth in the context of the neoclassical and new growth theories.

The microeconomic evidence suggests that R&D spillovers do matter,[16] but wide variations in results and conceptual difficulties warrant some caution. For example, Griliches (1995) points out that the impact of R&D in industry analyses is not larger than in firm analyses (as the presence of spillovers implies) and warns that "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 paucity of data and the methodological problems discussed earlier, it is difficult to draw definitive conclusions from these studies.

The empirical question of R&D spillovers can also be evaluated from the macroeconomic perspective and this research suggests that R&D is less important for productivity and growth. In a pair of influential papers, Jones (1995a, 1995b) tests R&D-based endogenous growth models using aggregate data on R&D inputs in industrialized countries and finds the models lacking. The empirical difficulty is due to a "scale effect," since these models typically predict that growth is proportional to economy-wide R&D investment. As can be seen in Chart 1, which plots the number of scientists and engineers employed in R&D activities and U.S. TFP growth estimates from Jones (1995b), the data show no obvious relationship.[17] Using more sophisticated econometrics, Jones (1995b) concludes that "R&D-based models are rejected by this evidence" (p. 519). This influential critique lead to a surge of papers, e.g. Segerstrom (1998) and Young (1998a), that remove the link between scale and growth found in many endogenous growth models. Jones (1999) provides a review.

Chart 1
R&D Scientists and Engineers, and Aggregate TFP Growth in the United States, 1950-88



Source: Jones (1995b), Figures IV and V; http://www.stanford.edu/~chadj/TimeEGM.asc.

In more recent work, Jones and Williams (1998) formalize the macroeconomic impact of external R&D effects in a model similar to that of Romer (1990). Their goal is to estimate the optimal amount of R&D investment using a general growth framework:

(10) $Y_t = F(A_t, X_t)$

and

(11) $A_{t+1} - A_t = G(R_t, A_t)$,

where Y is output, A is the stock of knowledge, X is private inputs, and R is R&D investment.

The model incorporates various externalities, e.g. congestion effects through R&D duplication, knowledge spillovers, and the replacement of old ideas with new ones, that are outside the control of individual firms and thus generate spillovers and endogenous growth. Jones and Williams

(1998) calibrate the model and estimate that optimal investment in R&D is two to four times actual investment in the United States. This suggests an important role for R&D, but remains consistent with the empirical refutation of the R&D models in Jones (1995a, 1995b).

Policy implications should also be considered. At first blush, the potential presence of R&D productivity spillovers suggests an obvious role for government intervention based on standard market failure arguments. It is not clear, however, that this is in fact appropriate: Boskin and Lau (1996) point out that, at the margin, R&D investment might not generate spillovers; Griliches (1995) notes a strong premium on company-financed R&D over government supported R&D projects; Hall (1996) reports that the excess private returns to federal R&D are zero in the United States and other countries; and Aghion and Howitt (1992) provide a theoretical argument where over-investment in R&D occurs in markets with imperfect competition. Jones and Williams (1998), Boskin and Lau (1996), Grossman (1996), and Hall (1993, 1996) discuss this point at some length; the enormous difficulties encountered in measuring the impact of R&D investment prevent strong policy prescriptions.

A final area of interest is the role of R&D spillovers in an international context. For example, Coe and Helpman (1995), working with a more general class of models developed by Grossman and Helpman (1991), argue that cross-country R&D spillovers are an important source of productivity growth. That is, productivity levels in a given country appear correlated with past R&D investments of close trading partners. However, Keller (1998) disputes these findings empirically after repeating the Coe and Helpman exercise with random trading patterns, and finding more explanatory power than with the observed bilateral trade data.

Keller (1998) also makes a second critique, perhaps more relevant to this endogenous-exogenous comparison. In his discussion of the general models of Grossman and Helpman, Keller points out that productivity spillovers exist if “the importing country pays less than the intermediate good’s full marginal product” (p. 1470). This is reminiscent of the distinction made by Griliches (1995) between true spillovers and conventional pricing problems. While very difficult to do in practice, if all attributes and quality characteristics were correctly priced, then the increased quality or variety of intermediate inputs would not be a source of productivity spillovers.

The Computer Productivity Paradox

Over the last few decades investment in high-tech equipment, particularly computers, exploded but aggregate productivity growth remained sluggish. This apparent contradiction, the so-called "computer productivity paradox," has disappointed many observers and initiated a broad research effort at both the macro and micro levels. Despite difficult measurement and identification issues, this work has generated interesting results and several alternative explanations. This section reviews the relevant literature and suggests areas for future work.[18]

The defining characteristic of the information technology (IT) revolution is the enormous improvement in the quality of computers, peripherals, and related high-tech equipment. As epitomized by Moore's Law — the doubling of the number of transistors on a computer chip every 18 months — each new generation of computers easily outperforms models considered state-of-the-art just a few years earlier. Based on the early hedonic work of Cole, Chen, Barquin-Stolleman, Dulberger, Helvacian, and Hodge (1986), the U.S. Bureau of Economic Analysis (BEA) developed constant-quality price deflators for computer and peripheral equipment in 1986 to translate the massive quality improvements into increased real investment and real output. These series, now incorporating more recent estimates from the Bureau of Labor Statistics' Producer Price Index program, show an annual decline in the constant-quality price of computer investment of over 18 percent per year for nearly four decades.[19] Assuming that this sort of quality adjustment is appropriate,[20] the first question to ask is what does basic economic theory predict from such dramatic changes in relative prices?

Jorgenson and Stiroh (1999, 2000) isolate the importance of computer investment in a complete quality-adjusted model of the U.S. economy and emphasize the rapid substitution of profit-maximizing firms and utility-maximizing consumers towards relatively cheap computer and away from other inputs like labour and other types of capital. As shown in Table 6 from Jorgenson and Stiroh (1999), the quality-adjusted investment price of computers fell 17 percent and the user cost fell 15 percent from 1990 to 1996. Prices of other inputs rose over the same period. In response to these enormous relative price changes, U.S. firms have invested heavily in computers and accumulated computers much more rapidly than other inputs.

Table 6
Price and Quantity Growth Rates
1990–96

	Price	Quantity
Outputs		
Total output	2.33	2.36
Non-computers	2.60	2.01
Computers	–18.69	30.37
Investment goods (I_c)	–16.55	28.32
Consumption goods (C_c)	–24.23	37.32
Consumers' durables services (S_c)	–23.41	31.92
Inputs		
Capital services (K)	3.24	1.82
Non-computers (K_n)	3.59	1.50
Computers (K_c)	–14.94	18.71
Consumers' durables services (D)	1.95	2.87
Non-computers (D_n)	2.28	2.49
Computers (D_c)	–23.41	31.92
Labour input (L)	2.25	2.19

All values are average, annual percentages.
Source: Jorgenson and Stiroh (1999), Table 1.

Haimowitz (1998), Jorgenson and Stiroh (1995, 1999, 2000), Oliner and Sichel (1994, 2000), and Whelan (1999) incorporate these investment trends into a neoclassical growth accounting framework to estimate the contribution of computers to growth, defined as the share-weighted real growth rate as in Equation (3). Haimowitz (1998) reports a growth contribution of 0.38 from 1992 to 1996, Oliner and Sichel (2000) estimate that computer hardware and software contributed 0.93 percentage points from 1996 to 1999, and Jorgenson and Stiroh (2000), reproduced as Table 1, estimate a contribution from computers and software of 0.39 from 1990 to 1998.[21] While small in an absolute sense, widespread substitution and rapid accumulation lead to a contribution to growth that is large relative to other types of capital goods.

While U.S. firms were investing so heavily in computers, however, productivity remained slow. The Bureau of Labor Statistics (1999a, 1999b) reports U.S. private non-farm average labour productivity (ALP) growth of only 1.2 percent per year and total factor productivity (TFP) growth of 0.4 percent from 1990 to 1997. In contrast, ALP and TFP increased 2.9 percent and 1.9 percent per year, respectively, from 1948 to 1973. Given the enormous promise and rapid investment, slow productivity is disappointing to some.[22]

To understand the productivity impact, one must make a careful distinction between the *use* of computers and the *production* of computers. Since computers are both an output from one industry (the computer-producing sector) and an input to others (the computer-using industries), one should expect different impacts across industries. Since the same constant-quality deflator is used to estimate real computer investment as an output (part of GDP as a final demand good) and as an input (part of the capital stock), the massive quality improvements in computers contribute to faster output growth in the computer-producing sector and faster input accumulation in the computer-using industries. Thus, one should expect rapid capital accumulation and ALP growth in computer-using industries, and technical progress and TFP growth in the computer-producing sector. This fundamental dichotomy is apparent in the seminal article of Solow (1957), but has often been overlooked in discussions of the computer productivity paradox.

Consider the productivity of firms and industries that invest in and use computers. As in Equation (4) and as emphasized by Stiroh (1998a), computer investment contributes directly to ALP growth through the traditional capital accumulation channel. By providing workers with more and better capital equipment to work with, investment in computers should raise labour productivity in the computer-using industries. However, TFP will not be directly affected by computer investment since all output contributions will be captured by the capital accumulation term. Computer-use increases TFP only if there are non-traditional effects like production spillovers or network externalities, or if inputs are measured incorrectly.

Now consider the productivity of firms and industries that produce computers and other high-tech goods. These industries are experiencing fundamental technical progress — the ability to produce more output from the same inputs — which should be measured as TFP and ALP growth, as in Equation (4).

Despite the straightforward conceptual relationship, the empirical evidence has been mixed. In terms of computer use and ALP growth, Gera, Gu, and Lee (1999) and McGuckin and Stiroh (1998) find a positive impact of computer investment in most industries, McGuckin, Streitwieser, and Doms (1998) report higher productivity in manufacturing plants that use high-tech equipment, while Berndt and Morrison (1995) report a negative impact. In terms of TFP growth, Siegel and Griliches (1992) and Siegel (1997) estimate a positive impact of computer investment, while Berndt and Morrison (1995) and Stiroh (1998a) report either a negative or an insignificant relationship.

Consistent with the notion that fundamental technical progress is the driving force behind these new high-tech investments, Stiroh (1998a), the Bureau of Labor Statistics (1998b), and Oliner and Sichel (2000) report strong industry TFP growth in the high-tech producing industries, e.g. U.S. SIC nos. 35 and 36. As an important caveat, however, Triplett (1996) shows that one must incorporate quality adjustments for all inputs to correctly allocate TFP across sectors. Since the Bureau of Economic Analysis recently incorporated constant-quality price deflators for semi-conductors into the U.S. national accounts, an obvious area for future research is to update industry TFP estimates using the new input deflators.

There is also a large microeconomic literature that econometrically estimates the returns to computer or information technology (IT) investment across firms or industries.[23] This research, e.g. Gera, Gu, and Lee (1999), Brynjolffson and Hitt (1993, 1995, 1996), Lehr and Lichtenberg (1999), and Lichtenberg (1995), has typically estimated returns to computers that far exceed other forms of capital. In contrast, Berndt and Morrison (1995) and Morrison (1997) report evidence of over-investment in high-tech capital goods. Even the findings of super-returns, however, are not necessarily inconsistent with the neoclassical model and one does not need alternative answers like spillovers or network effects. Rather, computers must have high marginal products because they become obsolete so rapidly.[24] That is, while computers may have a low acquisition price, rapid obsolescence makes them expensive to use. Moreover, recent work by Brynjolffson and Yang (1997) suggests 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. Thus, the empirical evidence from the micro studies leads back to the neoclassical model of growth.

This still leaves the question of why ALP growth remains slow, and many authors have suggested that persistent measurement problems might be the culprit since computers are highly concentrated in service industries, where output and productivity are notoriously hard to measure. For example, Gera, Gu, and Lee (1999) report that in 1990, service industries accounted for 91 percent of all IT investment in Canada and 83 percent in the United States. Similarly, Triplett (1999b) and Stiroh (1998a) report only a slightly lower share in the United States. This has lead some commentators, for example Diewert and Fox (1999), Griliches (1994), Maclean (1997) and McGuckin and Stiroh (1999), to suggest that measurement errors may play a substantial role in the computer productivity paradox.

Mismeasurement can be important in two ways. First, Griliches (1994) points out that computer-intensive service industries are steadily growing as a share of developed economies, so any existing measurement error now leads to a larger understatement of aggregate productivity. However, Sichel (1997a) evaluates this channel empirically and concludes that the growing share of the service sector can account for only a small part of the productivity slowdown. Second, computers may be worsening measurement problems within computer-intensive industries. While the Bureau of Labor Statistics has made major improvements in the U.S. CPI to reduce bias,[25] the growing role of computers through the proliferation of new products, input substitution, and product improvements may have aggravated existing measurement problems in some industries. Dean (1999) and Gullickson and Harper (1999) provide details on the measurement problems in U.S. service industries.

As an important caveat, however, Baily and Gordon (1988) argue that many computer services are sold as intermediate goods, so the impact on final demand, i.e. the GDP, is likely to be small. In addition, Triplett (1999b) argues against the “new product” explanation. Nonetheless, this is an important area for future research since it is essentially unknown if measurement problems have worsened in computer-intensive, service 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. David (1989, 1990), in particular, has received considerable attention for drawing a parallel between the slow productivity benefits from electricity and from the computer age. However, Triplett (1999a) argues convincingly that the massive decline in computer prices, and hence the diffusion patterns, are unprecedented and he cautions against such analogies. Moreover, computers are no longer really a new investment — the first commercial purchase of an IBM UNIVAC mainframe computer occurred in 1954 and computer investment has been a separate entity in the U.S. national accounts since 1958 — so this critical mass hypothesis is beginning to lose credibility.[26]

A final explanation for slow productivity growth is simply that computers are perhaps not that productive. 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. Gordon (1998) provides a summary of this pessimistic view. However, this implies enormous investment errors by businesses and is inconsistent with much of the empirical literature.

Despite the ongoing debate, the computer revolution is largely a neoclassical story of relative price decline and substitution. Technical change in the production of high-tech goods lowers their relative price, induces massive high-tech investment, and is ultimately responsible for changing the behavior of households and firms. These benefits, however, accrue primarily to the producers and users of high-tech investment goods with little evidence of large spillovers from computers. Future research should focus on the impact of computers in hard-to-measure service industries in a broader context that encompasses associated investments in software and training. Only by including all inputs can one correctly measure the productivity and returns from the computer revolution.

Labour Issues

The impact of investment on labour has been an area of much policy interest at least since the turn of the century, when the U.S. Bureau of Labor Statistics first began publishing labour productivity estimates in response to an outcry that new machinery was replacing jobs. The question of capital/labour substitution or complementarity is important since it directly affects labour market outcomes and living standards. Recent work has focused on whether new investment is biased towards certain types of labour and affects the wage premium for higher skills.

The impact of new investment and technological change on the composition and quality of the labour force is theoretically ambiguous.[27] Griliches (1969), for example, argues that capital is complementary to highly skilled labour due to increasing education needs to operate new equipment, while Braverman (1974) and Levy and Murnane (1996) argue that investment in high-tech equipment "de-skills" jobs, allowing tasks to be reassigned to lower levels and thus reduces the average skill level of labour. Likewise, the nature of skill-biased technological change, which is defined as an exogenous increase in the relative demand for skilled worker at a given relative wage ratio, is an empirical question.

Berman, Bound, and Griliches (1994) report evidence of equipment-skill complementarity, and conclude that skill-biased technological change was the dominant force behind the shift toward non-production workers in U.S. manufacturing during the 1980s. In particular, they find a positive correlation between skill upgrading and investment in computers and R&D, which they use as indicators of technological change. Berman, Bound, and Machin (1998) extend this work to developed countries and find similar results; Betts (1997) examines Canadian manufacturing industries and reports evidence of skill-biased technological change; Kahn and Lim (1998) report that productivity growth was concentrated in skill-intensive manufacturing industries; and Machin and Van Reenen (1998) find a significant link between skill upgrading and R&D intensity.[28] It is not clear, however, whether this really represents skill-biased technological change rather than neoclassical capital-skill complementarity. In Berman, Bound, and Griliches (1994) and Machin and Van Reenen (1998), for example, computer and R&D investments are used as the primary indicators of technology, but an alternative perspective would label these as specific types of investment and capital goods.

A related issue is how investment affects the wage structure. In the neoclassical model, investment and capital accumulation raise labour productivity and, since all inputs receive factor payments equal to their marginal product, this implies a direct increase in wages. Recent research has noted that new investment, particularly in information technology, is more likely to be used by highly educated workers and thus may be contributing to an increase in the wage premium associated with education. Likewise, skill-biased technical change should increase the productivity and returns to high-skill labour.

Krueger (1993) examines this issue and estimates a 10–15 percent wage premium for computer use and concludes that increased computerization accounts for a large share of the increased return to education. In a persuasive critique, however, DiNardo and Pischke (1997) reinterpret Krueger's results as evidence of unobserved heterogeneity that may be unrelated to computers *per se*, but is rewarded in the labour market. Likewise, Bartel and Sicherman (1997) find that wage premiums primarily reflect the sorting of workers and unobserved characteristics. Murphy, Riddell, and Romer (1998) report that technological progress has increased the relative demand for skilled workers in both the United States and Canada. Autor, Katz, and Krueger (1998) point out that the shift toward more-skilled workers has been going on for decades, and find that recent increases in high-skill labour are fastest in computer-intensive industries, although they point out a possible reverse causality.

Consistent with standard economic theory, these results show a wage premium for education and skills. While there is some disagreement on whether this premium reflects unobserved worker attributes, mismeasured complementary investment, or skill-biased technological change, the empirical facts are in agreement. Moreover, the distinction between capital quality and technology is partially semantic, which has generated much confusion in the literature. This issue is addressed next.

The Renewed "Embodiment Controversy"

Economists have spent considerable effort trying to unravel the sources of technological change and productivity growth. As discussed above, the modern neoclassical framework explicitly adjusts inputs for quality change and views technological progress as exogenous, while new growth theory explains technological progress as the result of spillovers, increasing returns, etc. An alternative perspective, however, argues that technological progress is embodied in new machinery and equipment and thus requires investment to affect output and productivity. In challenging papers, Greenwood, Hercowitz, and Krusell (1997) and Hercowitz (1998) recently brought this debate back to center stage and reopened the "embodiment controversy."[29]

The embodiment idea goes back at least to Solow (1960), who suggested that technical change is "embodied" in new investment goods, which are therefore needed to realize the benefits of technical progress. In response, Jorgenson (1966) showed that this is indistinguishable from the neoclassical view of exogenous technological change, depending critically on how investment prices are calculated, concluding that “one can eliminate growth in total factor productivity altogether by suitably ‘adjusting’ the measured price of investment goods” (p. 7). That is, by adjusting capital inputs for quality change, output and productivity growth are attributed to input accumulation and not to the total factor productivity (TFP) residual. This correspondence has led to some semantic confusion since the same force can be alternatively labeled input accumulation or TFP growth depending on how input and output price deflators are incorporated. An important conclusion of Jorgenson is that investment as both an input (via capital accumulation) and as an output should be adjusted for changes in quality.

As part of the debate on the appropriateness of quality-adjusted deflators for computers, Hulten (1992) presents a detailed growth accounting derivation and shows that failure to account for quality change in investment “suppresses the quality effects into the conventional total factor productivity residual” (p. 976). It should be pointed out that this type of quality adjustment reflects the improved productivity of particular assets and is different from the substitution between heterogeneous capital assets described above.

Greenwood, Hercowitz, and Krusell (1997) and Hercowitz (1998) recognize this perspective, but argue against it, attributing 60 percent of postwar productivity growth to investment-specific technological change that is conceptually distinct from capital accumulation and disembodied technological change. In particular, they argue that constant-quality price indexes are appropriate for deflating investment inputs, but not for investment as an output. This welfare-based perspective argues that real output should be measured in foregone consumption units, so that nominal investment should be deflated by the price of consumption goods.

As evidence, Greenwood, Hercowitz, and Krusell (1997) point out that Gordon (1990) has estimated that the relative price of equipment in the United States has fallen 3 percent per year in the postwar era. 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 that “both input price and output price indexes treat quality change consistently” (p. 52). Moreover, the Greenwood, Hercowitz, and Krusell approach severs the link between the sources of growth (labour, capital, and technology) and the uses of growth (consumption and investment goods) that constitute a complete model of production and welfare.

The debate between embodied and disembodied technological progress is clearly a difficult theoretical issue and is far from decided. It seems, however, that a resolution requires a complete sectoral model that explicitly distinguishes total factor productivity in the production of investment goods from labour productivity in the use of investment goods.[30] A full resolution of this controversy is beyond the scope of this review, however, and remains an important area for subsequent research.

Plant-Level Evidence on Investment and Productivity

The recent availability of large longitudinal data sets, e.g. the U.S. Longitudinal Research Database (LRD) housed at the U.S. Census Bureau, has opened up a new channel for exploring the relationship between investment and productivity. Much of the work discussed above is at the industry or aggregate level, which can hide important variations in economic relationships. Likewise, theoretical and empirical work by Caballero, Engel, and Haltiwanger (1995) and others shows the importance of a micro perspective on investment dynamics.[31] Since the LRD includes an enormous number of manufacturing plants observed at five-year intervals over a large time span, it can provide new insights on the productivity process.[32]

In an influential paper, Baily, Hulten, and Campbell (1992) explore the dynamics of plant productivity growth and find strong firm-effects, an important role for reallocation from low-productivity to high-productivity plants, and a strong association between relative productivity and relative wages. They also find some evidence of "vintage effects," as old plants are systematically less productive than new plants, although the contribution of capital to output is small. Jensen, McGuckin, and Stiroh (1998) present more recent evidence of this type of vintage effect as recent cohorts with access to a modern generation of plant and equipment capital enter with higher productivity levels.

Power (1998) uses the LRD to explore the relationship between investment and productivity. After controlling for relevant characteristics, she finds no evidence of a correlation between productivity and measures of recent equipment investment. These remarkable results suggest that other plant characteristics, e.g. location and management, are more important determinants of productivity, and question the importance of investment as a source of productivity. The counter-intuitiveness of these results, however, requires that much more work be done before they can be taken as a stylized fact or incorporated into policy. In particular, these results need to be reconciled with the theoretical literature that makes opposing predictions, and verification against other data sets and alternative approaches is required.

Determinants of Investment

As a final note, it should be pointed out that this paper has focused on the impact of investment on productivity, but it has not addressed the microeconomic factors, e.g. tax policy, cost of capital components, or capital market features, that drive investment decisions. That is, the paper examines the effects of investment, but not its causes. This is clearly important for understanding the role that investment plays as a source of growth and there is a large body of literature that explores this issue. Cummins, Hassett, and Hubbard (1994), Hassett and Hubbard (1996), and Hubbard (1998) provide recent reviews and list the relevant papers.

4. CONCLUSIONS AND FUTURE RESEARCH

This paper provides a broad overview of recent theoretical developments that link investment to productivity and summarizes the corresponding empirical evidence. While different schools of thought emphasize alternative transmission mechanisms and some empirical results are inconclusive, one conclusion appears universal: broadly defined investment is the crucial factor that increases productivity, generates economic growth, and raises living standards. Moreover, the neoclassical model of broadly defined investment and capital with returns that are primarily internal appears to provide the best explanation for observed variations in productivity.

The many contributors discussed above have made enormous progress in furthering our understanding of this singularly important topic, but many questions remain unanswered and much more research needs to be done. The remainder of this section outlines several research questions that appear to be both conceptually relevant and feasible.

How important are the non-traditional effects that form such a crucial part of the new growth literature? The current evidence suggests that investment benefits largely accrue to the economic agents who undertake the investment, but it is certainly possible that difficult measurement and identification issues are obscuring the importance of spillovers. A number of prominent researchers have focused on this area with some success, but more evidence from a variety of methodologies and data sets is needed to build a convincing case in that direction. This is an especially relevant topic since it leads directly to policy issues like tax incentives and subsidies for certain types of investment activities, and to a potential role for government provision of specific types of capital like infrastructure or R&D.

What is the contribution of different types of investment and capital to productivity growth? It seems clear, on both theoretical and empirical grounds, that the broader definition of investment is the appropriate concept. Investment in human capital, for example, involves a trade-off of current consumption for future consumption and it would be misleading to dismiss this contribution. Since the various investment components are highly correlated in practice, however, any attempt to measure the productivity impact of any type of investment must consider a broad specification with appropriate quality adjustments. Failure to do so will lead to biased estimates of the importance of the included variables and can lead to consequential policy errors.

Why is service sector productivity growth so slow? Despite massive investment in high-tech goods, measured labour productivity growth in services remains far below that of manufacturing in most developed countries. Future research should attempt to sort out whether this reflects data deficiencies, e.g. a lack of surveys and censuses, worsening measurement problems, or a real divergence in productivity trends. A fruitful avenue of research would reconcile aggregate and industry results with microeconomic studies, either from newly created longitudinal data sets for services or firm-specific studies from alternative sources. For example, many studies focus on the U.S. banking industry due to the large amount of data available from regulatory agencies. These micro-data sets offer an alternative way to explore the plausibility of the slow productivity growth reported at the aggregate and sectoral level.

What is the economic impact of the computer revolution? While a simple neoclassical story of input substitution goes a long way in explaining the behavior of firms and households, widespread capital deepening needs to be reconciled with sluggish labour productivity growth. As mentioned above, future research must approach this question with a broadly specified and quality-adjusted input concept in order to correctly measure the impact of the computer revolution. Moreover, since computers are highly concentrated in service industries, this issue is fundamentally linked to the question of slow productivity growth in services.

Are the rapid quality improvements and corresponding evolution of computer prices in the United States unique? Much of the empirical work on the computer productivity paradox has been done in the United States, where the dominant empirical fact is the massive decline in the quality-adjusted price of computers. Wyckoff (1995) shows that a dominating trend like this can have a large impact on measured productivity growth, even at the sectoral level, and thus must be accounted for in any international comparison. According to van Ark (1996), only Australia and Canada have incorporated hedonic price indices for computers similar to the one used in the United States. Future research that compares the productivity impact of computers across countries must address this deflation issue and determine the proper way to account for differences in pricing methodologies. For example, since the United States is a major exporter of computer equipment, is it appropriate to use the U.S. deflator in other countries? Alternatively, less-developed countries may be purchasing a different mix or vintage of equipment and thus the U.S. deflator could overstate quality improvements in these countries. Ultimately, this is a question that can only be addressed empirically on a country-by-country basis.

What do micro-data sets tell us that more aggregate data sets cannot? With the recent creation of longitudinal data sets, there has been an outpouring of new research showing that aggregate data hide much of the story behind productivity dynamics. In addition, this research has raised new questions and suggested areas for future work. For example, the recent findings by Power (1998) that investment does not lead to productivity at the plant level needs to be examined further and substantiated across alternative methodologies and data sets.

How real is the embodiment controversy and what is the proper way to resolve this question? Forty years after Solow’s work, there is still heated debate about the relative importance of embodied and disembodied technical progress. Is this debate illusory in the sense that the competing views are simply labeling the same force differently? Or are there deeper, underlying conceptual differences? While difficult, a useful theoretical contribution would model this debate in a common framework that allows each perspective to be examined and semantic differences to be separated from real ones.

NOTES

1 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, Aghion and Howitt (1998) for a detailed review of different strands of the new growth theory, and Klenow and Rodriguez-Clare (1997) and Mankiw (1995) for a comparison of neoclassical and endogenous growth models.

2 It is a straightforward change to make technology labour-augmenting or "Harrod-neutral," so that the production function is $Y = f(K,AL)$.

3 This also directly affects living standards, measured as per capita income. See McGuckin and van Ark (1999) for international estimates of how they differ empirically due to differences in unemployment rates, labor force participation rates, etc.

4 For example, Stiroh (1998b) traces the evolution of the long-run projection models used by the U.S. government, e.g. the Social Security Administration, the Congressional Budget Office, the Office of Management and Budget, and the General Accounting Office, and shows that all are firmly embedded in this neoclassical tradition.

5 Mankiw (1995), particularly on pp. 280–9, discusses empirical objections to the neoclassical model.

6 It should be pointed out that Solow (1957) explicitly favored using the annual flow of capital services, but data limitations forced him to use the "less utopian measures of the stock of capital goods" (p. 313).

7 Griliches (1996) provides a summary of the early work on human capital.

8 In earlier work, Lucas (1988) incorporates human capital into a growth model, but explicitly includes an external spillover effect; this model is discussed below in the context of the new growth theory.

9 Griliches (1994, 1995) and Hall (1996) provide detailed surveys of the empirical literature.

10 Griliches (1995) uses the letter *K* to represent R&D capital, but it is changed to *R* here to avoid confusion.

11 The conference proceedings in Munnell (1990) explore these issues. Aaron (1990), in particular, is a good example of important critiques of the Aschauer work. Gramlich (1994) and Binder and Smith (1996) provide more recent reviews.

12 Mankiw (1995) makes a similar point when he discusses the “degrees of freedom” problem in the context of interpreting cross-sectional growth regressions. Wolff (1996) is a notable exception and includes R&D spending, mean education attainment, and the age of the capital stock in an attempt to unravel the productivity slowdown.

13 The following simplifications follow Romer (1994), who summarizes the evolution of endogenous growth models.

14 Coe and Helpman (1995) make this point explicitly (p. 875).

15 Good, Nadiri, and Sickles (1996), Hall (1996) and Griliches (1992, 1994, 1995) are recent examples.

16 Good, Nadiri, and Sickles (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. 43).

17 Griliches (1994) anticipates this finding when he notes that there is no reason to believe that knowledge externalities have slowed down in the last twenty years when aggregate productivity growth slowed.

18 Brynjolffson and Yang (1996) summarize recent empirical work, Sichel (1997b) provides a broad analysis of the impact of computers, and Triplett (1999a) presents a detailed critique of common explanations.

19 See Thomas and Kowal (1999) for recent estimates of computer prices in the producer price index series.

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

21 These empirical differences primarily reflect the time periods and output concept. Haimowitz (1998), for example, focuses on private non-farm business output, while Jorgenson and Stiroh (1999, 2000) use an extended output concept that includes imputations for consumers' durables and housing. In addition, Jorgenson and Stiroh (2000) use data following the BEA Benchmark Revision of 1999 that incorporate software as a separate investment good.

22 Ultimately, one would like to answer a difficult counterfactual question: How fast would labour productivity have grown in the absence of computers? But that is very difficult indeed. For example, the explosion of computing power occurred roughly in tandem 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 *The Decline in Productivity Growth*, Federal Reserve Bank of Boston Conference Series No. 22 (1980), Baily and Gordon (1988), Baily and Schultze (1990), Wolff (1996), and Gera, Gu, and Lee (1998) for a few examples of the large literature on the productivity slowdown.

23 Brynjolffson and Yang (1996) provide a review.

24 Oliner (1993, 1994) presents details on computer depreciation.

25 See Greenlees and Mason (1996) for details.

26 Gordon (1989) provides a history of the early evolution of computer prices and diffusion.

27 Binswanger (1974) provides details.

28 On a historical note, Goldin and Katz (1998) report evidence of capital-skill complementarity and skill-biased technological change in the United States from 1909 to 1940.

29 Van Ark (1996) discusses the controversy in the context of international productivity comparisons.

30 Note that Greenwood, Hercowitz, and Krusell (1997) calibrate a simple two-sector model, but do not fully integrate it with their empirical work on the sources of growth.

31 Caballero (1997) provides a review of this literature.

32 Jensen and McGuckin (1997) provide a review of the empirical work.

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