TECHNOLOGY IN GROWTH THEORY

Dale W. Jorgenson*

The early 1970s marked the emergence of a rare professional consensus on economic growth, articulated in two strikingly dissimilar books. Simon Kuznets, the greatest of twentieth century empirical economists, summarized his decades of research in *Economic Growth of Nations* (1971). The enormous impact of this research was recognized in the same year by the Royal Swedish Academy of Sciences in awarding the third Bank of Sweden Prize in Economic Sciences in Memory of Alfred Nobel to Kuznets "for his empirically founded interpretation of economic growth which has led to new and deepened insight into the economic and social structure and process of development" (Assar Lindbeck 1992, p. 79).

Robert Solow's book *Growth Theory* (1970), modestly subtitled "An Exposition," contained his 1969 Radcliffe Lectures at the University of Warwick. In these lectures Solow also summarized decades of research, initiated by the theoretical work of Roy Harrod (1939) and Evsey Domar (1946). Solow's seminal role in this research, beginning with his brilliant and pathbreaking essay of 1956, "A Contribution to the Theory of Economic Growth," was recognized, simply and elegantly, by the Royal Swedish Academy of Sciences in awarding Solow the Nobel Prize in Economics in 1987 "for his contributions to the theory of economic growth" (Karl-Goran Maler 1992, p. 191).

*Frederic Eaton Abbe Professor of Economics, Harvard University. The author has benefited greatly from the help of a colleague, Zvi Griliches, in exploring the recent empirical literature on investment in new technology. Susanto Basu and Charles Jones, as well as Griliches, have kindly provided access to unpublished material. Financial support was provided by the Program on Technology and Economic Policy of Harvard University. Responsibility for any remaining deficiencies rests solely with the author.

After a quarter of a century, the consensus on economic growth of the early 1970s has collapsed under the weight of a massive accumulation of new empirical evidence, followed by a torrent of novel theoretical insights. The purpose of this paper is to initiate the search for a new empirical and theoretical consensus. Any attempt at this thoroughly daunting task may be premature, since professional interest in growth currently appears to be waxing rather than waning. Moreover, the disparity of views among economists, always looming remarkably large for a discipline that aspires to the status of a science, is greater on growth than most other topics.

The consensus of the early 1970s emerged from a similar period of fractious contention among competing schools of economic thought, and this alone is grounds for cautious optimism. However, I believe it is critically important to understand the strengths and weaknesses of the earlier consensus and how it was dissolved by subsequent theory and evidence. It is also essential to determine whether elements have survived that could serve as a useful point of departure in the search for a new one.

Let me first consider the indubitable strengths of the perspective on growth that emerged victorious over its numerous competitors in the early 1970s. Solow's neoclassical theory of economic growth, especially his analysis of steady states with constant rates of growth, provided conceptual clarity and sophistication. Kuznets generated persuasive empirical support by quantifying the long sweep of historical experience of the United States and 13 other developed economies. He combined this with quantitative comparisons among a wide range of developed and developing economies during the postwar period.

With the benefit of hindsight, the most obvious deficiency of the neoclassical framework of Kuznets and Solow was the lack of a clear connection between the theoretical and the empirical components. This lacuna can be seen most starkly in the total absence of cross-references between the key works of these two great economists. Yet they were working on the same topic, within the same framework, at virtually the same time, and in the very same geographical location—Cambridge, Massachusetts.

Searching for analogies to describe this remarkable coincidence of views on growth, we can think of two celestial bodies on different orbits, momentarily coinciding from our earthbound perspective at a single point in the sky and glowing with dazzling but transitory luminosity. The indelible image of this extraordinary event has been burned into the collective memory of economists, even if the details have long been forgotten. The common perspective that emerged remains the guiding star for subsequent conceptual development and empirical observation.

In the next section I consider challenges to the traditional framework of Kuznets and Solow arising from new techniques for measuring economic welfare and productivity. The elaboration of production theory and the corresponding econometric techniques led to the successful implementation of constant-quality measures of capital and labor inputs and investment goods output. However, it was not until July 11, 1994, that these measures were incorporated into a new official productivity index for the United States by the Bureau of Labor Statistics!

The recent revival of interest in economic growth by the larger community of economists can be dated from Angus Maddison's (1982) updating of Kuznets' (1971) long-term comparisons of economic growth among industrialized countries. This was followed by the successful exploitation of the Penn World Table—created by Irving Kravis, Alan Heston, and Robert Summers (1978)—which provided comparisons among more than 100 developed and developing countries. Exploiting the panel data structure of these comparisons, Nasrul Islam (1995) was able to show that the Solow model is the appropriate point of departure for modeling the endogenous accumulation of tangible assets.

The new developments in economic measurement and modeling summarized in the following section have cleared the way for undertaking the difficult, if unglamorous, task of constructing quantitative models of growth suitable for the analysis of economic policies. Models based on the neoclassical framework of Kuznets and Solow determine growth by exogenous forces, principally spillovers from technological innovations. By contrast, models based on the new framework, described next, determine the great preponderance of economic growth endogenously, through investments in tangible assets and human capital.

Endogenous models of economic growth require concepts of an aggregate production function and a representative consumer that can be implemented econometrically. These concepts imply measurements of welfare and productivity that can best be organized by means of a system of national accounts. The accounts must include production, income and expenditure, capital formation, and wealth accounts, as in the United Nations (1993) *System of National Accounts*. Alternative economic policies can then be ranked by means of equivalent variations in wealth, providing the basis for policy recommendations.

I then describe quantitative models suitable for the analysis of economic policies. Econometric techniques have provided the missing link between the theoretical and empirical components of the consensus of the early 1970s. The development of these techniques was a major achievement of the 1970s and successful applications began to emerge only in the 1980s. These techniques were unavailable when Solow (1970) first articulated the objective of constructing econometric models of growth for the analysis of economic policies.

The growth of tangible assets is endogenous within a Solow (1956, 1970) neoclassical growth model. Kun-Young Yun and I constructed a complete econometric model for postwar U.S. economic growth with this feature in two papers published in 1986. We have used this model to analyze the economic impact of fundamental tax reforms. Subsequently, Mun Ho and I extended this model to incorporate endogenous growth in human capital; we have employed the extended model to analyze the impact of alternative educational policies (1995).

Although endogenous investment in new technology has been a major theme in growth theory for four decades, empirical implementation has foundered on the issue, first identified by Zvi Griliches (1973), of measuring the output of research and development activities. Until this issue has been successfully resolved, a completely endogenous theory of economic growth will remain a chimera, forever tantalizing to the imagination, but far removed from the practical realm of economic policy. The final section assesses the prospects for endogenizing investment in new technology and offers conclusions.

Sources and Uses of Growth

The objective of modeling economic growth is to explain the *sources* and *uses* of economic growth endogenously. National income is the starting point for assessments of the *uses* of economic growth through consumption and saving. The concept of a Measure of Economic Welfare, introduced by William Nordhaus and James Tobin (1972), is the key to augmenting national income to broaden the concepts of consumption and saving. Similarly, gross national product is the starting point for attributing the *sources* of economic growth to investments in tangible assets and human capital, but it could encompass investments in new technology as well.

The allocation of the *sources* of economic growth between investment and productivity is critical for assessing the explanatory power of growth theory. Only substitution between capital and labor inputs resulting from investment in tangible assets is endogenous in Solow's neoclassical model of economic growth. However, substitution among different types of labor inputs is the consequence of investment in human capital, while investment in tangible assets also produces substitution among different types of capital inputs. These were not included in Solow's (1957) model of production.

Productivity growth is *labor-augmenting* or equivalent to an increase in population in the simplest version of the neoclassical growth model. If productivity growth greatly predominates among the sources of economic growth, as indicated by Kuznets (1971) and Solow (1957), most of growth is exogenously determined. Reliance on the Solow residual as an explanatory factor is a powerful indictment of the limitations of the neoclassical framework. This viewpoint was expressed by Moses Abramovitz (1956), who famously characterized productivity growth as a "measure of our ignorance."

The appropriate theoretical framework for endogenous growth is the

Ramsey model of optimal growth introduced by David Cass (1965) and Tjalling Koopmans (1965). A promising start on the empirical implementation of this model was made in my 1967 paper with Griliches. It appeared that 85 percent of U.S. economic growth could be made endogenous; determinants of the remaining 15 percent were left for further investigation, but might be attributable to investments in new technology.[1]

The conclusions of my paper with Griliches were corroborated in two studies I published in 1969 and 1970 with Laurits Christensen. These studies provided a much more detailed implementation of the concept of capital as a factor of production. We utilized a model of the tax structure for corporate capital income that I had developed in a series of papers with Robert Hall (1967, 1969, 1971). Christensen and I extended this model to noncorporate and household capital incomes in order to capture the impact of additional differences in returns to capital due to taxation on substitutions among capital inputs.

In 1973, Christensen and I incorporated estimates of the sources of economic growth into a complete system of U.S. national accounts in our paper, "Measuring Economic Performance in the Private Sector."[2] Our main objective was the construction of internally consistent income, product, and wealth accounts. Separate product and income accounts were integral parts of both the U.S. Income and Product Accounts[3] and the United Nations (1968) *System of National Accounts* designed by Richard Stone.[4] However, neither system included wealth accounts consistent with the income and product accounts.

Christensen and I constructed income, product, and wealth accounts, paralleling the U.S. National Income and Product Accounts, for the period 1929 to 1969. We implemented our vintage accounting system for the United States on an annual basis. The complete system of vintage accounts gave stocks of assets of each vintage and their prices. The stocks were cumulated to obtain asset quantities, providing the perpetual inventory of assets accumulated at different points of time or different vintages employed by Raymond Goldsmith (1955–56; 1962).

The key innovation in our vintage system of accounts was the use of asset pricing equations to link the prices used in evaluating capital stocks

---

[1] See Jorgenson and Griliches (1967), Table IX, p. 272. We also attributed 13 percent of growth to the relative utilization of capital, measured by energy consumption as a proportion of capacity; however, this is inappropriate at the aggregate level, as Edward Denison (1974, p. 56), pointed out. For additional details, see Jorgenson, Frank Gollop, and Barbara Fraumeni (1987), especially pp. 179–81.

[2] This paper was presented at the thirty-seventh meeting of the Conference on Research in Income and Wealth, held at Princeton, New Jersey in 1971.

[3] See, for example, U.S. Office of Business Economics (1966).

[4] The United Nations System of National Accounts (SNA) is summarized by Stone (1984) in his Nobel Prize address. The SNA has been revised in United Nations (1993).

and the rental prices employed in our constant-quality index of capital input. In a prescient paper on the measurement of welfare, Paul Samuelson (1961) had suggested that the link between asset and rental prices was essential for the integration of income and wealth accounting proposed by Irving Fisher (1906).[5] Our system of accounts employed the specific form of this relationship developed in my 1967 paper, "The Theory of Investment Behavior."

Christensen and I distinguished two approaches to the analysis of economic growth. We identified the production account with a production possibility frontier describing technology. The underlying conceptual framework was an extension of the aggregate production function —introduced by Paul Douglas (1948) and developed by Jan Tinbergen (1942) and Solow (1957)—to include two outputs, investment and consumption goods. These two outputs were distinguished in order to incorporate constant-quality indices of investment goods.

We utilized constant-quality indices of capital and labor inputs in allocating the sources of economic growth between investment and productivity. Our constant-quality index of labor input combined different types of hours worked into a constant-quality index of labor input, using methodology Griliches (1960) had developed for U.S. agriculture. This considerably broadened the concept of substitution employed by Solow (1957) and altered, irrevocably, the allocation of economic growth between investment and productivity.[6]

Our constant-quality index of capital combined different types of capital inputs. We identified input prices with rental rates, rather than the asset prices appropriate for the measurement of capital stock. For this purpose we used a model of capital as a factor of production I had introduced in my 1963 article, "Capital Theory and Investment Behavior." This made it possible to incorporate differences in returns due to the tax treatment of different types of capital income.[7]

Our constant-quality measure of investment goods generalized Solow's (1960) concept of embodied technical change. My 1966 paper, "The Embodiment Hypothesis," showed that economic growth could be interpreted, equivalently, as "embodied" in investment or "disembodied" in productivity growth. My 1967 paper with Griliches removed this indeterminacy by introducing constant-quality indices for investment

[5] See Samuelson (1961), especially p. 309.

[6] Constant-quality indices of labor input are discussed in detail by Jorgenson, Gollop, and Fraumeni (1987), Chapters 3 and 8, pp. 69–108 and 261–300, and Jorgenson, Ho, and Fraumeni (1994).

[7] A detailed survey of empirical research on the measurement of capital input is given in my 1996 paper, "Empirical Studies of Depreciation," and Jack Triplett's (1996) paper, "Measuring the Capital Stock: A Review of Concepts and Data Needs," both presented at a meeting of the Conference on Research in Income and Wealth, held at Washington, D.C., in May 1992.

goods.[8] The U.S. Bureau of Economic Analysis (BEA 1986) has now incorporated a constant-quality price index for investment in computers into the U.S. national accounts.[9]

Constant-quality price indices for investment goods of different ages or vintages were developed by Hall (1971). This important innovation made it possible for Charles Hulten and Frank Wykoff (1982) to estimate relative efficiencies by age for all types of tangible assets included in the national accounts, putting the measurement of capital consumption onto a solid empirical foundation. Estimates of capital inputs presented in my 1987 book with Gollop and Fraumeni were based on the Hulten-Wykoff relative efficiencies. The BEA (1995) has incorporated these relative efficiencies into measures of capital consumption in the latest benchmark revision of the U.S. National Income and Product Accounts.[10]

Christensen and I identified the income and expenditure account with a social welfare function. The conceptual framework was provided by the representation of intertemporal preferences employed by Frank Ramsey (1928), Samuelson (1961), Cass (1965), Koopmans (1965), and Nordhaus and Tobin (1972). Following Kuznets (1961), we divided the *uses* of economic growth between current consumption and future consumption through saving. Saving was linked to the asset side of the wealth account through capital accumulation equations for each type of asset. Prices for different vintages were linked to rental prices of capital inputs through a parallel set of capital asset pricing equations.

The separation of production and welfare approaches to economic growth had important implications for the theory. The Ramsey model, so beautifully expounded by Solow (1970), had two separate submodels —one based on producer behavior and the other on consumer behavior. The production account could be linked to the submodel of production and the income and expenditure account to the submodel of consumption. This made it possible, at least in principle, to proceed from the design stage of the theory of economic growth, emphasized by Solow, to

[8] A detailed history of constant-quality price indices is given by Ernst Berndt (1991). Triplett's (1990) contribution to the Jubilee of the Conference on Research in Income and Wealth discusses obstacles to the introduction of these indices into government statistical programs. Robert Gordon (1990) constructed constant-quality indices for all types of producers' durable equipment in the national accounts and Paul Pieper (1989, 1990) gave constant-quality indices for all types of structures.

[9] Rosanne Cole, Y.C. Chen, Joan Barquin-Stolleman, Ellen Dulberger, Nurhan Helvacian, and James Hodge (1986) reported the results of a joint project conducted by BEA and IBM to construct a constant-quality index for computers. Triplett (1986) discussed the economic interpretation of constant-quality price indices in an accompanying article. Ellen Dulberger (1989) presented a more detailed report, while Triplett (1989) gave an extensive survey of empirical research on constant-quality price indices for computers. Allan Young (1989) answered Denison's (1989) objections and reiterated BEA's rationale for introducing a constant-quality price index for computers.

[10] The methodology is described by Fraumeni (1996).

econometric modeling, which he accurately described as "much more difficult and less glamorous."[11]

In summary, the dizzying progress of empirical work on economic growth by 1973 had created an impressive agenda for future research. Christensen and I had established the conceptual foundations for quantitative models of growth suitable for analyzing the impact of policies affecting investment in tangible assets. However, critical tasks, such as construction of constant-quality indices of capital and labor inputs and investment goods output, remained to be accomplished. The final step in this lengthy process was completed only with the benchmark revision of the U.S. National Income and Product Accounts in September 1995!

The Growth Revival

On October 16, 1973, the beginning of the Arab Oil Embargo ushered in a series of sharp increases in world petroleum prices that led to a rapidly deepening recession in industrialized countries, accompanied by a rise in inflation. Since this contradicted one of the fundamental tenets of the reigning Keynesian orthodoxy in macroeconomics, it engendered a shift in the focus of macroeconomic research from economic growth to stagflation. Debates among Keynesians, Old and New, monetarists, and New Classical macroeconomists took center stage, pushing disputes among the proponents of alternative views on economic growth into the background.

In graduate courses in macroeconomics the theory of economic growth was gradually displaced by newer topics, such as rational expectations and policy ineffectiveness. Elementary skills required for growth analysis—national income and product accounting, index number theory, the perpetual inventory method, and intertemporal asset pricing—were no longer essential for beginning researchers and fell into disuse. Even the main points of contention in the rancorous debates over growth in the early 1970s began to fade from the collective memory of economists.

Like a watercourse that encounters a mountain range, the stream of research on endogenous growth continued to flow unabated and unobserved, gathering momentum for its later reemergence into the light of professional debate. When it did erupt in the early 1980s, the initial impulse threatened to wash away the entire agenda that had been laboriously put into place following the canonical formulation of the neoclassical framework in the early 1970s. The renewed thrust toward endogenizing economic growth acquired startling but illusory force by

[11] See Solow (1970), p. 105. He went on to remark, "But it may be what God made graduate students for. Presumably he had something in mind."

channeling most of its energy into a polemical attack on the deficiencies of the "exogenous" theories of growth of Kuznets and Solow.

The flow of new talent into research on economic growth was interrupted for a decade, sapping the high level of intellectual energy that fueled the rapid progress of the early 1970s. The arrival of a new generation of growth economists in the early 1980s signaled a feverish period of discovery and rediscovery that is still under way. This has been followed by a revival of the latent interests of many economists in economic growth after a substantial time lapse. The consequence of this time lapse has been a form of amnesia, familiar to readers who recall Washington Irving's fictional character Rip Van Winkle. To remedy this collective lapse of memory it is essential to bring our story of the dissolution of the neoclassical framework up to date.

We can fix the revival of interest in economic growth by the larger community of economists with some precision at Maddison's (1982) updating and extension of Kuznets' (1971) long-term estimates of the growth of national product for 14 industrialized countries, including the United States. Maddison added Austria and Finland to Kuznets' list and presented growth rates covering periods beginning as early as 1820 and extending through 1979. Maddison (1991, 1995) has extended these estimates through 1992. Attempts to analyze Maddison's data led to the "convergence debate" initiated by Abramovitz (1986) and William Baumol (1986).

Denison (1967) had compared differences in growth rates for national income per capita for the period 1950 to 1962 with differences of levels in 1960 for eight European countries and the United States. He also compared sources of these differences in both growth rates and levels. The eight European countries as a whole were characterized by much more rapid growth and a lower level of national income per capita. However, this association was not monotonic for comparisons between individual countries and the United States. Nonetheless, Denison concluded: "Aside from short-term aberrations Europe should be able to report higher growth rates, at least in national income per person employed, for a long time. Americans should expect this and not be disturbed by it."[12]

Kuznets (1971) provided elaborate comparisons of growth rates for the 14 countries included in his study. Unlike Denison (1967), he did not provide comparisons of levels. Maddison (1982) filled this gap by comparing levels of national product for 16 countries. These comparisons were based on estimates of purchasing power parities by Kravis, Heston,

---

[12] See Denison (1967), especially Chapter 21, "The Sources of Growth and the Contrast between Europe and the United States," pp. 296–348.

and Summers (1978).[13] These estimates have been updated by successive versions of the Penn World Table.[14] These data have made it possible to reconsider the issue of convergence of productivity levels raised by Denison (1967).

Abramovitz (1986) was the first to take up the challenge of analyzing convergence of productivity levels among Maddison's 16 countries. He found that convergence appeared to characterize the postwar period, while the period before 1914 and the interwar period revealed no tendencies of productivity levels to converge. Baumol (1986) formalized these results by running a regression of growth rate of GDP per hour worked over the period 1870 to 1979 on the 1870 level of GDP per hour worked.[15]

In a notable paper on "Crazy Explanations for the Productivity Slowdown," Paul Romer (1987) derived a version of the growth regression from Solow's (1970) growth model with a Cobb-Douglas production function. An important empirical contribution of the paper was to extend the data set for growth regressions from Maddison's (1982) group of 16 advanced countries to the 115 countries included in the Penn World Table (Mark 3), presented by Robert Summers and Alan Heston (1984). Romer's key finding was that an indirect estimate of the Cobb-Douglas elasticity of output with respect to capital was close to three-quarters. The share of capital in GNP implied by Solow's model was less than half as great, on average.[16]

Gregory Mankiw, David Romer, and David Weil (1992) provided a defense of the neoclassical framework of Kuznets (1971) and Solow (1970). The empirical portion of their study is based on data for 98 countries from the Penn World Table (Mark 4), presented by Summers and Heston (1988). Like Paul Romer (1987), Mankiw, David Romer, and Weil derived a growth equation from the Solow (1970) model; however, they also augmented this model by allowing for investment in human capital.

The results of Mankiw, David Romer, and Weil (1992) produced

---

[13] For details see Maddison (1982, pp. 159-168). Purchasing power parities were first measured for industrialized countries by Milton Gilbert and Kravis (1954) and Gilbert et al. (1958).

[14] A complete list through Mark 5 is given by Summers and Heston (1991), while the results of Mark 6 are summarized by the World Bank in the *World Development Report 1993*.

[15] This "growth regression" has spawned a vast literature, summarized by Ross Levine and David Renelt (1992), Baumol (1994), and Robert Barro and Xavier Sala-I-Martin (1994). Much of this literature has been based on successive versions of the Penn World Table.

[16] Unfortunately, this Mark 3 data set did not include capital input. Romer's empirical finding has spawned a substantial theoretical literature, summarized at an early stage by Robert Lucas (1988) and, more recently, by Gene Grossman and Elhanan Helpman (1991, 1994), Romer (1994), and Barro and Sala-I-Martin (1994). Romer's own important contributions to this literature have focused on increasing returns to scale, as in Romer (1986), and spillovers from technological change, as in Romer (1990).

empirical support for the augmented Solow model. There was clear evidence of the convergence predicted by the model; in addition, the estimated Cobb-Douglas elasticity of output with respect to capital was in line with the share of capital in the value of output. The rate of convergence of productivity was too slow to be consistent with the 1970 version of the Solow model, but it is consistent with the augmented version.

Finally, Islam (1995) exploited an important feature of the Summers-Heston (1988) data set overlooked in prior empirical studies. This panel data set contains benchmark comparisons of levels of the national product at five-year intervals, beginning in 1960 and ending in 1985. This made it possible for Islam to test an assumption maintained in growth regressions, such as those of Mankiw, David Romer, and Weil. Their study, like that of Paul Romer (1987), was based on cross sections of growth rates. Both studies assumed identical technologies for all countries included in the Summer-Heston data sets.

Substantial differences in overall levels of productivity among countries have been documented by Denison (1967), my paper with Christensen and Dianne Cummings (1981), and, more recently, my paper with Chrys Dougherty (1996). By introducing econometric methods for panel data, Islam (1995) was able to allow for these differences in technology. He corroborated the finding of Mankiw, David Romer, and Weil (1992) that the elasticity of output with respect to capital input coincided with the share of capital in the value of output. This further undermined the empirical support for the existence of the increasing returns and spillovers analyzed in the theoretical models of Paul Romer (1986, 1990).

In addition, Islam (1995) found that the rate of convergence of productivity among countries in the Summers-Heston (1988) data set was precisely that required to substantiate the *unaugmented* version of the Solow model (1970). In short, "crazy explanations" for the productivity slowdown, like those propounded by Paul Romer (1987, 1994), are not required to explain the complexities of panels of data for advanced and developing countries. Moreover, the model did not require augmentation, as suggested by Mankiw, David Romer, and Weil (1992). However, differences in technology among these countries must be taken into account in econometric modeling of differences in growth rates.

The conclusion from Islam's (1995) research is that the Solow model is an appropriate point of departure for modeling the endogenous accumulation of tangible assets. For this purpose it is not essential to endogenize human capital accumulation as well. The rationale for this key empirical finding is that the transition path to balanced growth equilibrium requires decades after a change in policies, such as tax policies, that affect investment in tangible assets. By comparison, the transition after a change in policies affecting investment in human capital requires as much as a century.

Islam's conclusions are strongly reinforced in two important papers by Charles Jones (1995a, 1995b), testing alternative models of economic growth based on endogenous investment in new technology. Jones (1995a) tests models proposed by Paul Romer (1990), Grossman and Helpman (1991), and Phillippe Aghion and Peter Howitt (1992). This model is based on an endogenous growth rate, proportional to the level of resources devoted to research and development. Jones (1995a) demonstrates that this implication of the model is contradicted by evidence from the advanced countries that conduct the great bulk of research and development. While these countries have steadily increased the resources devoted to research and development, growth rates have been stable or declining.

Jones (1995b) tests models of endogenous investment in new technology proposed by Romer (1986, 1987), Lucas (1988), and Sergio Rebelo (1991), so-called AK models. These models have a growth rate that is proportional to the investment rate; Jones (1995b) shows that there are persistent changes in investment rates for advanced countries, while there are no persistent changes in growth rates. Jones (1995b, p. 519) concludes that "Both AK-style models and the R&D-based models are clearly rejected by this evidence." Jones (1995a) suggests, as an alternative approach, models that make investment in new technology endogenous, by preserving the feature of the Solow model that long-run growth rates are determined by exogenous forces. We consider the obstacles that remain to successful implementation of this approach below.

In summary, the convergence debate provided an excellent medium for the revival of interest in growth. The starting point for this debate was the revival of Kuznets' program for research on long-term trends in the growth of industrialized countries by Maddison (1982, 1991, 1995). As the debate unfolded, the arrival of successive versions of the Penn World Table engaged the interests of new entrants into the field in cross-section variations in patterns of growth. However, a totally novel element appeared in the form of relatively sophisticated econometric techniques. In the work of Islam (1995) these were carefully designed to bring out the substantive importance of cross-section differences in technology. This proved to be decisive in resolving the debate.

Endogenous Growth

Despite substantial progress in endogenizing economic growth over the past two decades, profound differences in policy implications militate against any simple resolution of the debate on the relative importance of investment and productivity. Proponents of income redistribution will not easily abandon the search for a "silver bullet" that will generate economic growth without the necessity of providing incentives for investment in tangible assets and human capital. Advocates of growth strategies based on capital formation will not readily give credence to claims of the importance of external benefits that "spill over" to beneficiaries that are difficult or impossible to identify.

The proposition that investment is a more important source of economic growth than productivity is just as controversial today as it was in 1973. The distinction between substitution and technical change emphasized by Solow (1957) parallels the distinction between investment and productivity as sources of economic growth. However, Solow's definition of investment, like that of Kuznets (1971), was limited to tangible assets. Both specifically excluded investments in human capital by relying on undifferentiated hours of work as a measure of labor input.

Kuznets (1971) and Solow (1957) identified the contribution of tangible assets with increases in the stock, which does not adequately capture substitution among different types of capital inputs. Constant-quality indices of both capital and labor inputs and investment goods output are essential for successful implementation of the production approach to economic growth. By failing to adopt these measurement conventions, Kuznets and Solow attributed almost all of U.S. economic growth to the Solow residual.[17]

To avoid the semantic confusion that pervades popular discussions of economic growth, it is essential to be precise in distinguishing between investment and productivity. Investment is the commitment of current resources in the expectation of future returns and can take a multiplicity of forms. This is the definition introduced by Fisher (1906) and discussed by Samuelson (1961). The distinctive feature of investment as a source of economic growth is that the returns can be internalized by the investor. The most straightforward application of this definition is to investments that create property rights, including rights to transfer the resulting assets and benefit from incomes that accrue to the owners.[18]

Investment in tangible assets provides the most transparent illustration of investment as a source of economic growth. This form of investment creates transferable property rights with returns that can be internalized. However, investment in intangible assets through research and development also creates intellectual property rights that can be transferred through outright sale or royalty arrangements and returns that can be internalized. Private returns to this form of investment—

[17] The measurement conventions of Kuznets and Solow remain in common use. See, for example, the references given in my 1990 article, "Productivity and Economic Growth," presented at The Jubilee of the Conference on Research in Income and Wealth, held in Washington, D.C., in 1988. For recent examples, see Martin Baily and Gordon (1988), Steven Englander and Axel Mittelstadt (1988), Olivier Blanchard and Stanley Fischer (1989), pp. 2–5, Baily and Charles Schultze (1990), Gordon (1990), Englander and Andrew Gurney (1994), and Lawrence Lau (1996).

[18] Fisher (1906) discusses property rights in Chapter 2, pp. 18–40.

returns that have been internalized—have been studied intensively in the literature surveyed by Griliches (1994, 1995) and Bronwyn Hall (1996).

The seminal contributions of Gary Becker (1993), Fritz Machlup (1962), Jacob Mincer (1974), and Theodore Schultz (1961) have given concrete meaning to the concept of "wealth in its more general sense" employed by Fisher (1906). This notion of wealth includes investments that do not create property rights. For example, a student enrolled in school or a worker participating in a training program can be viewed as an investor. Although these investments do not create assets that can be bought or sold, the returns to higher educational qualifications or better skills in the workplace can be internalized. The contribution of investments in education and training to economic growth can be identified in the same way as for tangible assets.

The mechanism by which tangible investments are translated into economic growth is well understood. For example, an investor in a new industrial facility adds to the supply of assets and generates a stream of rental income. The investment and the income are linked through markets for capital assets and capital services. The income stream can be divided between the increase in capital input and the marginal product of capital or rental price. The increase in capital contributes to output growth in proportion to the marginal product. This is the basis for construction of a constant-quality index of capital input.

Griliches (1973, 1979, 1995) has shown how investments in new technology can be translated into economic growth. An investor in a new product design or process of production adds to the supply of intellectual assets and generates a stream of profits or royalties. The increase in intellectual capital contributes to output growth in proportion to its marginal product in the same way as the acquisition of a tangible asset. However, investments in research and development, unlike those in tangible assets, are frequently internal to the firm, so that separation of the private return between the input of intellectual capital and the marginal product or rental price of this capital is highly problematical. The U.S. Bureau of Labor Statistics (1994) and Griliches have provided estimates of the contribution of these investments to economic growth.

Finally, an individual who completes a course of education or training adds to the supply of people with higher qualifications or skills. The resulting income stream can be decomposed into a rise in labor input and the marginal product of labor or wage rate. The increase in labor contributes to output growth in proportion to the marginal product. This provides the basis for constructing a constant-quality index of labor input. Although no asset markets exist for human capital, investments in human and nonhuman capital have the common feature, pointed out by Fisher (1906), that returns are internalized by the investor.

The defining characteristic of productivity as a source of economic growth is that the incomes generated by higher productivity are external to the economic activities that generate growth. These benefits "spill over" to income recipients not involved in these activities, severing the connection between the creation of growth and the incomes that result. Since the benefits of policies to create externalities cannot be appropriated, these policies typically involve government programs or activities supported through public subsidies. Griliches (1992, 1995) has provided detailed surveys of "spillovers" from investment in research and development.[19]

Publicly supported research and development programs are a leading illustration of policies to stimulate productivity growth. These programs can be conducted by government laboratories or financed by public subsidies to private laboratories. The justification for public financing is most persuasive for aspects of technology that cannot be fully appropriated, such as basic science and generic technology. The benefits of the resulting innovations are external to the economic units conducting the research and development, and these must be carefully distinguished from the private benefits of research and development that can be internalized through the creation of intellectual property rights.

An important obstacle to resolution of the debate over the relative importance of investment and productivity is that it coincides with ongoing disputes about the appropriate role for the public sector. Productivity can be identified with spillovers of benefits that do not provide incentives for actors within the private sector. Advocates of a larger role for the public sector advance the view that these spillovers can be guided into appropriate channels only by an all-wise and beneficent government sector. By contrast, proponents of a smaller government search for means to privatize decisions about investments by decentralizing investment decisions among participants in the private sector of the economy.

Kevin Stiroh and I (1995) have shown that investments in tangible assets are the most important sources of postwar U.S. economic growth. These investments appear on the balance sheets of firms, industries, and the nation as a whole as buildings, equipment, and inventories. The benefits appear on the income statements of these same economic units as profits, rents, and royalties. The BLS (1983) compiled an official constant-quality index of capital input for its initial estimates of total factor productivity, renamed as multifactor productivity.

The BLS retained hours worked as a measure of labor input until July 11, 1994, when it released a new multifactor productivity measure incorporating a constant-quality index of labor input as well as the BEA's (1986) constant-quality index for investment in computers. The final step

[19] Griliches (1992) also gives a list of survey papers on spillovers. Griliches (1979, 1995) has shown how to incorporate spillovers into a growth accounting.

in empirically implementing a constant-quality index of the services of tangible assets was the incorporation of Hulten-Wykoff (1982) relative efficiencies into the U.S. National Income and Product Accounts by the BEA (1995). Four decades of empirical research, initiated by Goldsmith's (1955-56) monumental treatise, *A Study of Saving,* have provided a sound empirical foundation for endogenizing investment in tangible assets.

Stiroh and I have shown that the growth of labor input is second in importance only to capital input as a source of economic growth. Increases in labor incomes have made it possible to measure investments in human capital and assess their contributions to economic growth. In 1989 Fraumeni and I extended the vintage accounting system developed in my 1973 paper with Christensen to incorporate these investments. Our essential idea was to treat individual members of the U.S. population as human assets with "asset prices" given by their lifetime labor incomes. Constant-quality indices of labor input are an essential first step in incorporating investments in human capital into empirical studies of economic growth. We implemented our vintage accounting system for both human and nonhuman capital for the United States on an annual basis for the period 1948 to 1984.

Asset prices for tangible assets can be observed directly from market transactions in investment goods; intertemporal capital asset pricing equations are used to derive rental prices for capital services. For human capital, wage rates correspond to rental prices and can be observed directly from transactions in the labor market. Lifetime labor incomes are derived by applying asset pricing equations to these wage rates. These incomes are analogous to the asset prices used in accounting for tangible assets in the system of vintage accounts I had developed with Christensen (1973).

Fraumeni and I have developed a measure of the output of the U.S. education sector, presented in Jorgenson and Fraumeni (1992b). Our point of departure was that while education is a service industry, its output is investment in human capital. We estimated investment in education from the impact of increases in educational attainment on the lifetime incomes of all individuals enrolled in school. We found that investment in education, measured in this way, is similar in magnitude to the value of working time for all individuals in the labor force. Furthermore, the growth of investment in education during the postwar period exceeded the growth of market labor activities.

Second, we have measured the inputs of the education sector, beginning with the purchased inputs recorded in the outlays of educational institutions, in Jorgenson and Fraumeni (1992a). A major part of the value of the output of educational institutions accrues to students in the form of increases in their lifetime incomes. Treating these increases as compensation for student time, we evaluated this time as an input into the educational process. Given the outlays of educational institutions and the value of student time, we allocated the growth of the education sector to its sources.

An alternative approach, employed by Schultz (1961), Machlup (1962), Nordhaus and Tobin (1972), and many others, is to apply Goldsmith's (1955–56) perpetual inventory method to private and public expenditures on educational services. Unfortunately, this approach has foundered on the absence of a satisfactory measure of the output of the educational sector and the lack of an obvious rationale for capital consumption. The approach fails to satisfy the conditions for integration of income and wealth accounts established by Fisher (1906) and Samuelson (1961).[20]

Given vintage accounts for human and nonhuman capital, Fraumeni and I (1989) have constructed a system of income, product, and wealth accounts, paralleling the system I had developed with Christensen. In these accounts the value of human wealth was more than 10 times the value of nonhuman wealth, while investment in human capital was five times investment in tangible assets. We defined "full" investment in the U.S. economy as the sum of these two types of investment. Similarly, we added the value of nonmarket labor activities to personal consumption expenditures to obtain "full" consumption. Our product measure included these new measures of investment and consumption.

Since our complete accounting system included a production account with "full" measures of capital and labor inputs, we were able to generate a new set of accounts for the *sources* of U.S. economic growth. Our system also included an income and expenditure account with income from labor services in both market and nonmarket activities. We combined this with income from capital services and allocated "full" income between consumption and saving.[21] This provided the basis for a new Measure of Economic Welfare and a set of accounts for the *uses* of U.S. economic growth. Our system was completed by a wealth account containing both human wealth and tangible assets.

We aggregated the growth of education and noneducation sectors of the U.S. economy to obtain a new measure of U.S. economic growth. Combining this with measures of input growth, we obtained a new set of accounts for the *sources* of growth of the U.S. economy. Productivity contributes almost nothing to the growth of the education sector and only a modest proportion to output growth for the economy as a whole. We also obtained a second approximation of the proportion of U.S. economic growth that can be made endogenous. Within a Ramsey model with separate education and noneducation sectors, we find that exogenous productivity growth accounts for only 17 percent of growth.

---

[20] For more detailed discussion, see Jorgenson and Fraumeni (1989).

[21] Our terminology follows that of Becker's (1965, 1993) theory of time allocation.

The introduction of endogenous investment in education increases the explanatory power of the Ramsey model of economic growth to 83 percent. However, it is important to emphasize that growth without endogenous investment in education is measured differently. The traditional framework for economic measurement of Kuznets (1971) and Solow (1970) excludes nonmarket activities, such as those that characterize the major portion of investment in education. The intuition is familiar to any teacher, including teachers of economics: What the students do is far more important than what the teachers do, even if the subject matter is the theory of economic growth.

A third approximation to the proportion of growth that could be attributed to investment within an extended Ramsey model results from incorporation of all forms of investment in human capital. This would include education, child rearing, and addition of new members to the population. Fertility could be made endogenous by using the approach of Robert Barro and Becker (1989) and Becker and Barro (1988). Child rearing could be made endogenous by modeling the household as a producing sector along the lines of the model of the educational sector I have outlined above. The results presented by Jorgenson and Fraumeni (1989) show that this would endogenize 86 percent of U.S. economic growth. This is a significant, but not overwhelming, gain in explanatory power for the Ramsey model.

In summary, endogenizing U.S. economic growth at the aggregate level requires a distinction between investment and productivity as sources of growth. There are two important obstacles to empirical implementation of this distinction. First, the distinctive feature of investment as a source of growth is that the returns can be internalized. Decisions can be successfully decentralized to the level of individual investors in human capital and tangible assets. Productivity growth is generated by spillovers that cannot be captured by private investors. Activities generating these spillovers cannot be decentralized and require collective decision-making through the public sector. Successive approximations to the Ramsey model of economic growth increase the proportion of growth that can be attributed to investment, rather than productivity.

Econometric Modeling

We are prepared, at last, for the most difficult and least glamorous part of the task of endogenizing economic growth—constructing quantitative models for the analysis of economic policies. The Ramsey growth model of Cass (1965) and Koopmans (1965) requires the empirical implementation of two highly problematical theoretical constructs, namely, a model of producer behavior based on an aggregate production function and a model of a representative consumer. Each of these abstracts from important aspects of economic reality, but both have important advantages in modeling long-term trends in economic growth.

My 1980 paper on "Accounting for Capital" presented a methodology for aggregating over sectors. The existence of an aggregate production function imposes very stringent conditions on production patterns at the industry level. In addition to value-added functions for each sector, an aggregate production function posits that these functions must be identical. Furthermore, the functions relating sectoral capital and labor inputs to their components must be identical and each component must receive the same price in all sectors.[22]

Although the assumptions required for the existence of an aggregate production function appear to be highly restrictive, Fraumeni and I estimated that errors of aggregation could account for less than 9 percent of aggregate productivity growth.[23] In 1987, Gollop, Fraumeni, and I published updated data on sectoral and aggregate production accounts in our book, *Productivity and U.S. Economic Growth.* We generated the data for sectoral production accounts in a way that avoids the highly restrictive assumptions of the aggregate production function. These data were then compared with those from the aggregate production account to test for the existence of an aggregate production function. We demonstrated that this hypothesis is inconsistent with empirical evidence. However, our revised and updated estimate of errors arising from aggregation over industrial sectors explained less than 3 percent of aggregate productivity growth over the period of our study, 1948 to 1979.[24]

Gollop, Fraumeni, and I also presented statistical tests of the much weaker hypothesis that a value-added function exists for each industrial sector, but this hypothesis was also rejected.[25] The conclusion of our research on production at the sectoral level was that specifications of technology such as the aggregate production function and sectoral valued-added functions result in substantial oversimplifications of the empirical evidence. However, these specifications are useful for particular but limited purposes. For example, sectoral value-added functions are indispensable for aggregating over sectors, while the aggregate production function is a useful simplification for modeling aggregate long-run growth, as originally proposed by Tinbergen (1942).

Sectoral value-added functions were employed by Hall (1988, 1990a)

---

[22] A detailed survey of econometric modeling of production is included in my 1986 paper, "Econometric Modeling of Producer Behavior." This is also the focus of Solow's 1967 survey article, "Some Recent Developments in the Theory of Production." The conceptual basis for the existence of an aggregate production function was provided by Robert Hall (1973).

[23] Fraumeni and Jorgenson (1980), Table 2.38, lines 4 and 11.

[24] Jorgenson, Gollop, and Fraumeni (1987), Table 9.5, lines 6 and 11.

[25] Jorgenson, Gollop, and Fraumeni (1987), Table 7.2, pp. 239–41. The existence of an aggregate production function requires *identical* value-added functions for all sectors.

in modeling production at the sectoral level. In measuring capital and labor inputs, he adhered to the traditional framework of Kuznets (1971) and Solow (1970) by identifying labor input with hours worked and capital input with capital stock. He found large, apparently increasing returns to scale in the production of value added.[26] Producer equilibrium under increasing returns requires imperfect competition. However, Susanto Basu and John Fernald (1996) have pointed out that the value-added data employed by Hall are constructed on the basis of assumptions of constant returns to scale and perfect competition.

Basu and Fernald (1996) have employed the strategy for sectoral modeling of production recommended in my book with Gollop and Fraumeni (1987), treating capital, labor, and intermediate inputs symmetrically. They estimate returns to scale for the sectoral output and input data presented in my 1990 paper to be constant. These data include constant-quality measures of capital, labor, and intermediate input. Basu and Fernald (1996) also show that returns to scale in the production of value added are constant, when value added is defined in the same way as in my book with Gollop and Fraumeni and constant-quality measures of capital and labor inputs are employed.

Data for individual firms provide additional support for value-added production functions with constant or even decreasing returns to scale. Estimates incorporating intellectual capital have been surveyed by Griliches (1994, 1995) and Bronwyn Hall (1996).[27] These estimates are now available for many different time periods and several countries. Almost all existing studies employ value-added data for individual firms and provide evidence for constant or decreasing returns to scale. This evidence is further corroborated by an extensive study of plant-level data by Martin Baily, Charles Hulten, and Donald Campbell (1992), providing evidence of constant returns at the level of individual manufacturing plants.

Turning to the task of endogenizing investment in tangible assets and education, we first review the endogenous accumulation of tangible assets. An important objective of the Christensen-Jorgenson (1973) accounting system was to provide the data for econometric modeling of aggregate producer and consumer behavior. In collaboration with Lawrence Lau, Christensen and I introduced an econometric model of producer behavior in 1973. We modeled joint production of consumption and investment goods from inputs of capital and labor services, utilizing data on these outputs and inputs from the aggregate production account.

---

[26] Hall (1990a) reports a median degree of returns to scale in value added for 2-digit U.S. manufacturing industries of 2.2!

[27] Bronwyn Hall (1996) gives a list of survey papers.

In 1975 Christensen, Lau, and I constructed an econometric model of a representative consumer behavior. We estimated this model on the basis of data from the aggregate income and expenditure account of the Christensen-Jorgenson (1973) accounting system. We tested and rejected the implications of a model of a representative consumer. Subsequently, Lau, Thomas Stoker, and I (1982) constructed a model of consumer behavior based on exact aggregation over individual consumers that specializes to the representative consumer model for a fixed distribution of total expenditure over the population of consumers.[28]

Yun and I (1986a, 1986b)) constructed an econometric model for post-war U.S. economic growth with endogenous accumulation of tangible assets. Our model of consumer behavior involved endogenous labor-leisure choice, following Tinbergen's (1942) neoclassical econometric model of economic growth. Labor-leisure choice is exogenous in Solow's (1956) neoclassical model. In addition, we employed the Ramsey (1928) representation of intertemporal preferences to model saving-consumption behavior, following Cass (1965) and Koopmans (1965). In Solow's model the saving ratio is exogenous.

The econometric application of Ramsey's model of optimal saving was initiated by Hall (1978), removing the final remaining gap between theoretical and empirical perspectives on economic growth.[29] This occurred only eight years after Solow's (1970) classic exposition of the neoclassical theory of growth! The key to Hall's achievement in 1978 was the introduction of an econometrically tractable concept of "rational expectations," which he successfully combined with Ramsey's theoretical model. Building on Hall's framework, Lars Hansen and Kenneth Singleton (1982, 1983) have tested and rejected the underlying model of a representative consumer.

Yun and I (1990) have revised and updated our econometric model of U.S. economic growth and analyzed the consequences of the Tax Reform Act of 1986. We also considered alternative proposals for fundamental tax reform, including proposals now under consideration by the U.S. Congress, such as consumption-based and income-based value-added taxes. We found that the 1986 Act resulted in a substantial increase in social welfare. However, we also discovered that several of the alternative proposals would have produced substantially higher gains.

The econometric model of U.S. economic growth I developed with Yun (1990, 1991a) provides the starting point for the endogenous growth model of the U.S. economy that I constructed with Ho (1995). While the

---

[28] A survey of empirical approaches to aggregation is given by Stoker (1993).

[29] Hall's 1978 paper and his subsequent papers on this topic have been reprinted in his 1990 book, *The Rational Consumer*. Hall (1990b) and Angus Deaton (1992) have presented surveys of the literature on econometric modeling of consumer behavior within the Ramsey framework.

model with Yun endogenized capital input, the endogenous growth model also endogenizes investment in human capital. This model includes all of the elements of our Ramsey model of U.S. economic growth. However, the new model also includes a highly schematic model of production for the U.S. educational system.

Our production model includes a production possibility frontier for the noneducation sector that is analogous to the frontier in my papers with Yun (1990, 1991a). The model also includes a production function for the education sector with investment in education as the output. The inputs include capital and labor services as well as purchases of goods and services from the noneducation sector. For both submodels, we allow for exogenous growth of productivity; however, Jorgenson and Fraumeni (1992a) show that this is negligible for the education sector.

Ho and I (1995) have evaluated alternative educational policies through the equivalent variation in wealth associated with each policy. As an *alternative case* we consider an educational policy that would raise the participation rates and policies, keeping taxes and expenditures constant. Presumably, this would result in a lower level of "quality." We also consider an *alternative case* that would retain the *base case* participation rates, but raise "quality" by increasing expenditures on consumption goods and capital and labor services in the education sector and the corresponding taxes. Eric Hanushek (1994) has shown that the second of these alternative policies, substantial improvement in educational quality through increased expenditure, is closely comparable to the actual educational policy pursued during the 1980s.

Ho and I (1995) have shown that increasing participation rates without altering expenditure would produce substantial gains in social welfare. In this sense the "quality" level of the existing educational system is too high to be cost-effective. On the other hand, increasing "quality" with no change in participation rates would result in a sizable loss in social welfare. These results are consistent with the literature on educational production functions surveyed by Hanushek (1986, 1989).[30]

With endogenous accumulation of tangible capital, as in the model I constructed with Yun (1986), almost three-quarters of growth is endogenous. By contrast, the model with endogenous investment in education I constructed with Ho (1995) accounts for 83 percent of growth. By endogenizing fertility behavior and child rearing it would be possible, at least in principle, to add an incremental 3 percentage points to the

[30] Note that the meaning of "production function" in this context is different from the meaning of this term in our model of the education sector. In Hanushek's terminology, the output of the education sector is measured in terms of measures of educational performance, such as graduation rates or test scores. Our terminology is closer to Hanushek's (1994) concept of "value-added" by the educational system. The output of the education system is the addition to the lifetime incomes of all individuals enrolled in school.

explanatory power of the Ramsey model of economic growth. Modeling population growth endogenously is clearly feasible. However, the construction of an econometric model with this feature would require considerable new data development and is best left as an opportunity for future research.

In summary, the endogenous models of growth I constructed with Yun (1986a, 1986b) and Ho (1995) require the econometric implementation of concepts of an aggregate production function and a representative consumer. While each of these concepts has important limitations, both are useful in modeling long-run economic trends. Furthermore, these concepts lead naturally to a substantial increase in the level of sophistication in data generation, integrating investment and capital into a complete system of national accounts.

CONCLUSION

The key innovation in economic measurement required for endogenizing growth is a wealth account that can be integrated with production and income and expenditure accounts. This encompasses the system of vintage accounts for tangible assets implemented in my work with Christensen (1973) as well as the vintage accounts for human capital I developed with Fraumeni (1989). These incorporate accumulation equations for tangible assets and human capital, together with asset-pricing equations. Both are essential in constructing *endogenous* models of growth to replace the *exogenous* models that emerged from the professional consensus of the early 1970s.

The framework for economic measurement developed in my work with Christensen (1973) and Fraumeni (1989) incorporates the principal features of the United Nations (1993) *System of National Accounts*. This provides a production account for allocating the *sources* of economic growth between investment and growth in productivity. It also includes an income and expenditure account for analyzing the *uses* of economic growth through consumption and saving. Alternative policies are ranked by means of equivalent variations in wealth for the representative consumer.

In principle, investment in new technology could be made endogenous by extending the accounting framework to incorporate investment in R&D. The BEA (1994) has provided a satellite system of accounts for research and development, based on Goldsmith's (1955-56) perpetual inventory method, applied to private and public expenditures. Unfortunately, this is subject to the same limitations as the approach to human capital of Schultz (1961) and Machlup (1962). The BEA satellite system has foundered on the absence of a satisfactory measure of the output of research and development and the lack of an appropriate rationale for capital consumption.

The standard model for investment in new technology, formulated by Griliches (1973), is based on a production function incorporating inputs of services from intellectual capital accumulated through investment in research and development. Intellectual capital is treated as a factor of production in precisely the same way as tangible assets in my work with Christensen (1973). Bronwyn Hall (1993) has developed the implications of this model for the pricing of the services of intellectual capital input and the evaluation of intellectual capital assets.[31]

Griliches (1973) represented the process of research and development by means of a production function that included the services of previous research and development. This captures the notion of "standing on the shoulders of giants," originated by Jacob Schmookler (1966) and elaborated by Riccardo Caballero and Adam Jaffe (1993) and Jones and Williams (1996). Under constant returns to scale, this representation also captures the "congestion externality" modeled by Jones and Williams and by Nancy Stokey (1995). Research and development, leading to investment in intellectual capital, is conducted jointly with production of marketable output, and this poses a formidable obstacle to measuring the output of new intellectual capital.

The model of capital as a factor of production that I first proposed in 1963 has been applied to tangible assets and human capital. However, successful implementation of this model for intellectual capital would require a system of vintage accounts including not only accumulation equations for stocks of accumulated research and development, but also asset pricing equations. These equations are essential for separating the revaluation of intellectual property due to price changes over time from depreciation of this property due to aging. This is required for measuring the quantity of intellectual capital input and its marginal product.

Pricing of intellectual capital is the key issue remaining before investment in new technology can be endogenized in quantitative models for the analysis of alternative economic policies. Bronwyn Hall (1993) has constructed prices for stocks of accumulated intellectual capital from stock market valuations of the assets of individual firms. However, she points out that the high degree of persistence in expenditures on research and development at the firm level has made it virtually impossible to separate the effects of the aging of assets from changes in the value of these assets over time. Her evaluation of intellectual capital is conditional upon a pattern of relative efficiencies imposed on past investments in new technology.

Nonetheless, Hall's pioneering research on pricing of intellectual assets has yielded interesting and valuable insights. For example, the

[31] These implications of the model are also discussed by Charles Jones and John Williams (1996).

gross rate of return in the computer and electronics industry, including depreciation and revaluation of these assets, greatly exceeds that in other industries. This can be rationalized by the fact that revaluation in this industry, as measured by Hall, is large and negative, mirroring the rapid decline in the price of the industry's output. This is evidence for the empirical significance of the process of creative destruction described by Joseph Schumpeter (1942) and modeled by Phillippe Aghion and Peter Howitt (1992), Stokey (1995), and Jones and Williams (1996). Since revaluation enters negatively into the gross rate of return, this rate of return exceeds that for industries with positive revaluations.

Another important result that emerges from Bronwyn Hall's (1996) survey of gross rates of return to research and development is the repeated finding that investment funded by the federal government has a zero private return. Even private firms conducting this research under government contract have been unable to internalize the returns. This has the very important policy implication that public investments in new technology can be justified only by comparisons of the costs and benefits to the government. Measurement of these benefits requires careful case studies like those of civilian space technology by Henry Herzfeld (1985) and commercial aircraft by David Mowery (1985). Grandiose visions of spillovers from public research and development have been exposed as a fleeting mirage.

The final issue that must be resolved in order to complete the endogenization of economic growth is modeling of spillovers. Griliches (1995) has provided a detailed survey of alternative methodologies and results, based on the model he originated in 1979. The essential idea is to include aggregate input of intellectual capital, together with the inputs of individual producers, as a determinant of output. Unfortunately, this requires precisely the same separation of marginal product and capital input for intellectual capital needed for the identification of returns that can be internalized by the individual producer.

Caballero and Richard Lyons (1990, 1992) have attempted to circumvent the problem of measuring intellectual capital by including aggregate output as a determinant of sectoral productivity. However, Basu and Fernald (1995) have shown that the positive results of Caballero and Lyons depend on the same value added data employed by Robert Hall (1988, 1990a). Treating capital, labor, and intermediate inputs symmetrically, as in their research on economies of scale, Basu and Fernald show that the evidence for spillovers evaporates. This leaves open the question of the importance of spillovers from investment in new technology, which must await satisfactory measures of the output of research and development.

An elegant and impressive application of the Griliches (1979) framework for modeling spillovers across international boundaries has been presented by David Coe and Elhanan Helpman (1995). The key idea is to trace the impact of these spillovers through trade in intermediate goods. For each country, the stock of accumulated research and development of its trading partners is weighted by bilateral import shares. However, Wolfgang Keller (1996) has shown that the evidence of spillovers is even more impressive if the bilateral trade shares are assigned randomly, rather than matched with the countries conducting the research and development. Another vision of spillovers can be assigned to the lengthening roll of unproven theoretical hypotheses.

In summary, a great deal has been accomplished, but much remains to be done to complete the endogenization of economic growth. An important feature of recent research, for example, in the seminal papers of Paul Romer (1986, 1987, 1990), has been the linking of theoretical and empirical investigations. This integration need no longer be left to the remarkable coincidence of empirical and theoretical perspectives that led Kuznets (1971) and Solow (1970) to the neoclassical framework. In the absence of a clear and compelling link between the theoretical model and the data generation process, the breakdown of this framework had left economists without a guide to long-run economic policy for two decades.

Fortunately, a new empirical and theoretical consensus on economic growth would require only a relatively modest reinterpretation of the neoclassical framework established by Solow (1956, 1970, 1988), Cass (1965), and Koopmans (1965). However, the traditional framework of economic measurement established by Kuznets (1961, 1971) and imbedded in the U.S. National Income and Product Accounts will have to be augmented considerably. The most important change is a reinterpretation of the concepts of investment and capital to encompass Fisher's (1906) notion of "wealth in its more general sense."

In closing, I must emphasize that my goal has been to provide a new starting point in the search for a consensus on economic growth, rather than to arrive at final conclusions. The new framework I have outlined is intended to be open-ended, permitting a variety of different approaches to investment—in tangible assets, human capital, and new technology. Ample, if carefully delimited, space is available within this framework for endogenizing spillovers, for example, by using the Lindahl-Samuelson theory of public goods. New entrants to the field will continue to find a plethora of opportunities for modeling economic growth.

References

Abramovitz, Moses. 1956. "Resource and Output Trends in the United States since 1870." *The American Economic Review*, vol. 46, no. 2 (May), pp. 5–23.

———. 1986. "Catching Up, Forging Ahead, and Falling Behind." *Journal of Economic History*, vol. 46, no. 2 (June), pp. 385–406.

Aghion, Phillippe and Peter Howitt. 1992. "A Model of Growth through Creative Destruction." *Econometrica*, vol. 60, no. 2 (March), pp. 323–51.

Baily, Martin N. and Robert J. Gordon. 1988. "Measurement Issues, the Productivity Slowdown, and the Explosion of Computer Power." *Brookings Papers on Economic Activity*, no. 2, pp. 1–45.

Baily, Martin N., Charles R. Hulten, and Donald Campbell. 1992. "Productivity Dynamics in Manufacturing Plants." *Brookings Papers on Economic Activity: Microeconomics*, vol. 1, pp. 187–267.

Baily, Martin N. and Charles L. Schultze. 1990. "The Productivity of Capital in a Period of Slower Growth." *Brookings Papers on Economic Activity: Microeconomics*, vol. 1, pp. 369–406.

Barro, Robert J. and Gary S. Becker. 1989. "Fertility Choice in a Model of Economic Growth." *Econometrica*, vol. 7, no. 2 (March), pp. 481–502.

Barro, Robert J. and Xavier Sala-i-Martin. 1994. *Economic Growth*. New York: McGraw-Hill.

Basu, Susanto and John G. Fernald. 1995. "Are Apparent Productive Spillovers a Figment of Specification Error?" *Journal of Monetary Economics*, vol. 36, no. 1 (August), pp. 165–88.

———. 1996. "Returns to Scale in U.S. Production: Estimates and Implications." *International Finance Discussion Papers*, No. 546, Board of Governors of the Federal Reserve System, March.

Baumol, William J. 1986. "Productivity Growth, Convergence, and Welfare: What the Long-Run Data Show." *The American Economic Review*, vol. 76, no. 5 (December), pp. 1072–85.

———. 1994. "Multivariate Growth Patterns: Contagion and Common Forces as Possible Sources of Convergence." In William J. Baumol, Richard R. Nelson, and Edward N. Wolff, eds., *Convergence of Productivity*, pp. 62–85. New York: Oxford University Press.

Becker, Gary S. 1965. "A Theory of the Allocation of Time. "*Economic Journal*, vol. 75, no. 296 (September), pp. 493–517.

———. 1967. "Human Capital and the Personal Distribution of Income: An Analytical Approach." Woytinsky Lecture No. 1, Institute of Public Administration, University of Michigan, Ann Arbor.

———. 1993. *Human Capital*, 3rd ed., (1st ed., 1964; 2nd ed., 1975). Chicago, IL: University of Chicago Press.

Becker, Gary S. and Robert J. Barro. 1988. "A Reformulation of the Economic Theory of Fertility." *Quarterly Journal of Economics*, vol. 103, no. 1 (February), pp. 1–25.

Berndt, Ernst R. 1991. *The Practice of Econometrics: Classic and Contemporary*. Reading, PA: Addison-Wesley.

Blanchard, Olivier J. and Stanley Fischer. 1989. *Lectures on Macroeconomics*. Cambridge, MA: The MIT Press.

Caballero, Riccardo J. and Adam B. Jaffe. 1993. "How High Are the Giants' Shoulders?: An Empirical Assessment of Knowledge Spillovers and Creative Destruction in a Model of Economic Growth." In O. J. Blanchard and S. Fischer, eds., *NBER Macroeconomics Annual 1993*, pp. 15–74. Cambridge, MA: The MIT Press.

Caballero, Riccardo J. and Richard K. Lyons. 1990. "Internal and External Economies in European Industries." *European Economic Review*, vol. 34, no. 4 (April), pp. 805–30.

———. 1992. "External Effects in U.S. Procyclical Productivity." *Journal of Monetary Economics*, vol. 29, no. 2 (April), pp. 209–26.

Carson, Carol and Steven Landefeld. 1994. "Integrated Economic and Environmental Satellite Accounts." *Survey of Current Business*, vol. 74, no. 4 (April), pp. 33–49.

Cass, David. 1965. "Optimum Growth in an Aggregative Model of Capital Accumulation." *Review of Economic Studies*, vol. 32(3), no. 91 (July), pp. 233–40.

Christensen, Laurits R. and Dale W. Jorgenson. 1969. "The Measurement of U.S. Real Capital Input, 1929–1967." *Review of Income and Wealth*, series 15, no. 4 (December), pp. 293–320.

———. 1970. "U.S. Real Product and Real Factor Input, 1929–1967." *Review of Income and Wealth*, series 16, no. 1 (March), pp. 19–50.

———. 1973. "Measuring Economic Performance in the Private Sector." In M. Moss, ed., *The Measurement of Economic and Social Performance*, pp. 233–338.

Christensen, Laurits R., Dianne Cummings, and Dale W. Jorgenson. 1981. "Relative Productivity Levels, 1947–1973." *European Economic Review*, vol. 16, no. 1 (May), pp. 61–94.

Christensen, Laurits R., Dale W. Jorgenson, and Lawrence J. Lau. 1973. "Transcendental Logarithmic Production Frontiers." *Review of Economics and Statistics*, vol. 55, no. 1 (February) pp. 28–45.

———. 1975. "Transcendental Logarithmic Utility Functions." *The American Economic Review*, vol. 65, no. 3 (June), pp. 367–83.

Coe, David T., and Elhanan Helpman. 1995. "International R&D Spillovers." *European Economic Review*, vol. 39, no. 5 (May), pp. 859–87.

Cole, Rosanne, Y. C. Chen, Joan A. Barquin-Stolleman, Ellen Dulberger, Nurhan Helvacian, and James H. Hodge. 1986. "Quality-Adjusted Price Indexes for Computer Processors and Selected Peripheral Equipment." *Survey of Current Business*, vol. 66, no. 1 (January), pp. 41–50.

Deaton, Angus. 1992. *Understanding Consumption*, pp. 76–135. Oxford: Oxford University Press.

Denison, Edward F. 1967. *Why Growth Rates Differ*. Washington, DC: The Brookings Institution.

———. 1974. *Accounting for United States Economic Growth*. Washington, DC: The Brookings Institution.

———. 1989. *Estimates of Productivity Change by Industry*. Washington, DC: The Brookings Institution.

Domar, Evsey. 1946. "Capital Expansion, Rate of Growth and Employment." *Econometrica*, vol. 14, no. 2 (April), pp. 137–47.

Dougherty, Chrys and Dale W. Jorgenson. 1996. "International Comparisons of the Sources of Economic Growth." *The American Economic Review*, vol. 86, no. 2 (May), pp. 25–29.

Douglas, Paul H. 1948. "Are There Laws of Production?" *The American Economic Review*, vol. 38, no. 1 (March) pp. 1–41.

Dulberger, Ellen. 1989. "The Application of a Hedonic Model to a Quality-Adjusted Index for Computer Processors." In D. W. Jorgenson and R. Landau, eds., *Technology and Capital Formation*, pp. 37–76. Cambridge, MA: The MIT Press.

Englander, A. Steven and Andrew Gurney. 1994. "OECD Productivity Growth: Medium-Term Trends." *OECD Economic Studies*, vol. 22 (Spring), pp. 111–30.

Englander, A. Steven, and Axel Mittelstadt. 1988. "Total Factor Productivity: Macroeconomic and Structural Aspects of the Slowdown." *OECD Economic Studies*, vol. 10 (Spring), pp. 7–56.

Fisher, Irving. 1906. *The Nature of Capital and Income*. New York: Macmillan.

Fraumeni, Barbara M. 1996. "The Measurement of Depreciation in the U.S. National Income and Wealth Accounts." *Survey of Current Business*, forthcoming.

Fraumeni, Barbara M. and Dale W. Jorgenson. 1980. "The Role of Capital in Economic Growth, 1948–1976." In G. M. von Furstenberg, ed., *Capital, Efficiency, and Growth*, pp. 9–250. Cambridge, MA: Ballinger.

Gilbert, Milton, Wilfred Beckerman, John Edelman, Stephen Marris, Gerhard Stuvel, and Manfred Teichert. 1958. *Comparative National Products and Price Levels*. Paris: OEEC.

Gilbert, Milton and Irving B. Kravis. 1954. *An International Comparison of National Products and the Purchasing Power of Currencies*. Paris: OEEC.

Goldsmith, Raymond. 1955–56. *A Study of Saving in the United States*, 3 Vols. Princeton, NJ: Princeton University Press.

———. 1962. *The National Wealth of the United States in the Postwar Period*. New York: National Bureau of Economic Research.

Gordon, Robert J. 1990. *The Measurement of Durable Goods Prices*. Chicago, IL: University of Chicago Press.

Griliches, Zvi. 1960. "Measuring Inputs in Agriculture: A Critical Survey." *Journal of Farm Economics*, vol. 40, no. 5 (December), pp. 1398–1427.

———. 1973. "Research Expenditures and Growth Accounting." In B. R. Williams, ed., *Science and Technology in Economic Growth*, pp. 59–95. London: Macmillan.

———. 1979. "Issues in Assessing the Contribution of Research and Development to Productivity Growth." *Bell Journal of Economics*, vol. 10, no. 1 (Spring), pp. 92–116.

———. 1992. "The Search for R&D Spillovers." *Scandinavian Journal of Economics*, vol. 94, Supplement, pp. 29–47.

———. 1994. "Productivity, R&D, and the Data Constraint." *The American Economic Review*, vol. 84, no. 1 (March), pp. 1–23.

———. 1995. "R&D and Productivity: Econometric Results and Measurement Issues." In P. Stoneman, ed., *Handbook of the Economics of Innovation and Technological Change*, pp. 52–89. Oxford: Basil Blackwell.

Grossman, Gene M. and Elhanan Helpman. 1991. *Innovation and Growth in the Global Economy.* Cambridge, MA: The MIT Press.

———. 1994. "Endogenous Innovation in the Theory of Growth." *Journal of Economic Perspectives*, vol. 8, no. 1 (Winter), pp. 23–44.

Hall, Bronwyn H. 1993. "Industrial Research during the 1980s: Did the Rate of Return Fall?" *Brookings Papers on Economic Activity: Microeconomics*, no. 2, pp. 289–330.

———. 1996. "The Private and Social Returns to Research and Development." In B. L. R. Smith and C. E. Barfield, eds., *Technology, R&D, and the Economy*, pp. 140–62. Washington, DC: The Brookings Institution and American Enterprise Institute.

Hall, Robert E. 1971. "The Measurement of Quality Change from Vintage Price Data." In Z. Griliches, ed., *Price Indexes and Quality Change*, pp. 240–71. Cambridge, MA: Harvard University Press.

———. 1973. "The Specification of Technology with Several Kinds of Output." *Journal of Political Economy*, vol. 81, no. 4 (July/August), pp. 878–92.

———. 1978. "Stochastic Implications of the Life Cycle-Permanent Income Hypothesis: Theory and Evidence." *Journal of Political Economy*, vol. 86, no. 6 (December), pp. 971–87.

———. 1988. "The Relation between Price and Marginal Cost in U.S. Industry." *Journal of Political Economy*, vol. 96, no. 5 (October), pp. 921–47.

———. 1990a. "Invariance Properties of Solow's Productivity Residual." In P. Diamond, ed., *Growth/Productivity/Employment*, pp. 71–112. Cambridge, MA: The MIT Press.

———. 1990b. *The Rational Consumer.* Cambridge, MA: The MIT Press.

Hall, Robert E. and Dale W. Jorgenson. 1967. "Tax Policy and Investment Behavior." *The American Economic Review*, vol. 57, no. 3 (June), pp. 391–414.

———. 1969. "Tax Policy and Investment Behavior: Reply and Further Results." *The American Economic Review*, vol. 59, no. 3 (June), pp. 388–401.

———. 1971. "Applications of the Theory of Optimal Capital Accumulation." In G. Fromm, ed., *Tax Incentives and Capital Spending*, pp. 9–60. Amsterdam: North-Holland.

Hansen, Lars P. and Kenneth J. Singleton. 1982. "Generalized Instrumental Variables Estimation of Nonlinear Rational Expectations Models." *Econometrica*, vol. 50, no. 6 (November), pp. 1269–86.

———. 1983. "Stochastic Consumption, Risk Aversion, and the Temporal Behavior of Stock Market Returns." *Journal of Political Economy*, vol. 91, no. 2 (April), pp. 249–65.

Hanushek, Eric A. 1986. "The Economics of Schooling." *Journal of Economic Literature*, vol. 24, no. 4 (December), pp. 1141–78.

———. 1989. "The Impact of Differential Expenditures on School Performance." *Educational Researcher*, vol. 18, no. 4 (May), pp. 45–51.

———. 1994. *Making Schools Work.* Washington, DC: The Brookings Institution.

Harrod, Roy. 1939. "An Essay in Dynamic Theory." *Economic Journal*, vol. 49, no. 194 (March), pp. 14–33.

Hertzfeld, Henry R. 1985. "Measuring the Economic Impact of Federal Research and Development Activities." Workshop on the Federal Role in Research and Development, National Academies of Science and Engineering, November 21–22.

Hulten, Charles R. and Frank C. Wykoff. 1982. "The Measurement of Economic Depreciation." In C. R. Hulten, ed., *Depreciation, Inflation and the Taxation of Income from Capital*, pp. 81–125.

Inter-Secretariat Working Group on National Accounts. 1993. *System of National Accounts 1993*, pp. 379–406. New York: United Nations.

Islam, Nasrul. 1995. "Growth Empirics: A Panel Data Approach." *Quarterly Journal of Economics*, vol. 110, no. 4 (November), pp. 1127–70.

Jones, Charles I. 1995a. "R&D-Based Models of Economic Growth." *Journal of Political Economy*, vol. 103, no. 4 (August), pp. 759–84.

———. 1995b. "Time Series Tests of Endogenous Growth Models." *Quarterly Journal of Economics*, vol. 110, issue 2 (May), pp. 495–526.

Jones, Charles I. and John C. Williams. 1996. "Too Much of a Good Thing? The Economics of Investment in R&D." Department of Economics, Stanford University, February 26.

Jorgenson, Dale W. 1963. "Capital Theory and Investment Behavior." *The American Economic Review*, vol. 53, no. 2 (May), pp. 247–59.

———. 1966. "The Embodiment Hypothesis." *Journal of Political Economy*, vol. 74, no. 1 (February), pp. 1–17.

———. 1967. "The Theory of Investment Behavior." In Ferber, R., ed., *Determinants of Investment Behavior*, pp. 129–55. New York: Columbia University Press.

———. 1973. "The Economic Theory of Replacement and Depreciation." In W. Sellekaerts, ed., *Econometrics and Economic Theory*, pp. 189–221, New York: Macmillan.

———. 1980. "Accounting for Capital." In G.M. von Furstenberg, ed., *Capital, Efficiency, and Growth*, pp. 251–319, Cambridge, MA: Ballinger.

———. 1986. "Econometric Modeling of Producer Behavior." In Z. Griliches and M. D. Intriligator, eds., *Handbook of Econometrics*, vol. 3, pp. 1841–1915. Amsterdam: North-Holland.

———. 1990. "Productivity and Economic Growth." In E. R. Berndt and J. Triplett, eds., *Fifty Years of Economic Measurement*, pp. 19–118. Chicago, IL: University of Chicago Press.

———. 1996 "Empirical Studies of Depreciation." *Economic Inquiry*, vol. 34, no. 1 (January), pp. 24–42.

Jorgenson, Dale W. and Barbara M. Fraumeni. 1989. "The Accumulation of Human and Nonhuman Capital, 1948–1984." In R. E. Lipsey and H. S. Tice, eds., *The Measurement of Saving, Investment, and Wealth*, pp. 227–82. Chicago, IL: University of Chicago Press.

———. 1992a. "Investment in Education and U.S. Economic Growth." *Scandinavian Journal of Economics*, vol. 94, Supplement, pp. 51–70.

———. 1992b. "The Output of the Education Sector." In Z. Griliches, ed., *Output Measurement in the Services Sector*, pp. 303–38. Chicago, IL: University of Chicago Press.

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

Jorgenson, Dale W. and Zvi Griliches. 1967. "The Explanation of Productivity Change." *Review of Economic Studies*, vol. 34, no. 99 (July), pp. 249–80.

Jorgenson, Dale W. and Mun S. Ho. 1995. "Modeling Economic Growth." Harvard University, Department of Economics.

Jorgenson, Dale W., Mun S. Ho, and Barbara M. Fraumeni 1994. "The Quality of the U.S. Work Force, 1948–90." Harvard University, Department of Economics.

Jorgenson, Dale W., Lawrence J. Lau, and Thomas M. Stoker. 1982. "The Transcendental Logarithmic Model of Aggregate Consumer Behavior." In R. L. Basmann and G. Rhodes, eds., *Advances in Econometrics*, vol. 1, pp. 97–238. Greenwich, CT: JAI Press.

Jorgenson, Dale W. and Kevin Stiroh. 1995. "Computers and Growth." *Economics of Innovation and New Technology*, vol. 3 (December), pp. 295–316.

Jorgenson, Dale W. and Kun-Young Yun. 1986a. "The Efficiency of Capital Allocation." *Scandinavian Journal of Economics*, vol. 88, no. 1, pp. 85–107.

———. 1986b. "Tax Policy and Capital Allocation." *Scandinavian Journal of Economics*, vol. 88, no. 2, pp. 355–77.

———. 1990. "Tax Reform and U.S. Economic Growth." *Journal of Political Economy*, vol. 98, no. 5, part 2 (October), pp. 151–93.

———. 1991a. "The Excess Burden of U.S. Taxation." *Journal of Accounting, Auditing, and Finance*, vol. 6, no. 4 (Fall), pp. 487–509.

———. 1991b. *Tax Reform and the Cost of Capital*, pp. 1–38. Oxford: Oxford University Press.

Keller, Wolfgang. 1996. "Are International R&D Spillovers Trade-Related? An Analysis Using Monte-Carlo Techniques." Department of Economics, University of Wisconsin, Madison, March 16.

Koopmans, Tjalling C. 1965. "On the Concept of Optimum Growth." In *The Econometric Approach to Development Planning*, pp. 225–300. Chicago, IL: Rand-McNally.

Kravis, Irving B., Alan Heston, and Robert Summers. 1978. *International Comparisons of Real Product and Purchasing Power*. Baltimore, MD: Johns Hopkins University Press.

Kuznets, Simon. 1961. *Capital in the American Economy*. Princeton, NJ: Princeton University Press.

———. 1971. *Economic Growth of Nations*. Cambridge, MA: Harvard University Press.

———. 1992. "Modern Economic Growth: Findings and Reflections." In A. Lindbeck, ed., *Nobel Lectures: Economic Sciences, 1969-1980*, pp. 87–102.

Lau, Lawrence J. 1996. "The Sources of Long-Term Economic Growth: Observations from the Experience of Developed and Developing Countries." In R. Landau, T. Taylor, and G. Wright, eds., *The Mosaic of Economic Growth*, pp. 63–91. Stanford, CA: Stanford University Press.

Levine, Ross and David Renelt. 1992. "A Sensitivity Analysis of Cross-Country Growth Regressions." *The American Economic Review*, vol. 82, no. 4 (September), pp. 942–63.

Lindbeck, Assar. 1992. ed., *Nobel Lectures in Economic Sciences, 1969–1980*. River Edge, NJ: World Scientific Publishing Company.

Lucas, Robert E. 1988. "On The Mechanics of Economic Development." *Journal of Monetary Economics*, vol. 22, no. 1 (July) pp. 2–42.

Machlup, Fritz. 1962. *The Production and Distribution of Knowledge in the United States*. Princeton, NJ: Princeton University Press.

Maddison, Angus. 1982. *Phases of Capitalist Development*. Oxford: Oxford University Press.

———. 1991. *Dynamic Forces in Capitalist Development*. Oxford: Oxford University Press.

———. 1995. *Monitoring the World Economy, 1820–1992*. Paris: Organisation for Economic Co-operation and Development.

Maler, Karl-Goran. 1992. *Nobel Lectures in Economic Sciences, 1981–1990*. River Edge, NJ: World Scientific Publishing Company.

Mankiw, N. Gregory, David Romer, and David Weil. 1992. "A Contribution to the Empirics of Economic Growth." *Quarterly Journal of Economics*, vol. 107, no. 2 (May), pp. 407–37.

Mincer, Jacob. 1974. *Schooling, Experience, and Earnings*. New York: Columbia University Press.

Mowery, David C. 1985. "Federal Funding of R&D in Transportation: The Case of Aviation." Workshop on the Federal Role in Research and Development, National Academies of Science and Engineering, November 21–22.

Nordhaus, William D. and James Tobin. 1972. *Is Growth Obsolete?* New York, National Bureau of Economic Research; reprinted in M. Moss, ed., *The Measurement of Economic and Social Performance*, 1973, pp. 509–32. New York: Columbia University Press.

Pieper, Paul E. 1989. "Construction Price Statistics Revisited." In D. W. Jorgenson and R. Landau, eds., *Technology and Capital Formation*, pp. 293–330. Cambridge, MA: The MIT Press.

———. 1990. "The Measurement of Construction Prices: Retrospect and Prospect." In E. R. Berndt and J. Triplett, eds., *Fifty Years of Economic Measurement*, pp. 239–68. Chicago, IL: University of Chicago Press.

Ramsey, Frank. 1928. "A Mathematical Theory of Saving." *Economic Journal*, vol. 28, no. 112 (December), pp. 543–59.

Rebelo, Sergio. 1991. "Long-Run Policy Analysis and Long-Run Growth." *Journal of Political Economy*, vol. 99, no. 3 (June), pp. 500–521.

Romer, Paul. 1986. "Increasing Returns and Long-Run Growth." *Journal of Political Economy*, vol. 94, no. 5 (October), pp. 1002–37.

———. 1987. "Crazy Explanations for the Productivity Slowdown." In Stanley Fischer, ed., *NBER Macroeconomics Annual*, pp. 163–201. Cambridge, MA: The MIT Press.

———. 1990. "Endogenous Technological Change." *Journal of Political Economy*, vol. 98, no. 5, part 2 (October), pp. S71–S102.

———. 1994. "The Origins of Endogenous Growth." *Journal of Economic Perspectives*, vol. 8, no. 1 (Winter), pp. 3–20.

Samuelson, Paul A. 1961. "The Evaluation of 'Social Income': Capital Formation and Wealth." In F. A. Lutz and D. C. Hague, eds., *The Theory of Capital*, pp. 32–57. London: Macmillan.

Schmookler, Jacob. 1966. *Invention and Economic Growth.* Cambridge, MA: Harvard University Press.

Schumpeter, Joseph. 1942. *Capitalism, Socialism, and Democracy.* New York: Harper.

Schultz, Theodore W. 1961. "Investment in Human Capital." *The American Economic Review,* vol. 51, no. 1 (March), pp. 1–17.

Solow, Robert M. 1956. "A Contribution to the Theory of Economic Growth." *Quarterly Journal of Economics,* vol. 70, no. 1 (February), pp. 65–94.

———. 1957. "Technical Change and the Aggregate Production Function." *The Review of Economics and Statistics,* vol. 39, no. 3 (August), pp. 312–20.

———. 1960. "Investment and Technical Progress." In K. J. Arrow, S. Karlin, and P. Suppes, eds., *Mathematical Methods in the Social Sciences, 1959,* pp. 89–104. Stanford, CA: Stanford University Press.

———. 1970. *Growth Theory: An Exposition.* New York: Oxford University Press.

———. 1967. "Some Recent Developments in the Theory of Production." In Brown, M., ed., *The Theory and Empirical Analysis of Production,* pp. 25–50. New York: Columbia University Press.

———. 1988. "Growth Theory and After." *The American Economic Review,* vol. 78, no. 3 (June), pp. 307–17.

———. 1992. *Growth Theory,* 2nd ed. New York: Oxford University Press.

———. 1994. "Perspectives on Growth Theory." *Journal of Economic Perspectives,* vol. 8, no. 1 (Winter), pp. 45–54.

Stoker, Thomas M. 1993. "Empirical Approaches to the Problem of Aggregation over Individuals." *Journal of Economic Literature,* vol. 31, no. 4 (December), pp. 1827–74.

Stokey, Nancy L. 1995. "R&D and Economic Growth." *Review of Economic Studies,* vol. 62, no. 3 (July), pp. 469–89.

Stone, Richard. 1984. "The Accounts of Society." In K.-G. Maler, ed., 1992, *Nobel Lectures in Economic Sciences, 1981–1990,* pp. 115–39.

Summers, Robert, and Alan Heston. 1984. "Improved International Comparisons of Real Product and Its Composition: 1950–1980." *Review of Income and Wealth,* series 30, no. 2 (June), pp. 207–62.

———. 1988. "A New Set of International Comparisons of Real Product and Price Levels: Estimates for 130 Countries, 1950–1985." *Review of Income and Wealth,* series 34, no. 1 (March), pp. 1–25.

———. 1991. "The Penn World Table (Mark 5): An Expanded Set of International Comparisons, 1950–1988." *Quarterly Journal of Economics,* vol. 106, issue 2 (May), pp. 327–68.

Summers, Robert, Irving B. Kravis, and Alan Heston. 1980. "International Comparisons of Real Product and Its Composition, 1950–77." *Review of Income and Wealth,* series 26, no. 1 (March), pp. 19–66.

Tinbergen, Jan. 1942. "On the Theory of Trend Movements." In Jan Tinbergen, *Selected Papers,* Amsterdam, North-Holland, 1959, pp. 182–221 (translated from "Zur Theorie der Langfristigen Wirtschaftsentwicklung," *Weltwirtschaftliches Archiv,* Band 55, Nu. 1, 1942, pp. 511–49).

Triplett, Jack. 1986. "The Economic Interpretation of Hedonic Methods." *Survey of Current Business,* vol. 66, no. 1 (January), pp. 36–40.

———. 1989. "Price and Technological Change in a Capital Good: Survey of Research on Computers." In D. W. Jorgenson and R. Landau, eds., *Technology and Capital Formation,* pp. 127–213. Cambridge, MA: The MIT Press.

———. 1990. "Hedonic Methods in Statistical Agency Environments: An Intellectual Biopsy." In E. R. Berndt and J. Triplett, eds., *Fifty Years of Economic Measurement,* pp. 207–38.

———. 1996. "Measuring the Capital Stock: A Review of Concepts and Data Needs." *Economic Inquiry,* vol. 34, no. 1 (January), pp. 93–115.

United Nations. 1968. *A System of National Accounts.* New York: United Nations.

———. 1993. *System of National Accounts 1993.* New York: United Nations.

U.S. Bureau of Economic Analysis. 1982. *Measuring Nonmarket Economic Activity: BEA Working Papers,* U.S. Bureau of Economic Analysis Working Paper 2. Washington, DC: U.S. Department of Commerce, December.

———. 1986. "Improved Deflation of Purchases of Computers." *Survey of Current Business*, vol. 66, no. 3 (March), pp. 7–9.
———. 1994. "A Satellite Account for Research and Development." *Survey of Current Business*, vol 74. no. 11 (November), pp. 37–71.
———. 1995. "Preview of the Comprehensive Revision of the National Income and Product Accounts: Recognition of Government Investment and Incorporation of a New Methodology for Calculating Depreciation." *Survey of Current Business*, vol. 75, no. 9 (September), pp. 33–41.
U.S. Bureau of Labor Statistics. 1983. *Trends in Multifactor Productivity*, Bulletin 2178. Washington, DC: U.S. Department of Labor.
———. 1993. *Labor Composition and U.S. Productivity Growth, 1948–90*, Bulletin 2426. Washington, DC: U.S. Department of Labor.
———. 1994. "Multifactor Productivity Measures, 1991 and 1992." *News Release USDL 94-327*, July 11.
U.S. Office of Business Economics. 1966. *The National Income and Product Accounts of the United States, 1929–1965, A Supplement to the Survey of Current Business*. Washington, DC: U.S. Department of Commerce.
World Bank. 1994. *World Development Report 1993*. Washington, DC: World Bank.
Young, Allan. 1989. "BEA's Measurement of Computer Output." *Survey of Current Business*, vol. 69, no. 7 (July), pp. 108–15.

DISCUSSION

Susanto Basu*

Dale Jorgenson has written a provocative and challenging paper based on many years of research on theory and measurement. He takes a position that challenges important elements of both the neoclassical growth theory of the 1960s and 1970s and the "New Growth" theory of the 1980s. He adopts the standard neoclassical framework of an aggregate production function with constant returns to scale, perfect competition, and no externalities or spillovers between firms. On the other hand, he agrees with the basic tenet of New Growth theory that long-run growth rates should be "endogenous"—explained by economic forces—instead of being taken as exogenous to the economic system. In this paper, Jorgenson argues that a slightly augmented version of Robert Solow's (1957) growth-accounting framework is sufficient to explain all of postwar economic growth as the outcome of purposeful investment.[1] In particular, one need not invoke "exogenous technological progress." To understand the ambition of this project, note that Solow found that capital accumulation explained only 12.5 percent of per capita output growth, with the remainder attributed to exogenous changes in technology!

In order to assess the success of Jorgenson's project, I want to ask how well his framework does at explaining three fundamental questions of growth theory.

- Why does per capita income increase over time?

*Assistant Professor of Economics, University of Michigan.

[1] In Jorgenson's lexicon, "investment" means that all returns are appropriated by the investor, in a model that has perfect competition. Understanding this terminology is important, since the New Growth theory also explains all growth as the outcome of capital accumulation, but must invoke either increasing returns or spillovers to do so.

- Why are some countries rich and others poor?
- Why has economic growth slowed down in developed countries?

The framework that Jorgenson uses leaves him very few degrees of freedom—a virtue in any scientific hypothesis. Thus, his answers to all three questions must be, "Variations in the quality and quantity of investment in a standard neoclassical setting." The setting is that of a standard constant-returns production function for every producer (and therefore for the economy):

$$Y = AF(K, L, T), \tag{1}$$

where K is capital, L is labor, and T stands for technology. As noted, we assume constant returns to scale, perfect competition, and no spillovers. This is the standard setting of growth accounting and productivity measurement using the Solow (1957) residual:

$$\Delta p = \Delta y - \alpha_L \Delta l - (1 - \alpha_L)\Delta k. \tag{2}$$

Lowercase letters represent natural logarithms and α_L is the share of labor income in national income. Under Jorgenson's conditions, Δp is proportional to Δt. To simplify matters, assume that a fixed fraction of national output is devoted to capital accumulation:

$$\Delta K = s_K Y - \delta_K K. \tag{3}$$

So far, everything is standard neoclassical theory. Unlike Solow, however, Jorgenson does not allow for exogenous change in technology. In his framework, "technology" is just knowledge (a shorthand for R&D and other forms of human capital), and knowledge is a form of capital that is accumulated like any other. 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. These two positions can be summed up as special cases of the following general equation:

$$\Delta T = (s_T Y)T^{\phi} - \delta_T T. \tag{4}$$

ϕ indexes the size of knowledge spillovers—the degree to which previous knowledge reduces the cost of accumulating new knowledge. Jorgenson holds that $\phi = 0$; note that in this case equation (4) is an exact analog of equation (3), so there is nothing special about knowledge capital. On the other hand, New Growth theory requires very strong spillovers: At a minimum, it needs $\phi = 1$.

Both of these extreme positions have some unpleasant implications. Jorgenson's position implies that, in the long run, no per capita output growth can occur (since his model has capital accumulation as the only source of growth, but the marginal product of capital is diminishing). This seems to contradict both recent human experience (since the Industrial Revolution) and very long-run experience (the rise in living standards since Neolithic times). On the other hand, the parameters of the New Growth theory imply that the long-run growth rate of per capita output depends on the rate of saving in knowledge. Jones (1995) shows that postwar time series data for the United States and other advanced economies reject this implication.

However, as Jones (1995) points out, a whole range of intermediate positions is possible: We can have $0 < \phi < 1$. An intermediate position of this sort is consistent with many studies that find significant positive spillovers to R&D investment, and with our intuition that something is indeed special about knowledge. It also avoids both the counterfactual implications noted above. The intermediate model predicts that long-run per capita growth will occur, but says that this growth rate is not influenced by policy.

But while I believe that the data do not fully support Jorgenson's answer to the first question, I think his answer is closer to being correct than either the neoclassical model or the New Growth model. In particular, his conclusion—that growth is driven by investment but growth *rates* are not—is robust to adding spillovers of moderate size.

It is in answering the second question, however, that Jorgenson's framework shows greater problems. The recent work of Islam (1995) shows that production functions seem to differ significantly across countries: That is, differences in capital per worker seem insufficient to explain cross-country differences in output per worker. Thus, we need a modification of equation (1):

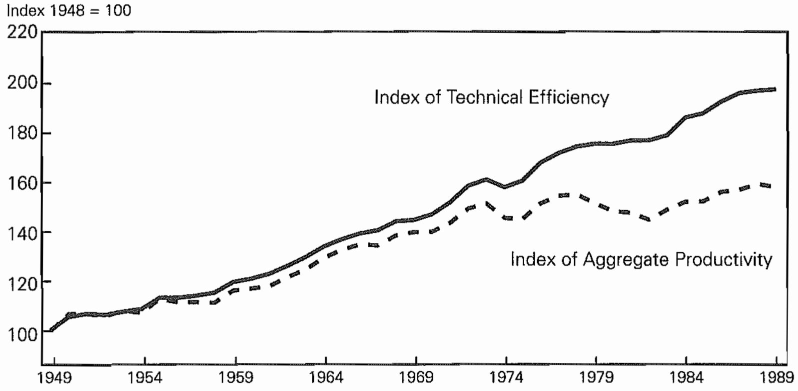
$$Y_i = A_i F(K, L, T), \tag{5}$$

where i indexes "location." What are the economics of "location"? In the context of cross-country growth, it is easy to identify "location" with geography. But in the sense that matters for economics, location means a factor that is relevant for production. Such factors can certainly be country-specific—for example, political and legal institutions—but they probably also have a great deal to do with technology diffusion and infrastructure, factors that can vary even within countries (and sometimes be approximately constant across countries).

These cross-country results suggest that we augment the Jorgenson "Quality, Quantity" paradigm with one other factor: "Quality, Quantity, Location." I conclude by asking whether location in the sense I have defined it might matter for short-run productivity dynamics within countries—for example, the productivity slowdown that has been the focus of much public discussion.

Figure 1

A Comparison of Productivity Growth and Technological Change



Location matters if identical factors of production have different marginal products in different uses. In the context of within-country differences, location might matter if different sectors (firms, industries) have different degrees of market power or different returns to scale, or pay identical workers different wages. Basu and Fernald (1995) discuss these ideas in detail. Their conclusion can be summarized as saying that a gap exists between productivity change and technology change, and this gap comes from factor reallocation:

$$\Delta p = \Delta t + R. \tag{6}$$

Recall that Δp is productivity growth and Δt is technology change. R stands for "reallocation." One implication of equation (6) is that changes in the growth rate of productivity may not represent changes in the growth rate of technology, as most of the discussion surrounding the productivity slowdown assumes. Instead, a change in the growth rate of productivity may represent a change in the allocation of inputs over time. This is an important conjecture to examine, since the policy responses to the two would likely be quite different.

Using the methods of Basu and Fernald (1995), I construct the *R* in equation (6). To allow for a trend break in *R* around the time of the productivity slowdown, I estimate *R* separately over two subsamples: 1949 to 1969, and 1970 to 1989. Subtracting the implied series for *R* from the series for productivity growth defined in equation (2) yields the implied series for technology change. Figure 1 presents the results. As the figure shows, the calculations imply that changes in input allocation accounted for the bulk of the productivity slowdown, with only a small reduction in the growth rate of technology. This calculation is subject to all of the caveats noted by Basu and Fernald (1995), but it is at least suggestive.

To summarize, Dale Jorgenson has written a paper that shows the explanatory power of standard neoclassical theory when combined with careful measurement. For the reasons I have outlined, I think that model will need to be augmented by allowing for small knowledge spillovers and a modest degree of imperfect competition. Nevertheless, the amended model will retain much of the flavor of the neoclassical framework, particularly in the conclusion that economic policy does not determine the rate of long-term growth. However, policy may have an important effect on the *level* of output (and hence welfare), and thus is likely to be far from irrelevant.

References

Basu, Susanto and John G. Fernald. 1995. "Aggregate Productivity and the Productivity of Aggregates." International Finance Discussion Paper No. 532, Board of Governors of the Federal Reserve System, December.

Islam, Nazrul. 1995. "Growth Empirics: A Panel Data Approach." *Quarterly Journal of Economics*, vol. 110, no. 4 (November), pp. 1127–70.

Jones, Charles I. 1995. "R&D-Based Models of Economic Growth." *Journal of Political Economy*, vol. 103, no. 4 (August), pp. 759–84.

Solow, Robert M. 1957. "Technical Change and the Aggregate Production Function." *The Review of Economics and Statistics*, vol. 39, no. 3 (August), pp. 312–20.

Discussion

Gene M. Grossman*

Despite the title of his paper, Dale Jorgenson devotes relatively few words to elucidating the place of technology in growth theory. Many of what I consider to be the most important questions about technology and growth are not addressed. Therefore, I will devote most of my space to explaining how I would have interpreted the topic "technology in growth theory," while addressing a few comments to the particulars of his paper, in passing.

It seems to me that one could ask four levels of questions about the place and treatment of technology in growth theory. First:

- Is technological progress needed to sustain growth? That is, can and would growth continue indefinitely if more and more of the tangible factors could be accumulated but there were no improvements in the ability to combine these factors in producing final output?

As we now know, and in fact as Bob Solow knew already in 1956, growth can be sustained with an unchanging technology provided there are no long-run diminishing returns to the accumulable factors of production. That is, if as physical and human capital are accumulated indefinitely, their rates of return remain bounded above some minimum level, then growth can and will continue without any technological progress.

While we cannot know for sure whether or not this condition applies, both a priori reasoning and the available econometric evidence suggest

*Jacob Viner Professor of International Economics, Woodrow Wilson School of Public and International Affairs, Princeton University.

that it does not. On a priori grounds, it is easy to think of factors that are available in relatively fixed supply that should impart decreasing returns to those that can be accumulated. I am thinking in particular of natural endowments—land, water, minerals, fuels, and the like—but "raw" labor might become another constraining factor at some point. The econometric evidence presented by, for example, Mankiw, Romer, and Weil (1992) points to rather significant diminishing returns to physical and human capital, even if both types of capital accumulate together.

A simple thought experiment might make the issue more concrete. Imagine how the world economy would have evolved if none of the major inventions of the last 200 years had materialized—no steam engine, no electricity, no transistors, no computers, and so on. Would growth have proceeded nonetheless thanks to investments in ever more capital (more field animals and hand instruments?) and continued increases in levels of schooling?

Parenthetically, I would remark that growth accounting, no matter how carefully conducted, cannot shed light on this question. The reason is that growth accounting is just that—an *accounting* procedure, but not a structural model. It is easiest to see the point at the sectoral level, using the approach favored by Jorgenson and his coauthors, which includes intermediate goods as well as capital and labor as factors used in producing gross output. Suppose we observe that output of the automobile industry has doubled, that inputs of steel have doubled, and that steel accounts for 50 percent of the value of a car. Growth accountants would claim that they have "explained" half of the growth of output already; I would claim that they have explained nothing. Knowing that steel inputs have increased does not tell us why output has expanded, or whether it would have expanded under some alternative counterfactual scenario. Rather, steel inputs increased because firms wanted to produce more cars, for some other reason.

Similarly, observing that physical and human capital inputs have expanded does not tell us why growth has occurred, or whether it would have occurred absent technological progress. Individuals invest in these assets in the expectation of making a return, and until we explain the determinants and evolution of that return we have not explained the associated growth. In other words, the statement that investment is more important in the growth process than productivity increases is a meaningless one, unless one believes that investments happen autonomously.

The second question I would ask about the role of technology in growth theory is as follows:

- Is technological progress the result of intentional (economic) activities or not? That is, is it endogenous to the economic system or exogenously determined?

Here again the verdict is still out, but my own view is that a lot of technological progress is endogenous. For one thing, firms in the United States now spend more than 100 billion dollars per year in activities labeled as formal R&D. Presumably, they are being driven to do so by a profit motive, and they believe they are getting something for their money. The more convincing evidence, to me, comes from looking across time and across space. Baumol (1990) provides a compelling account of how the allocation of entrepreneurial effort to innovation has varied across historical epochs and how this variation seems to align closely with the types of incentives confronting these entrepreneurs. And the great variation in productivity levels across regions and countries also seems to relate to the nature of the various economic environments and the rules of the game.

Let me remark briefly on an often-heard comment, which is also implicit in many of the growth accounting exercises: that R&D is too small a percentage of GDP to be an important determinant of technological progress and growth. It is true that an allocation of 2 to 3 percent of output per year, even with high rates of return, can directly account for only a small fraction of aggregate output growth. But again, the accounting perspective is not the correct one. In our 1994 *Journal of Economic Perspectives* article, Elhanan Helpman and I report a simple back-of-the-envelope calculation to show that a small amount of R&D might drive a good deal of growth, once the investments in capital that are undertaken to implement the new innovations are taken into account.

Jorgenson confuses the issue, I feel, when he equates identifying the "sources of growth" with "endogenizing" growth. He believes that it is important to allocate the sources of growth between investment and productivity, and that the part of output expansion that can be accounted for by investment has been endogenized, whereas productivity growth (the residual) remains exogenous. I would rather reserve the words "endogenous growth" for growth that can be traced to its fundamental economic determinants. An accounting procedure that attributes output growth to investment has not endogenized growth, unless the factors that generate incentives for investment are also explained. On the other hand, growth that can be traced to productivity increases might be endogenous, if the productivity increases themselves can be tied convincingly to economic activities.

The third question I would ask is this:

- Is formal R&D responsible for most technological progress?

Here I would guess the answer is "probably not." One negative observation is that made by Charles Jones (1995): Formal R&D, as measured by either the number of scientists and engineers engaged in R&D or business spending on R&D, has been growing steadily and rapidly in the postwar period, while rates of total factor productivity growth and per capita output growth have not (on a related point, see Hall 1993). Also, declining R&D does not seem to explain the productivity slowdown that occurred after 1973 (Griliches 1988). Undoubtedly, many activities contribute to firms' productivities besides their formal R&D. Mansfield (1988) notes that Japanese firms have devoted as much as 40 percent of the cost of developing new products to activities that would be categorized as "process engineering"; for example, to tooling and manufacturing equipment and facilities. Even more informal activities—what the theory literature might designate as "learning by doing"—have been found to be empirically important in many industries. And improvements in the organization of firms and production also contribute significantly to productivity gains.

The theoretical literature on endogenous innovation so far has concentrated on formal R&D. I would guess that this has more to do with what theorists feel they know how to model than it does with any empirical assessment of what is more or less important. I could easily imagine growth theory evolving to a richer specification of the various activities firms undertake to improve their productivity.

The fourth and final question on my list, and the one that seems to interest Jorgenson the most, concerns the normative implications of our models of growth. In particular:

- Is the level of investment in new technologies determined by market forces the socially optimal one? Would welfare or growth rates rise dramatically if we promoted more R&D? And is the R&D tax credit, or another similar subsidy scheme, the appropriate way to do so?

As is well known, the normative questions hinge on the existence or not of positive spillovers in the process of creating knowledge. Griliches (1992) distinguishes two types of spillovers. Rent spillovers arise if innovating firms cannot act as perfectly discriminating monopolists and thereby capture all of the consumer-surplus benefits from their new and better products in the form of increased prices. Knowledge spillovers occur if learning activities undertaken by one set of agents make research more productive for others, and if the latter group does not need to compensate the former for these benefits.

Jorgenson clearly is suspicious of such spillovers. He explains how investments in R&D create "intellectual assets" which yield private returns in the form of profits and royalties. And he notes that an "increase in intellectual capital contributes to output growth in proportion to its marginal product in the same way as the acquisition of a tangible asset." Both of these points are of course correct. But intellectual capital is different from physical capital, certainly in degree if not in kind. Whereas the property rights to physical capital can easily be defined and enforced, the property rights for intellectual capital are notoriously difficult to protect. And whereas physical capital is a "rival input" in the sense that it can only be used in one place at one time, intellectual capital is "nonrival" inasmuch as the same knowledge can be deployed in many places simultaneously. Therefore, while investments in intellectual capital can and do generate private returns, the scope for social returns in excess of private returns far exceeds that for other types of investment.

A myriad of studies have attempted to measure spillovers by examining different firms, industries, and countries, using a variety of case-study and econometric techniques. These studies have been surveyed many times, for example, by Griliches (1992) and Mairesse and Mohnen (1995). The specific findings vary widely, and the many methodological problems would shake one's confidence in any single one of them. Nonetheless, most of the studies find private rates of return in excess of 20 percent and social rates of return more than twice as high as the private rates. Moreover, the estimated rates of return are invariably higher than those found in the same studies for physical capital. All of this leads Griliches to conclude:

> In spite of all these 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 (1992, p. S43).

Even so, one cannot immediately conclude that there is too little innovation. As Aghion and Howitt (1992) and Grossman and Helpman (1991) have shown, the existence of positive knowledge spillovers from R&D is not sufficient for the conclusion that it would be socially beneficial to allocate greater resources to this activity; in markets with imperfect competition, firms might invest too much in R&D if their private benefits came largely from taking business from their rivals rather than from expanding the size of the social pie. But calibration exercises performed by Stokey (1995) and Jones and Williams (1996) suggest that this caveat probably has more bite in theory than it does in practice.

The question of whether an R&D tax credit or another subsidy is a good way to encourage industrial innovation is a different one entirely. Many observers (for example, Mansfield 1986) believe that an R&D tax credit does as much or more to encourage firms to redefine their activities as R&D as it does to promote greater innovation effort. And even if the government could somehow monitor R&D expenses closely, it is not at all clear that the social return to this sort of learning activity exceeds that for the other things that firms do in their efforts to enhance their productivity.

Jorgenson seems to believe that growth accounting can shed light on the appropriateness of R&D promotion and other similar policy problems. In particular, he associates "spillovers" with the size of the Solow residual. I fail to see this correspondence. There might be a sizable residual in aggregate growth accounting due to, for example, an important component of exogenous technological progress, and yet no spillovers from research activities and no call for (economic) policy intervention in the growth process. Alternatively, the residual might be reasonably small, and yet spillovers large and government intervention very much warranted. The latter could occur if the well-known problems of measuring product quality meant that actual output growth were greater than what is measured, or if a relatively small amount of total factor productivity growth were sufficient to induce a great deal of investment in physical and human capital.

CONCLUSION

Let me summarize my own feelings about the role of technology in growth theory as follows. First, there is no reason at all to deny or diminish the accomplishments of neoclassical growth theory. Undoubtedly, understanding the incentives for investment are important for understanding growth. But so too, I would argue, is understanding the incentives for innovation, the more so the longer the growth horizon. The neoclassical model, with its built-in assumptions of constant returns to scale and perfect competition, is not well suited for studying innovation. Investments in knowledge are up-front investments that naturally imply increasing returns to scale in production. Firms cover these fixed costs by charging prices in excess of marginal cost. Therefore, there is little choice but to study innovation in a setting that allows for imperfect competition, despite the ambiguities in policy advice that this implies. Growth theory has made some modest progress along these lines in recent years, but much more remains to be done.

REFERENCES

Aghion, Philippe and Peter Howitt. 1992. "A Model of Growth through Creative Destruction." *Econometrica*, vol. 60, no. 2 (March), pp. 323–51.

Baumol, William J. 1990. "Entrepreneurship: Productive, Unproductive and Destructive." *Journal of Political Economy*, vol. 98, pp. 893–921.

Griliches, Zvi. 1988. "Productivity Puzzles and R&D: Another Nonexplanation." *Journal of Economic Perspectives*, vol. 2, pp. 9–21.

———. 1992. "The Search for R&D Spillovers." *Scandinavian Journal of Economics*, vol. 94, Supplement, pp. 29–47.

Grossman, Gene M. and Elhanan Helpman. 1991. "Quality Ladders in the Theory of Growth." *Review of Economic Studies*, vol. 58, pp. 43–61.

———. 1994. "Endogenous Innovation in the Theory of Growth." *Journal of Economic Perspectives*, vol. 8, no. 1 (Winter), pp. 23–44.

Hall, Bronwyn H. 1993. "Industrial Research During the 1980's: Did the Rate of Return Fall?" *Brookings Papers on Economic Activity*, Microeconomics, no. 2, pp. 289–330.

Jones, Charles I. 1995. "R&D-Based Models of Economic Growth." *Journal of Political Economy*, vol. 103, no. 4 (August), pp. 759–84.

Jones, Charles I. and John C. Williams. 1996. "Too Much of a Good Thing? The Economics of Investment in R&D." HIID Discussion Paper No. 538, Harvard University.

Mairesse, Jacques and Pierre Mohnen. 1995. "Research and Development and Productivity: A Survey of the Econometric Literature." Mimeo.
Mankiw, N. Gregory, David Romer, and David Weil. 1992. "A Contribution to the Empirics of Economic Growth." *Quarterly Journal of Economics*, vol. 107, no. 2 (May), pp. 407–37.
Mansfield, Edwin. 1986. "The R&D Tax Credit and Other Technology Policy Issues." *The American Economic Review*, vol. 76 (May), Papers and Proceedings, pp. 190–94.
———. 1988. "Industrial Innovation in Japan and the United States." *Science*, vol. 241, pp. 1769–74.
Stokey, Nancy L. 1995. "R&D and Economic Growth." *Review of Economic Studies*, vol. 62, no. 3 (July), pp. 469–89.