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MODELING LONG-RUN ECONOMIC GROWTH

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Abstract

This paper reviews the recent empirical literature on long-run growth to determine what factors influence growth in total factor productivity (TFP) and whether there are any channels of influence that should be added to standard models of long-run growth. Factors affecting productivity fall into three general categories: physical capital, human capital, and innovation (including other factors that might influence TFP growth). Recent empirical evidence provides little support for the idea that there are extra-normal returns to physical capital accumulation, nor is there solid justification for adding a separate channel of influence from capital to TFP growth. The paper finds evidence that human capital—as distinct from labor hours worked—is an important factor for growth but also that there is not yet a consensus about exactly how it should enter the model. Some argue that human capital should enter as a factor of production, while others argue that it merely spurs innovation. The forces governing TFP growth are not well understood, but there is evidence that R&D spending is a significant contributor and that its benefit to society may exceed its benefit to the company doing the spending—that is, it is a source of spillovers. The paper concludes with some examples of how standard models of growth could be modified to reflect some of the channels of influence identified in the empirical review.

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INTRODUCTION

Long-run economic growth is the key determinant of living standards over time and among countries. Despite its importance, economists do not have complete answers to some fundamental questions about long-run growth. Why were living standards essentially stagnant for thousands of years, before accelerating rapidly in certain European countries during the Industrial Revolution? Why are some countries twenty or thirty times as wealthy as others? Long-run growth is of interest to the Congressional Budget Office (CBO) as it analyzes a number of long-run issues, including possible future burdens on the economy of the growing number of retirees and their medical costs.

In 1994, CBO published an evaluation of models in the endogenous growth literature, which were put forward as an alternative to the more traditional neoclassical model. That study concluded that the balance of evidence did not support discarding the neoclassical model in favor of a newer one. In fact, the best of the new theories, namely those that model the factors that explain technological change, can be interpreted as extensions of the neoclassical model rather than as replacements for it.

Since that paper was released, there has been a steady stream of empirical investigations of the sources of long-run growth. That body of empirical work provides CBO with an opportunity to update its models of economic growth with new insights. In addition, CBO is developing a new model that will be used to analyze Social Security and other issues related to the budget outlook over a 75-year horizon. In so doing, CBO will have to make a host of choices about how to model long-run economic growth, including the specification of the production function, the values of key parameters, and the channels of influence for changes in government policy. The latter issue is particularly important since the major purpose of the model will be to analyze the effects of fiscal policy on the economy. Although improving CBO's models for making baseline projections is an important task in and of itself, a major challenge facing CBO is to develop a better understanding of the economic effects of changes of policy. With those considerations in mind, have any new channels of influence been uncovered that should be included in the new model?

CBO's current projections for real gross domestic product (GDP) come from a neoclassical (Solow) growth model in which the saving rate (including net saving from abroad) determines the rate of investment which, in turn, determines the growth in the amount of capital per worker in the economy. (For a given saving rate, growth of per-capita income is driven by growth of total factor productivity—TFP—in the long run).[1] The key advantage of this model is that it is a simple, robust model that

[1] Total factor productivity is average real output per unit of combined labor and capital input. The growth of TFP is defined as the growth of real output that is not explained by the growth of labor and capital.

automatically captures the effects of changes in the rate of saving (including changes in government saving). It also produces results that are intuitive and relatively transparent. The primary disadvantage of the model is that it is silent on the determinants of TFP growth, which is projected using a deterministic time trend.

In contrast, the endogenous growth literature offers the prospect of perpetual growth in output per capita that does not rely on exogenous growth in TFP. Although all endogenous growth models share the same basic idea—they lack the Solow model's restrictive property that growth in per-capita output can only be increased temporarily when an economy shifts to a higher rate of saving and investment—they rely on different mechanisms to drive long-run growth. Some focus on explaining technological change, while others modify the structure of the model so that investment in physical or human capital sustains growth. These models are of interest to policymakers because they imply that some policy changes can have much larger effects on growth in the long run than the Solow model would predict.[2]

This paper reviews the recent empirical literature on long-run growth and productivity to determine what factors, if any, influence productivity growth. The intent is not to revisit the debate on endogenous versus neoclassical growth but instead to identify channels of influence that drive the growth in labor productivity and TFP. Are there any lessons from the recent literature that can inform our modeling effort? Are there any promising areas of research where CBO should concentrate its efforts?

One possible channel of influence runs through the stock of physical capital. Some economists noticed that the observed empirical correlation between the investment share of GDP and long-run growth in real GDP (or TFP) was larger than would be predicted by the Solow growth model. The elevated correlation could be the result of externalities, or spillovers, from the installation and use of physical capital. If true, such spillovers would suggest a long-run model with a coefficient on capital that is higher than the Solow model's or a model with a direct link from capital to TFP growth. However, estimates of the correlation between investment and growth have been criticized on econometric grounds; researchers have found that such estimates are sensitive to the specification of the regression and they are not statistically significant after controlling for simultaneity bias. Stronger evidence against this type of model comes from its inability to account for the conditional convergence of income per (effective) worker observed among regions and certain countries.[3]

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2 See CBO (1994) for a more complete discussion of the neoclassical model and several examples of endogenous growth models.

3 Convergence is a process by which economies with low levels of per-capita output grow faster than those with higher levels. The Solow model predicts conditional convergence: economies that are identical in terms of parameters such as tastes and technology will converge to the same steady-state level of output per capita.

Human capital will undoubtedly play an important role in any convincing theory of long-run growth. The key question is how it should enter the model. Some would argue that it should be a separate factor of production while others would argue that it spurs innovation. There is not yet a consensus about how human capital should be modeled, and further, any approach would have to rely on imperfect measures of human capital. However, some researchers have included human capital in empirical growth models, and CBO could follow a similar approach.

It is generally agreed that innovation is the fundamental source of true (as opposed to measured) technological change.[4] However, data are scarce, making it difficult to empirically evaluate models of endogenous innovation. Researchers rely on public and private R&D expenditures—a subset of innovative effort—because that is where data exist. Empirical evidence indicates that the social rate of return to R&D is higher than the private rate of return, suggesting the possibility that R&D spending by one company benefits other companies in the economy. Although measuring the degree of spillovers is quite challenging, the consensus seems to be that they do exist and could be quite large. Some researchers have developed models that link R&D spending to growth, and CBO could do the same.

Channels of Influence

The resurgence of interest in long-run growth, spurred in part by Paul Romer's 1986 paper suggesting the possibility of endogenous growth, has brought to light many possible channels of influence that could be used to model productivity growth. The channels of influence fall into three general categories, physical capital, human capital and total factor productivity. One recurring question is whether a particular variable has a spillover or externality associated with it. If so, then the Solow model underestimates the coefficient on that variable and, therefore, its contribution to growth.

Physical Capital. Accumulation of physical capital is at the heart of the growth mechanism in the neoclassical model and the core of the production sector in CBO's models of medium-term and long-term growth. After the neoclassical model was developed, economists devised a method to estimate the contributions of the factor inputs (labor and capital) to the growth of output. Early efforts found that a large fraction of growth, over 40 percent by some estimates, went unexplained by the inputs and had to be attributed to TFP and, by implication, technological progress. This finding called into question the usefulness of the neoclassical model since the model does not address the causes of technological progress. Subsequent refinements, however, have reduced the proportion of unexplained growth and point to a

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[4] Growth in TFP is often interpreted as technological change, which it is if all of the assumptions of the neoclassical model are satisfied and if all concepts are measured correctly. However, in practice, TFP growth reflects technological change and anything else that causes GDP growth to exceed the growth attributed to labor and capital.

larger contribution from the inputs, and from capital in particular.[5]

CBO's projections for real GDP growth, because they rely on models built on the neoclassical framework, incorporate the effects of changes in saving and investment. For example, changes in government policy that affect investment—by changing national saving or through other channels—will affect output by changing the size of the capital stock. Similarly, changes in the outlook for business investment that are not the result of policy changes will also influence the long-run rate of growth through their impact on capital accumulation.

The explosion of empirical research spurred by the endogenous growth revolution hinted that the influence of saving and investment was more powerful than was assumed by the neoclassical model. During the 1980s, researchers found a strong correlation between the ratio of investment to GDP and economic growth in cross-section regressions across countries. That is, countries with high rates of investment during the post-war period tended to grow faster than those that did not.[6] That correlation is not inconsistent with the Solow model, which predicts a positive relationship between real GDP growth and the investment rate, at least during the transition from one steady state to another.[7] Once the economy completes the transition to a new steady state, the effect of capital accumulation tapers off and only TFP growth raises per-capita GDP, according to the neoclassical model.

However, some researchers noticed that the correlation between growth and investment was larger than would be predicted by the neoclassical model. That finding led them to question one of the model's fundamental assumptions, that the coefficient on capital in the model's production function is equal to capital's share in income. Instead, they speculated that there were externalities or spillovers associated with investment and that the coefficient on capital was larger than what was assumed by the neoclassical model.[8] That observation led some to propose the so-called "AK" endogenous growth model, in which output is modeled as a function of a single input, capital. Others interpreted the evidence to mean that capital has

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5 See Denison (1967) for an example of an early growth accounting estimate. Dale Jorgenson has been responsible for many of the subsequent refinements. See, for example, Jorgenson (1990), Jorgenson, Gollop, and Fraumeni (1987), and Christensen and Jorgenson (1970).

6 See, for example, Paul Romer (1987), Kormendi & Meguire (1985), and Levine and Renelt (1992). DeLong and Summers (1991) argue that equipment investment is the category that has extra-normal returns.

7 Note that the Solow model predicts a positive relationship between real GDP growth and the *saving rate*. Since data on the saving rate is unavailable for a wide sample of countries, most researchers use the investment rate as a proxy for the saving rate.

8 Romer (1987) suggested the possibility of such spillovers, but later returned his focus to spillovers associated with knowledge. See also Romer (1994). If the spillover is large enough, then endogenous growth is possible. CBO (1994) provides a more complete description of so-called "AK" models of endogenous growth.

two influences, a direct one through the factor input and an indirect one via TFP. Empirical studies have documented a positive correlation between investment and TFP growth, which is consistent with the idea that there is a second channel of influence.[9]

Such a finding would be significant because it would overcome one of the primary shortcomings of the neoclassical model, namely the inability to explain large differences in per-capita income across countries. According to the neoclassical model, differences in the level of per-capita output across countries must stem from one of two forces: increases in either the amount of capital per worker or increases in TFP. Researchers have found that differences in per-capita output across countries are much larger than what can be explained by differences in capital per worker.[10] Hence those relying on the neoclassical model must attribute the rest of the differences to TFP, which is exogenous in the neoclassical model. New growth models do not have to rely on unexplained TFP growth to generate large differences in per-capita output. In 1994, CBO concluded that, although such work was in its infancy, empirical research did not support the idea of spillovers to physical capital (and, by implication, the AK model).

The intervening years have not provided compelling empirical evidence to revise that view. Although it is hard to reject almost any hypothesis convincingly using macro data, empirical evidence released since 1994 has not favored the idea of extra-normal returns to capital. The evidence has not overturned the observed correlation between capital and growth—it is one of the more robust correlations to be found in cross-sectional regression. However, it probably does not arise because of spillovers.

There are several reasons to be skeptical of the idea that the high correlation between capital and growth implies the existence of spillovers to physical capital. First, microeconomic evidence of such spillovers is lacking. It is not clear why a new machine installed in one factory should benefit the productivity of a machine installed in another. (Knowledge embodied in a new machine would have widespread benefits, but that is a separate issue). One possible justification, known as learning-by-doing, is that knowledge is created as a by-product of the production of new capital goods, which implies that productivity increases along with investment.[11]

Second, it is possible that the strong correlation may arise in part because some technological change is embodied in new capital goods. If the price indexes

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9 See Dowrick & Nguyen (1989), Wolff (1991) and Bernanke & Gurkaynak (2001).

10 See Lucas (1990), D. Romer (1996), Temple (1999).

11 Romer (1986) used the stock of physical capital as a proxy for the stock of knowledge.

used to deflate investment spending are not adjusted for changes in quality, then any technological change that is embodied in capital goods will not be captured in the capital stock and will show up in TFP. The U.S. adjusts the prices of some investment goods for quality change in its national accounts, but most countries do not adjust any. If foreign countries followed the U.S. in their measurement of investment prices, then some of their economic growth that is currently attributed to the residual would be moved into the capital input. Since the component that gets moved would be correlated with investment, this shift would probably lower the correlation between TFP and the investment ratio in cross-sectional regressions.

Third, the correlation between the investment ratio and growth could arise because of the influence of an unobserved third variable. Technological progress would be an obvious example. A country experiencing rapid technical change would not only have faster TFP growth, but would have many profitable investment opportunities. That combination could cause the country to have a high investment share and rapid real growth over prolonged periods, perhaps as long as several decades. In addition, the rapid technological change would likely reduce the relative price of capital goods, encouraging further investment.[12]

Another reason to be suspicious of the correlation between physical capital and growth is that changes in the method used to estimate this correlation have reduced its magnitude. Early estimates found a very strong correlation between physical investment—especially equipment investment—and growth in output, which was interpreted by some as evidence of spillovers.[13] It appears that this conclusion was premature. Subsequent research showed that, although it is one of the more robust correlations in the growth literature, it is not as strong as early estimates indicated. Moreover, it does not necessarily imply an inconsistency with the neoclassical model. For example, changing the specification of the basic growth regression equation by adding explanatory variables—meant to control for differences in the fundamental characteristics of different economies—or estimating the equation using instrumental variables reduces the statistical significance of the investment ratio in cross-sectional regressions.[14] In addition, the idea that equipment investment conveys extra-normal returns has lost favor in light of evidence that the relationship is not robust to changes in sample. For example, the relationship holds for a sample that include both high- and low-growth countries, but not for a sample that includes only OECD nations, or for a sample of LDCs if it excludes Botswana.[15]

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12 For more on the link between technology and the output elasticity of investment, see Benhabib and Jovanovic (1991) or Benhabib and Spiegel (1994).

13 See Romer (1986) and DeLong and Summers (1991).

14 See Barro and Sala-i-Martin (1995), p. 434.

15 See Auerbach et. al. (1994).

Aside from questions about whether the correlation implies the presence of spillovers, there are reasons to question whether the correlation is valid in the first place. First and foremost is the problem of simultaneity bias, which arises because these regressions probably violate an assumption of ordinary least squares (OLS)—that the explanatory variables and the equation's error term are independent. For example, the rate of investment is a function of, among other things, output growth. If so, any unobserved shock to productivity that raises output could indirectly raise investment, inducing a correlation between an explanatory variable (the investment rate) and the error term in the output equation. Under these circumstances, output and capital are simultaneously determined, and OLS estimates of the coefficient on investment will be biased. Simultaneity bias is a concern for many explanatory variables in cross-sectional growth regressions, but is particularly acute for investment.[16] This problem is most pronounced in time-series regression equations, but it also affects cross-sectional regressions using data that has been averaged over long periods, such as the ones described above.

The presence of simultaneity bias means that one cannot be certain about the direction of causality between the investment ratio and the rate of growth. One would expect a positive correlation based on the Solow model, at least for economies on the transition path, because an increase in the saving rate would raise investment and the capital stock, which in turn raises output. Hence, the original interpretation was that the positive correlation implied that causality runs from the investment ratio to growth. However, investment is clearly endogenous, and using a cross-sectional regression with data averaged over long periods may not totally avoid the statistical problems caused by using an endogenous variable on the right-hand-side of a regression equation. Some analysts have concluded from the empirical evidence that causation runs in the other direction: faster growth causes countries to save more, which in turn raises the rate of investment.[17] This question is by no means settled, but it raises a red flag about the correlation between investment and growth.

One of the primary motivations of the literature examining cross-sectional regressions was to determine whether economies converged, as predicted by the Solow model. Convergence, or catch-up, is a process by which poor countries (those with low levels of per-capita GDP) grow faster than rich counties. Evidence of convergence would constitute another strike against the AK model because it predicts no convergence of any sort. A vast literature arose during the 1990s in which researchers used cross-sectional regressions of growth across countries to examine the convergence question. A consensus in favor of convergence emerged from that

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16 This concern has been used repeatedly in surveys of the empirical growth literature. See, for example, McGratten and Schmitz (1999) or Temple (1999).

17 See Barro & Sala-i-Martin (1995). For related work, see , Carroll et. al. (2000), Attanasio et. al. (2000), Blomstrom, Lipsey, and Zejan (1996), and Carroll and Weil (1994). Note that this is an empirical regularity. Some theoretical models of consumption behavior predict the opposite result—faster income growth will cause people to save less.

literature, at least from the studies that included variables in the regressions to control for differences in steady states across countries.[18] Convergence of this sort is known as "conditional convergence" and is entirely consistent with the neoclassical model of growth. It implies that countries with wider gaps between per-capita output and its steady-state level will grow faster than those with smaller gaps.

Even stronger evidence comes from studies of conditional convergence that use data from regional data sets (e.g., states, provinces or prefectures within a single country or region). These studies are important because the data sets better correspond to the assumptions that underlie the Solow model, meaning that the regions are more similar in terms of their preferences, endowments, and, most importantly, access to technology. Essentially, regressions that use regional data implicitly control for 'other' factors without the need to include regressors that measure those other factors. Cross-section regressions that use regional data sets find solid evidence that poorer regions tend to catch up to richer regions, meaning that areas with lower levels of capital per worker grow faster than areas with higher levels, on average.[19] This is stronger evidence of convergence than cross-sectional regressions that use country-level data.[20]

Corroborating evidence supporting the existence of convergence comes from other studies that employ time-series methods instead of cross-section estimates. Most of the evidence relating to the question of convergence and the returns to physical capital comes from cross-sectional regressions, which use data averaged over long periods for individual countries or regions within countries. Their results stem from the differences across countries in certain variables, generally finding, for example, that countries with higher average rates of investment have grown more quickly during the post-war period than countries with lower rates of investment. In contrast, time-series studies rely on differences in certain variables through time, either in a single country or for a collection of countries.

For example, regressions using panel data from a variety of countries exploit variation in the long-run growth rates of individual countries while allowing researchers to relax the assumption (implicit in most cross-section regressions) that aggregate production functions are identical across countries. Instead of assuming a common production technology, panel data studies allow for country-specific effects, meaning differences in tastes or technology across countries. Ignoring such effects will bias the estimated coefficients in an OLS regression if the effects are

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18 The empirical literature on convergence is enormous. For surveys, see CBO (1994), Pack (1994), Barro and Sala-i-Martin (1995) and Temple (1999).

19 See Barro & Sala-i-Martin (1995).

20 Arnold Harberger quipped that you can't make too much of "regression lines that draw much of their slope from the differences between Sudan and Switzerland." See Harberger (1998), p.21.

correlated with other explanatory variables. Panel data studies generally provide strong support for the idea of conditional convergence, although their results differ with respect to the speed at which convergence occurs.[21]

Other types of time-series evidence can be used to examine the predictions of endogenous growth models. For example, some endogenous growth models predict the existence of "scale" effects, meaning that permanent increases in the levels of certain variables can lead to a permanent increase in an economy's *growth rate*, rather than a permanent increase in the *level* of real GDP. In the AK model, for example, the presence of constant returns to physical capital ensures that an increase in the investment ratio will permanently raise the growth rate. If true, that property suggests that policy actions can have very powerful effects on living standards in the long run. However, the prediction of scale effects appears to be at odds with the time-series evidence in both the U.S. and in the larger group of OECD economies. Specifically, there has been a steady upward movement through time in the rate of gross investment in the United States and other OECD countries without any concomitant increase in the rate of economic growth.[22]

To summarize, the best evidence suggests that the neoclassical model, with its assumption of decreasing returns to physical capital, is appropriate for analyzing and projecting long-run economic growth. This is Jonathan Temple's conclusion in his review of the "New Growth" evidence in a 1999 *Journal of Economic Literature* survey. He states that the "strongest result in the investment-growth literature is that the returns to physical capital are almost certainly diminishing, in agreement with the Solow-Swan growth model and most theoretical work since."[23] Although it is difficult to reject any hypothesis decisively in the area of long-run growth, the empirical evidence favors models that assume decreasing returns to physical capital rather than models that assume constant returns or externalities.

Human Capital. Economists have long recognized that human capital plays a major role in long-run economic growth. Workers who are better educated and trained are better able to perform their tasks, to solve problems, and to embrace the latest production techniques. Indeed, human capital can be viewed as the fundamental source of technological progress since it is the means by which the stock of knowledge is embodied and transmitted. Human capital allows less-developed

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[21] See Islam (1995), Evans (1998), Evans and Karras (1996), Caselli, *et. al.* (1996), Lee *et. al.* (1997), Knight *et. al.* (1993), and Duffy and Papageorgiou (2000). Among these studies, only the paper by Caselli *et. al.* attempts to correct for simultaneity bias as well as country-specific effects.

[22] See Jones (1995). The evidence for the OECD countries is less conclusive, but Jones notes that those economies were much more heavily affected by the two World Wars. McGrattan (1998) argues that there is a positive correlation if one uses a longer historical sample and a broader definition of physical investment.

[23] See Temple (1999), p.138.

countries to imitate, and thereby to catch up to, countries at the technological frontier. Undoubtedly, human capital will play a key role in any convincing theory of long-run growth, but it is not yet clear how it should be modeled. Does human capital operate through the factor inputs? Or is it a separate factor of production? Or does it influence TFP growth, by affecting a country's ability to innovate? Or is there perhaps a spillover associated with human capital, in which an increase in the economy-wide stock of human capital raises the productivity of all workers, even those who didn't receive any extra training or education.

The microeconomic evidence is fairly clear: workers with more education are better paid than those with less education. Estimates of the return to education vary slightly through time and across countries and are bit higher for women than for men, but standard regression equations show that each additional year of schooling raises earnings by roughly 10 percent.[24] These estimates come from generally-accepted micro-based equations that relate earnings to education (among other variables) and generally fit the data well.

A natural implication of these results is that a country could raise its long-run growth rate if it were able to raise the average educational attainment of it population. Unfortunately, that implication doesn't necessarily follow. The micro equations identify the private return to education, which is the increase in earnings reaped by a worker with more education. What is relevant for long-run growth is the social return to education, which is the increase in productivity that could result from an increase in educational attainment. It is possible for the social return to education to be larger than the private return if there are spillovers associated with education.[25] It is also possible for the social return to be smaller than the private return. This would occur if the increase in private earnings arose as a result of "signaling." If workers with a lot of innate ability tend to acquire more education than workers with less ability, then more education will appear to "cause" an increase in wages, when in fact it is merely signaling the presence of more ability.[26] The social return to education could be lower than the private return for another reason. If education does in fact raise ability, but that increased ability is put to use in profitable, but unproductive activities, such as corruption, then the increase in earnings would not imply an increase in aggregate income.[27] This phenomenon would be more likely in less-developed countries rather than the United States.

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24 There is a large literature examining this question. Surveys can be found in Kreuger & Lindahl (2001) and Card (1999). The arguments in this paragraph come from Kreuger & Lindahl (2001).

25 There are models of endogenous growth that rely on spillovers to human capital, but they are not well supported by the empirical evidence. See the discussion in CBO (1994).

26 Kreuger and Lindahl (2001) argue that the question is not fully settled, but that these estimates are not merely capturing differences in unobserved ability.

27 This argument can be found in Pritchett (2001).

Macroeconomic studies attempt to estimate the social return to education and, unfortunately, the evidence from those studies is more equivocal than is the microeconomic evidence on the private return. Many macroeconomic studies, especially cross-sectional empirical studies, have found a significant role for human capital in long-run growth. A canonical example is the 1992 study by Mankiw, Romer and Weil (MRW), in which the authors use a cross section of 98 countries to show that growth during the 1960-1985 period is positively related to the level of human capital during that period, measured by the average percentage of the working-age population enrolled in secondary school from 1960 through 1985.[28] Essentially, those results indicate that countries with higher school enrollment rates tended to grow faster during this period. Results like that of MRW seemed to confirm the intuition that human capital is an important factor in long-run growth and were consistent with the microeconomic evidence of a private return to education.

In contrast, other macroeconomic studies that approach the question from a different angle find little impact on long-run growth from human capital. These studies examine the relationship between growth in per-capita output and *growth* in human capital (rather than the *stock* of human capital) have not generally found a significant effect for human capital. For example, Jess Benhabib and Mark Spiegel regressed growth in per-capita income over the 1965-1985 period on the growth in physical capital, human capital, and labor force for a sample of 121 countries. They found that growth in physical capital and labor force entered the regression significantly, with the correct sign and expected magnitude, but that two different measures of growth in human capital were insignificant.[29] Benhabib and Spiegel interpret these results as support for the idea that human capital is important because it facilitates innovation and the adoption of new technologies, rather than because it directly contributes to the productive process as a factor of production.[30]

What are we to make of these disparate strands of evidence? Why has the striking increase in educational enrollments in the U.S. and other countries not been matched by a corresponding increase in economic growth? It's hard to believe that human capital has no effect on growth, but there are several reasons why it is difficult to tease out the effects of human capital on economic growth:

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28 See Mankiw, Romer, and Weil (1992). Similar results are reported by Barro (1991) and Barro and Sala-i-Martin (1995). For further discussion of Mankiw *et. al.*, see CBO (1994).

29 See Benhabib & Spiegel (1994). Other studies that report similar results include Klenow & Rodriguez-Clare (1997), Islam (1995), and Pritchett (2001). Kreuger and Lindahl (2001) challenge these results, arguing that the measures of human capital are tainted by measurement error.

30 See Benhabib & Spiegel (1994), p. 155. The authors cite the work of Nelson and Phelps (1966), who argue that the pace of innovation is a function of the stock of capital rather than the flow of human capital accumulation. See also Aghion and Howitt (1998), pp. 327-328.

- o Measurement error. Many studies measure educational attainment using school enrollment rates, which are a poor proxy for total years of schooling. Even those studies that measure schooling more accurately still do not measure the quality of education and they miss other forms of human capital accumulation, such as training programs and the informal training that occurs on the job.

- o Timing issues. Economic theory is unable to predict how long it takes for increases in educational attainment to affect growth. The lags could be as short as one year, or for as long as twenty years. Moreover, the lags could vary through time. This means that empirical equations may be mis-specified.

- o Endogeneity. Similar to the problem estimating the effect of physical capital, it is hard to tell if increased education causes an increase in per-capita GDP or if rich countries merely demand more education because they can afford it.[31] Estimation using instrumental variables can correct for this problem, but it requires variables that are correlated with education but are uncorrelated with the error term in the growth regression. Such variables are hard to find.

In conclusion, the results of these empirical studies do not help us answer the basic question that needs to be answered for our models. If educational attainment in the U.S. were to increase, would productivity rise? It is hard to predict that outcome with confidence based on the research to date. Moreover, it's quite likely that the social return to education would shrink if such a policy were implemented because the marginal students (i.e., those who would increase their educational attainment under a policy change) would tend to be less able than the average student.

Total Factor Productivity. Technological progress is the fundamental source of long-run growth in living standards. The neoclassical model is silent on the causes of TFP growth, largely because economists have yet to provide a complete description of the sources of growth in technology.[32] However, few economists believe that TFP growth is truly exogenous. Clearly, companies and governments try to expand the technological frontier with explicit expenditures on R&D and other activities.[33] Research on the link between R&D and growth has focused on three

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31 See Bils and Klenow (2000).

32 Although growth in total factor productivity is often interpreted as technical change, the difficulties inherent in measuring TFP mean that it captures technical change and any other factor that contributes to GDP growth apart from labor and capital, including measurement error and cyclical variation.

33 R&D spending is not the only activity that expands the knowledge stock. However, it is the activity that is most amenable to measurement and statistical estimation. Hence, it has been the focus of most empirical work.

questions: what drives R&D spending, how big R&D's contribution to growth is, and whether there are externalities to R&D spending.

It is possible to analyze R&D spending squarely in the neoclassical tradition by treating it as a factor of production. Under this approach, R&D spending accumulates into a stock of R&D "capital," which earns a rate of return that is captured by the innovating firm.[34] If there are any external benefits, they are purely accidental. Studies of this type typically find that private R&D spending has a positive and significant impact on productivity growth across firms and industries, with social rates of return that range from 20 to 50 percent. (The link between government R&D spending and productivity is generally estimated to be smaller and is less robust statistically). A reasonable approach would be to calculate a stock of private R&D capital and add it to the production function in CBO's long-term models. Another approach would be to follow the lead of some researchers who have developed growth accounting models based on the growth of capital, raw labor, R&D labor, and human capital.[35]

Treating R&D as a separate factor input formalizes the process of innovation and reduces the contribution to growth made by the residual, but leaves the residual as an exogenous variable. An important contribution made by Paul Romer, as well as other analysts who developed endogenous growth models, was to stress two key differences between technical knowledge and other types of capital goods. First, technical knowledge is nonrival in consumption, which means that it can be used by an unlimited number of people at the same time, and second, it is at least partially nonexcludable, which means that the owner of an idea cannot completely prevent others from using it.[36]

An important implication of these properties is the existence of increasing returns to scale, meaning that a given percentage increase in the factors of production will lead to a larger percentage increase in output. To see this concept, consider a firm that produces $10 million using one factory, 10 workers, and a certain amount of technical knowledge. This firm could produce $20 million by building a second plant, hiring 10 more workers, and using the same amount of knowledge. Since output has doubled with a less-than-doubling of inputs, output would more than double if all inputs were doubled. Thus, production is characterized by increasing returns to scale.

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34 See Griliches (1994) and Griliches (1988).

35 See Jones (2002).

36 See CBO (1994) for a more complete discussion. Also, see Aghion & Howitt (1998) or Grossman & Helpman (1991) for more discussion of endogenous innovation models.

Models of endogenous innovation have a lot of intuitive appeal. R&D spending in the U.S. is not trivial. In 2000, for example, private companies spent $181 billion and the federal government spent $70 billion on research and development.[37] And that is only the spending that is caught in the government's statistical net. Entrepreneurs devote resources to invent, innovate, and nurture companies that sell products derived from new ideas. It seems unlikely that innovation would have continued for so long if these companies and individuals were not getting some sort of return to their efforts. To be successful, innovators must be able to prevent others to some extent from using their discovery, through patents and other means. Many models of endogenous innovation assume that inventors earn monopoly rents, at least temporarily, to compensate them for their investments.

Does innovation have significant spillovers? It is one thing to say that spillovers to R&D exist. It is another matter to say that they are large enough to drive TFP growth at the economy-wide level. Measuring the degree of spillovers at the firm or industry level is quite challenging, largely because the requisite data do not exist.[38] Nevertheless, after surveying the micro evidence, Zvi Griliches concluded that:

> 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.[39]

The existence of international spillovers has been hinted at in an oft-cited paper that found positive and significant effects for domestic and foreign R&D stocks on domestic TFP growth.[40] Foreign R&D was found to be particularly important for smaller countries.

The macro evidence supporting the stronger versions of the endogenous innovation models is less persuasive. This evidence would include the class of models that predict so-called "scale" effects and permanent effects on TFP growth resulting from policy changes. Scale effects refers to a prediction of some models that changes in the level of resources dedicated to R&D can affect the economy's growth rate. For example, there has been a secular increase in the share of labor devoted to R&D in the U.S. and other industrialized nations during the postwar

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37 National Science Board, *Science and Engineering Indicators 2002*, (Arlington, VA: National Science Foundation, 2002).

38 The issues are discussed at length in Griliches (1979) and in the Appendix to Chapter 12 in Aghion & Howitt (1998). David Romer (1996) notes that the spillovers to R&D could be positive or negative.

39 See Griliches (1992), p. S43.

40 See Coe & Helpman (1995).

period. According to the predictions of some models of endogenous innovation, such an increase should cause an increase in the growth of TFP in those countries, but that hasn't been observed.[41] In addition, the data do not seem to support the idea that R&D spending playing a significant role in the post-1973 productivity slowdown.[42]

Other factors that influence TFP growth. There is a large and growing literature that argues that there is no single 'silver bullet' to explain TFP growth. Instead, the sources of productivity growth are diffuse. Aggregate productivity growth arises as different firms in different industries aggressively cut costs and try to produce as efficiently as possible. Governments need to get the fundamentals right by first establishing a system of property rights and a functioning legal system and then by avoiding policies that would restrain productivity growth. As an example, consider the socialist economies in eastern Europe during the postwar period. Those countries failed to grow as quickly as other countries with comparable levels of physical and human capital, in part because their political system did not provide the incentive for entrepreneurs to innovate or for workers to increase efficiency.[43]

Empirical studies that employ cross-sectional regressions have found that measures of a country's policies and institutions help to explain differences in output per capita across countries.[44] Variables such as the degree of political instability, and the black-market premium on foreign exchange have been found to have a negative relationship with growth. Other researchers emphasize factors that allow resistance to the adoption of international best practice techniques. Examples include anything from zoning laws that prohibit large-scale retailers to compete with smaller operations, to laws that make the labor market less flexible, all the way up to outright corruption on the part of government officials.[45] These findings augur well for the U.S. economy because it ranks high with respect to the various measures that have been found to be associated with faster growth. However, none of the factors described in this section can be incorporated easily into a long-term model of the U.S. economy.

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41 See Jones (1995b). Jones (1995a) presents a model of endogenous innovation in which long-run growth is a positive function of variables, most notably population growth, that are normally treated as exogenous in growth models. Kremer (1983) has found evidence to support such "semi-endogenous" growth models. His results indicate that technological progress increases with population size, at least over very long periods of time.

42 See Griliches (1988).

43 See Phelps (1995).

44 See Barro (1991), Barro & Sala-i-Martin (1995), Hall & Jones (1999), and Easterly (1993).

45 See Prescott (1998), Harberger (1998), Olson (1996). Schmitz (2001) documents a doubling of out per worker in the iron-ore mining industry due solely to a relaxation of restrictive work rules.

Possible Approaches for Extending CBO's Long-Term Growth Model

Which approaches to modeling long-run growth are suggested by the latest empirical research? With regard to physical capital, the conclusion of CBO's 1994 paper has been reaffirmed—the core of the model should follow the standard neoclassical model in assuming that the returns to physical capital are decreasing. The latest research does not support the existence of spillovers to physical capital.

With regard to human capital, the empirical results are mixed, with cross-sectional studies generally finding a significant link and panel-data studies not. Hence, there is not yet a consensus among researchers about precisely how human capital should enter empirical models. Some would argue that it should enter the production function as a separate factor, while others would contend that it only affects TFP. This is not to say that there are not operational models that incorporate human capital, several examples exist.

One example of a model that reflects the impact of human capital accumulation derives from the growth accounting literature. This approach, used most notably by Dale Jorgenson and several co-authors, accounts for labor heterogeneity, or differences in the relative productivity of workers with different levels of education or experience.[46] Economic theory predicts that an hour worked by a person with more skills will yield a larger flow of "labor services" and more output than a lesser-skilled worker. Models that use total hours worked as the labor input, implicitly weight each hour worked identically, no matter whether it is worked by a veteran pilot or a newly-hired clerk. In contrast, Jorgenson's index of labor input reflects changes in both hours worked and labor quality. It does so by weighting the hours growth of different demographic groups—workers are divided into groups based on age, sex, and educational attainment—using data on relative earnings of each group. Earnings are used to weight the hours of each demographic group because worker productivity is difficult to observe directly. Economic theory predicts that, under certain conditions, a worker's marginal product will be equated to his or her earnings.

In principle, Jorgenson's method would provide a more accurate picture of the sources of economic growth over history because it would reclassify a portion of GDP growth as arising from growth in the labor input instead of attributing it to the unexplained residual, TFP. Using Jorgenson's approach might improve the long-run projection for GDP as well, to the extent that the demographic factors that go into the estimate can be projected. However, this method relies on the assumption that differences in relative earnings reflect differences in productivity across categories of workers, as implied by the assumption competitive labor markets. If markets fail

46 Jorgenson's method is first described in Jorgenson and Griliches (1967). More recent examples include Jorgenson, Ho, and Stiroh (2002), and Jorgenson and Stiroh (2000). Bureau of Labor Statistics (1993) describes a similar approach used to calculate multifactor productivity.

to assign earnings in this fashion, due possibly to market failure or because the competitive model does not accurately describe the workings of labor markets, then this method will give a faulty estimate of TFP during history and a misleading projection of GDP for the future.[47]

The preceding discussion also highlights a more general problem. Adopting Jorgenson's procedure for adjusting the labor input for quality would require projections of a greater number of demographic variables than are currently necessary. Doing so would complicate the model and potentially introduce more sources of forecast error. Although this problem is pronounced with Jorgenson's model—due to the large number of additional variables that would be required—it would arise in any alternate model with more variables.

Another approach would be to incorporate the stock of human capital explicitly into long-run models as a factor of production separate from hours worked. While following the spirit of Mankiw, Romer, and Weil, this approach would not have to rely on the rather crude estimate of the human capital stock used by MRW. Instead, it could use the research of Dale Jorgenson and Barbara Fraumeni or by Lant Pritchett, who each calculate stocks of human capital by combining estimates of the educational attainment of the labor force with micro earnings functions that relate earnings to years of schooling.[48] Alternatively, one could model TFP as a function of the human capital. This approach would follow from the results of Benhabib and Spiegel, who argue that differences in growth rates across countries arise due to differences in stocks of human capital rather than differences in rates of accumulation.

There are problems with all of these approaches. First and foremost, there is not yet a consensus among economists about how human capital should enter the production function, largely because empirical evidence on this question is ambiguous. If human capital truly is a factor of production, then it should enter significantly in regressions, whether those equations are estimated in levels or growth rates. Another problem is that these approaches would dramatically complicate CBO's models, by forcing CBO to model the process by which the stock of human capital grows. Examples of such models of human capital accumulation exist, but it's not clear that using them would improve the projection of GDP, which is the

[47] As noted in the discussion of human capital earlier in this paper, microeconomic wage equations indicate that earnings increase with education and experience, which suggests that earnings are correlated with productivity, as required by Jorgenson's model. However, there are alternate interpretations of the microeconomic evidence. Under these alternatives, workers with more education are also paid more on average, but an increase in education does directly increase an individual worker's marginal product. An excellent discussion of these alternate explanations can be found in BLS (1993), especially pages 41-43.

[48] For details, see Pritchett (2001) or Jorgenson and Fraumeni (1989).

variable that ultimately matters.[49]

Another approach would be to include both human capital and R&D spending in the model along the lines suggested by Charles Jones in a recent article in the *American Economic Review*.[50] In Jones' model, which follows in the spirit of Paul Romer's models of endogenous innovation, output is produced using physical capital, human capital, and the stock of ideas. Growth in the stock of ideas, in turn, arises from research effort (measured by the share of human capital devoted to research and development) as well as from the size of the stock of ideas itself. In steady state, growth arises solely from increases in the stock of ideas, which are a function of population growth. Jones used his model to carry out a growth accounting exercise. He found that the vast majority of U.S. growth during the 1950-1993 period can be attributed to transitional dynamics (associated with increases in research effort and educational attainment) rather than steady-state growth.

A major challenge of using any of these approaches for 75-year projections is that they would require making additional assumptions about variables that affect labor quality and technological progress, including educational attainment, returns to education, and R&D spending. (This, of course, leaves aside the important question about whether changes in government policy can affect educational attainment or R&D effort). Expanding CBO's model to include any of these channels of influence would require guesses about parameters on which little reliable evidence exists.

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49 See for example, Ho and Jorgenson (2002).

50 See Jones (2002).

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