Notes on Growth Accounting[1]

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Growth accounting provides a breakdown of observed economic growth into components associated with changes in factor inputs and a residual that reflects technological progress and other elements. Generally, the accounting exercise is viewed as a preliminary step for the analysis of fundamental determinants of economic growth. The final step involves the relations of factor growth rates, factor shares, and technological change (the residual) to elements such as government policies, household preferences, natural resources, initial levels of physical and human capital, and so on. The growth-accounting exercise can be particularly useful if the fundamental determinants that matter for factor growth rates are substantially independent from those that matter for technological change.

The basics of growth accounting were presented in Solow (1957), Kendrick (1961), Denison (1962), and Jorgenson and Griliches (1967). Griliches (1997, part 1) provides an overview of this intellectual history, with stress on the development of the Solow residual. The present paper begins with a short presentation of these basics in the form of a standard, primal model of growth accounting.

The analysis then turns to a number of issues that affect the interpretation of the Solow residual as a measure of technological change. The topics covered include dual approaches to growth accounting (which consider changes in factor prices rather than quantities), spillover effects and increasing returns, taxes, and multiple types of factor inputs.

Later sections place the growth-accounting exercise within the context of two recent strands of endogenous growth theory—varieties-of-products models and quality-ladders models. Within these settings, the Solow residual can be interpreted in terms of measures of the endogenously changing level of technology. This technology corresponds, in one case, to the number of types of intermediate products that have been invented and, in the other case, to an index of the aggregate quality of intermediate inputs. The models can also be used to assess and extend previous analyses in which the Solow residual is related to outlays on research and development (R&D). These analyses often use the concept of an R&D capital stock, and this stock has a clear meaning within the underlying theories.

1 Standard Primal Growth Accounting

Start with the neoclassical production function

$$Y = F(A, K, L) \tag{1}$$

where A is the level of technology, K is the capital stock, and L is the quantity of labor. Capital and labor can be disaggregated among types or qualities as in Jorgenson and Griliches (1967).

As is well known, the growth rate of output can be partitioned into components associated with factor accumulation and technological progress. Differentiation of equation (1) with respect to time yields, after division by Y and rearrangement of terms,

$$\dot{Y}/Y = g + (\frac{F_K K}{Y}) \cdot (\dot{K}/K) + (\frac{F_L L}{Y}) \cdot (\dot{L}/L) \tag{2}$$

where F_K, F_L are the factor (social) marginal products and g—the growth due to technological change—is given by

$$g \equiv (\frac{F_A A}{Y}) \cdot (\dot{A}/A) \tag{3}$$

If the technology factor appears in a Hicks-neutral way, so that $F(A, K, L) = A \cdot \tilde{F}(K, L)$, then $g = \dot{A}/A$.

The rate of technological progress, g, can be calculated from equation (2) as a residual,

$$g = \dot{Y}/Y - (\frac{F_K K}{Y}) \cdot (\dot{K}/K) - (\frac{F_L L}{Y}) \cdot (\dot{L}/L) \tag{4}$$

However, equation (4) is impractical because it requires knowledge of the social marginal products, F_K and F_L. Thus, in practice, the computations typically assume that the social marginal products can be measured by observed factor prices.

If the factors are paid their social marginal products, so that $F_K = R$ (the rental price of capital) and $F_L = w$ (the wage rate), then the standard primal estimate of the rate of technological progress follows from equation (4) as

$$\hat{g} = \dot{Y}/Y - s_K \cdot (\dot{K}/K) - s_L \cdot (\dot{L}/L) \tag{5}$$

where $s_K \equiv RK/Y$ and $s_L \equiv wL/Y$ are the respective shares of each factor payment in total product. The value $\hat{g}$ is often described as an estimate of total factor productivity (TFP) growth or the Solow residual.

The condition $s_K + s_L = 1$—or $Y = RK + wL$—must hold if all of the income associated with the gross domestic product, Y, is attributed to one of the factors, restricted here to capital and labor. In an international context, some net factor income may accrue to foreign owned factors, and $RK+wL$ would include this net factor income. The equation of output, Y, to total factor income is consistent with equality between the factor prices and marginal products if the production function, $F(\cdot)$, exhibits constant returns to scale in K and L, so that $Y = F_K K + F_L L$ holds. Using $s_K + s_L = 1$, equation (5) can also be rewritten in intensive form as

$$\hat{g} = \dot{y}/y - s_K \cdot (\dot{k}/k) \tag{6}$$

where $y \equiv Y/L$ and $k \equiv K/L$ are quantities per unit of labor.

Jorgenson and Griliches (1967) and Jorgenson, Gollop, and Fraumeni (1987) demonstrate the importance of disaggregating the inputs by quality classes. For example, L can be viewed as a vector that specifies the quantities of labor of various kinds, categorized by school attainment, age, sex, and so on. In an extended version of equation (5), the growth rate of labor quantity of type j, $\dot{L}_j/L_j$, is multiplied by the associated income share, s_{L_j}. As an example, if the population's average educational attainment is rising over time, then this procedure attributes a portion of economic growth to the rise of L_j in categories—such as college-educated workers—that receive relatively high wage rates, w_j. Failure to allow in this way for improvements in labor quality tends to overestimate the Solow residual, g, in equation (5).

The treatment of capital quality is analogous. One important element here concerns the distinction between short-lived and long-lived capital. For a given required rate of return on capital, the rental price, R_j, is higher if the depreciation rate is higher (due to more rapid physical deterioration or economic obsolescence). Hence, a shift from long-lived capital (say buildings) to short-lived capital (say machinery) would account for some part of economic growth. Failure to allow for this rise in capital quality tends to overstate the Solow residual in equation (5).

Table 1 summarizes estimates of TFP growth rates for various countries and time periods, using this approach. For the main OECD countries, the TFP estimates for 1947-73 ranged from 1.4% per year for the United States to 4.0% for Japan. The estimates shown for 1960-73 are roughly similar. However, the values shown for 1973-89 reflect the well-known "productivity slowdown" and are much smaller than those for the pre-1973 periods. The range of estimates for the main OECD countries in the post-1973 period is very narrow, going from 0.3% for Canada and the United States to 1.4% for France.

Estimates for seven Latin American countries from 1940 to 1990 ranged between -0.6% per year for Peru to 1.4% for Chile.[1] For four East Asian countries from 1966 to 1990 or 1991, the estimates varied from 0.2% for Singapore to 2.6% for Taiwan. Because of the stellar growth performances of these East Asian countries, many economists were surprised by the low TFP estimates for these cases. Some of these results will be reexamined in a later section.

An important point about the TFP estimates displayed in Table 1 is that they represent a direct implementation of equation (5)—extended to include multiple types of capital and labor—and do not involve econometric estimation. The estimated Solow residual, $\hat{g}$, is computed at each date by using time-series data on $\dot{Y}/Y, \dot{K}/K, \dot{L}/L, s_K$, and s_L.[2] In practice, researchers report an average of the computed $\hat{g}$ values for a designated time period.

An alternative approach would be to regress the growth rate of output, $\dot{Y}/Y$, on the growth rates of inputs, $\dot{K}/K$ and $\dot{L}/L$, in the form of equation (2). The intercept then measures g, and the coefficients on the factor growth rates measure $(\frac{F_K K}{Y})$ and $(\frac{F_L L}{Y})$, respectively. The main advantage of this approach is that it dispenses with the assumption that the factor social marginal products coincide with the observable factor prices, that is, $F_K = R$ and $F_L = w$.

The disadvantages of the regression approach are several:

[1] The estimated TFP growth rates in Latin America are particularly low—typically negative—from 1980 to 1990. The negative values are hard to understand as technical regress in the sense of literal forgetting of technology, but they may represent declining efficiency of market organization due to policy or other changes.

[2] With discrete data, the growth rates are typically measured, following Thӧrnqvist (1936), as log differences between the levels at dates $t+1$ and t, and the factor shares are arithmetic averages for dates $t+1$ and t. Diewert (1976) shows that the Thӧrnqvist procedure is exact if the production function takes the trans-log form, which was introduced by Christensen, Jorgenson, and Lau (1971).

•The variables $\dot{K}/K$ and $\dot{L}/L$ cannot usually be regarded as exogenous with respect to variations in g—in particular, the factor growth rates would receive credit for correlated variations in unobservable technological change.

•If $\dot{K}/K$ and $\dot{L}/L$ are measured with error, then standard estimates of the coefficients of these variables would deliver inconsistent estimates of $(\frac{F_K K}{Y})$ and $(\frac{F_L L}{Y})$, respectively. This problem is likely to be especially serious for the growth rate of capital input, where the measured capital stock is unlikely to correspond well to the stock currently utilized in production. This problem often leads to low estimates of the contribution of capital accumulation to economic growth when high-frequency data are employed.

•The regression framework has to be extended from its usual form to allow for time variations in factor shares and the TFP growth rate.

Given the drawbacks from the regression method, the usually preferred approach to TFP estimation is the non-econometric one exemplified by the studies shown in Table 1.

2 Dual Approach to Growth Accounting

Hsieh (1998) recently exploited a dual approach to growth accounting, whereby the Solow residual is computed from growth rates of factor prices, rather than factor quantities. This idea goes back at least to Jorgenson and Griliches (1967).

The dual approach can be derived readily from the equality between output and factor incomes:

$$Y = RK + wL \tag{7}$$

Differentiation of both sides of equation (7) with respect to time leads, after division by Y and rearrangement of terms, to

$$\dot{Y}/Y = s_K \cdot (\dot{R}/R + \dot{K}/K) + s_L \cdot (\dot{w}/w + \dot{L}/L)$$

where s_K and s_L are again the factor income shares. If the terms involving the growth rates of factor quantities are placed on the left-hand side of the equation, then the estimated TFP growth rate is given by

$$\hat{g} = \dot{Y}/Y - s_K \cdot (\dot{K}/K) - s_L \cdot (\dot{L}/L) = s_K \cdot \dot{R}/R + s_L \cdot \dot{w}/w \qquad (8)$$

Hence, the primal estimate of the TFP growth rate on the left-hand side of the equation—based on filtering $\dot{Y}/Y$ for the share-weighted growth in factor quantities—equals the share-weighted growth of factor prices on the right-hand side of the equation. The latter, dual estimate of the TFP growth rate uses the same factor-income shares, s_K and s_L, as the primal estimate, but considers changes in factor prices, rather than quantities.[3]

The intuition for the dual estimate on the right-hand side of equation (8) is that rising factor prices (for factors of given quality) can be sustained only if output is increasing for given inputs. Therefore, the appropriately weighted average of the growth of the factor prices measures the extent of TFP growth.

It is important to recognize that the derivation of equation (8) uses only the condition $Y = RK + wL$. No assumptions were made about the relations of factor prices to social marginal products or about the form

[3]This derivation was suggested to me by Susanto Basu. The approach was used earlier by Jorgenson and Griliches (1967, pp. 251-253), who also extend equation (8) to allow for changes over time in the relative prices of multiple outputs. In this case, $\dot{Y}/Y$ becomes a share-weighted average of output growth rates, and the right-hand side of the dual accounting expression subtracts off the share-weighted average of the growth rates of the output prices. This last term is zero in the present context (with a fixed relative price of a single form of output).

of the production function. If $Y = RK + wL$ holds, then the primal and dual estimates of TFP growth inevitably coincide. In some cases—notably when factor prices deviate from social marginal products—the estimated value $\hat{g}$ from equation (8) would deviate from the true value, g. However, the error, $g - \hat{g}$, from the dual approach will be the same as that from the primal approach.[4]

Hsieh (1998) used the dual approach—the right-hand side of equation (8)—to redo Young's (1995) estimates of TFP growth for the four East Asian countries included in Table 1. Hsieh's procedure uses an array of quality categories for L and K. The results, shown along with primal estimates that are similar to Young's findings, are in Table 2. The most striking conclusion is that the estimate for Singapore changes from the primal estimate of around zero to a dual estimate of 2.2% per year. The estimate for Taiwan is also revised upward substantially, but those for Hong Kong and South Korea change little. (Hsieh also observes that dual estimates for the United States are similar to primal estimates.)

If the condition $Y = RK + wL$ holds, then the discrepancy between the primal and dual estimates of TFP has to reflect the use of different data in the two calculations. Hsieh's discussion brings out the general nature of this data discrepancy for Singapore. The Singaporean national

[4] This equivalence does not generally hold if the factor-income shares, s_K and s_L, are replaced by the marginal-product weights, $(\frac{F_K K}{Y})$ and $(\frac{F_L L}{Y})$. If these marginal-product weights are used, then the primal estimate $\hat{g}$ calculated from equation (4) correctly measures the TFP growth rate, g. The corresponding dual estimate is

$$(\frac{F_K K}{Y}) \cdot (\dot{R}/R) + (\frac{F_L L}{Y}) \cdot (\dot{w}/w)$$

It is possible to show that this estimate equals the primal one if the ratios of the factor prices to social marginal products—R/F_K and w/F_L—do not vary over time. (It is not necessary for these ratios to equal unity.) However, the practical significance of these results is unclear because F_K and F_L would not generally be observable.

accounts show remarkable growth of K over time and—given the behavior of Y and wL—a correspondingly sharp decline in the rental price, R. However, direct estimates of returns on capital in Singapore—based on observed returns on financial markets—are relatively stable over time. If the path of R implied by the observed rates of return is accurate—and if information on Y and wL is also viewed as reasonable—then the implied path of K exhibits much more moderate growth than that indicated by the national-accounts data. Hsieh argues that the official statistics have, in fact, substantially overstated the growth of the capital stock and, hence, that the reduced estimates of capital growth implied by the observed R values are reasonable.

Hsieh's dual estimate of TFP growth for Singapore—2.2% per year—is a weighted average of the robust wage-rate growth (for given labor quality) and a small amount of rental-price growth. However, Hsieh could just as well have computed a primal estimate of TFP growth based on the time series for K that is implied by the observed and presumed accurate time series for R. (With multiple types of capital, K_j, this calculation would be applied to each type, given the estimated values of the rental prices, R_j.) Since $Y = RK + wL$ holds here by construction, the primal estimate would coincide with the dual estimate. Thus, it is not actually necessary ever to do the dual computation.

3 Problems with Growth Accounting

A key assumption in growth-accounting exercises is that factor prices coincide with social marginal products. If this assumption is violated, then the estimated value $\hat{g}$ calculated from equation (5)—or the corresponding dual estimate from equation (8)—deviates from the true contribution, g, of technical change to economic growth. The next sections illustrate these problems for models with increasing returns and spillovers, for environments with various kinds of taxes, and for settings with different types of factors.

3.1 An Increasing-Returns Model with Spillovers

A number of authors—including Griliches (1979), Romer (1986), and Lucas (1988)—have constructed models of economic growth with increasing returns and spillovers. Romer's analysis is a generalization of Arrow's (1962) learning-by-doing model, in which the efficiency of production rises with cumulated experience. In a simple version of the Romer model, the output, Y_i, of firm i depends not only on the standard private inputs, K_i and L_i, but also on the economy-wide capital stock, K. The idea is that producers learn by investing (a specific form of "doing") to produce more efficiently. Moreover, this knowledge spills over immediately from one firm to others so that each firm's productivity depends on the aggregate of learning, as reflected in the overall capital stock.

These ideas can be represented with a Cobb-Douglas production function as

$$Y_i = AK_i^{\alpha} \ K^{\beta} \ L_i^{1-\alpha} \tag{9}$$

where $0 < \alpha < 1$ and $\beta \geq 0$. For given K, this production function exhibits constant returns to scale in the private inputs, K_i and L_i. If $\beta > 0$, then the spillover effect is present.

In the Griliches (1979) version of the production function in equation (9), K_i represents firm $i's$ specific knowledge capital, whereas K (modeled as the sum of the K_i) is the aggregate level of knowledge in an industry. Hence, the spillovers again represent the diffusion of knowledge across firms. In the Lucas (1988) version, K_i is the firm's employment of human capital, and K is the aggregate (or possibly average) level of human capital in an industry or country. In this case, the spillovers involve benefits from interactions with smart people.

Returning to the Romer interpretation of equation (9), each firm behaves competitively, taking as given the economy-wide factor prices, R and w, and the aggregate capital stock, K. Hence, private marginal products are equated to the factor prices, thereby yielding

$$R = \alpha Y_i / K_i \text{ and } w = (1 - \alpha) \cdot Y_i / L_i \tag{10}$$

The factor-income shares are therefore given, as usual, by

$$s_k = \alpha \text{ and } s_L = 1 - \alpha \tag{11}$$

In equilibrium, each firm adopts the same capital-labor ratio, k_i, but the scale of each firm is indeterminate. The production function from equation (9) can be rewritten as

$$Y_i = A k_i^{\alpha} \ k^{\beta} \ L_i L^{\beta}$$

where $k \equiv K/L$. The equilibrium condition $k_i = k$ then implies

$$Y_i = A k^{\alpha+\beta} L_i L^{\beta}$$

which can be aggregated across firms to get

$$Y = A k^{\alpha+\beta} L^{1+\beta}$$

Finally, the condition $k \equiv K/L$ leads to the economy-wide production function

$$Y = A K^{\alpha+\beta} L^{1-\alpha} \tag{12}$$

This expression relates aggregate output, Y, to the aggregate inputs, K and L. If $\beta > 0$, then increasing returns to scale apply economy wide.

The right-hand side of equation (12) shows that the correct way to do the growth accounting with aggregate data is to compute

$$\hat{g} = \dot{A}/A = \dot{Y}/Y - (\alpha + \beta) \cdot (\dot{K}/K) - (1 - \alpha) \cdot (\dot{L}/L) \tag{13}$$

Hence, $s_L = 1 - \alpha$ is the correct weight for $\dot{L}/L$, but the coefficient $s_K = \alpha$ understates by $\beta \geq 0$ the contribution of $\dot{K}/K$. This understatement arises because—with the assumed investment-based spillovers of knowledge—the social marginal product of capital, $(\alpha + \beta) \cdot Y/K$, exceeds the private marginal product, $\alpha Y/K$. (This private marginal product does equal the factor price, R.) Note also that the weights on the factor-input growth rates in equation (13) add to $1 + \beta$, which exceeds one if $\beta > 0$ because of the underlying increasing returns to scale. The increasing returns arise because ideas about how to produce more efficiently are fundamentally non-rival (and spill over freely and instantaneously across firms).

The interpretation of K—the factor that receives a weight above its income share in the growth accounting of equation (13)—depends on the underlying model. Griliches (1979) identifies K with knowledge-creating activities, such as R&D. Romer (1986) stresses physical capital itself. Lucas (1988) emphasizes human capital in the form of education. It is, of course, also possible to have spillover effects that are negative, such as traffic congestion and environmental damage.

Implementation of the results from equation (13) is difficult because the proper weights on the factor growth rates cannot be inferred from income shares; specifically, no direct estimates are available for the coefficient β. If one instead computes the standard Solow residual within this model, then one gets

$$\tilde{g} = \dot{A}/A + \beta \cdot (\dot{K}/K) = \dot{Y}/Y - \alpha \cdot (\dot{K}/K) - (1 - \alpha) \cdot (\dot{L}/L) \tag{14}$$

Thus, the standard calculation includes the growth effect from spillovers and increasing returns—$\beta \cdot (\dot{K}/K)$—along with the rate of exogenous technological progress, $\dot{A}/A$, in the Solow residual.

It seems that the separation of the spillovers/increasing returns effect from exogenous technological progress requires a regression approach. In this approach, the usual Solow residual, $\tilde{g}$, calculated from equation (14) could be regressed on the factor growth rate, $\dot{K}/K$, that was thought to carry the spillover effects. This method does, however, encounter the usual econometric problems with respect to simultaneity.

3.2 Taxes

In most cases, taxes do not disturb the TFP calculations. Suppose, for example, that firms' net revenues are taxed, wage and rental payments are tax-deductible expenses for firms, and wage and rental incomes are taxed at the household level. In this case, competitive firms equate the marginal product of labor, F_L, to the wage, w, and the marginal product of capital, F_K, to the rental price, R. The condition $Y = RK + wL$ also holds (with firms' net revenue and taxes equal to zero in equilibrium). Therefore, the formula for $\hat{g}$ in equation (5) remains valid.

Suppose, instead, that firms acquire capital through equity finance, that wages and depreciation, δK, are tax deductible for firms, and that r is the required (gross-of-personal-tax) rate of return on equity. A competitive firm still equates the marginal product of labor to the wage rate, w. The firm also equates the after-tax net marginal product of capital, $(1-\tau) \cdot (F_K - \delta)$, to r, where τ is the marginal tax rate on the firm's earnings. Therefore, the marginal product of capital is given by

$$F_K = \frac{r}{1-\tau} + \delta$$

The growth-accounting formula in equation (4) implies, after substitution for F_K and F_L,

$$g = \dot{Y}/Y - \left[\frac{r}{(1-\tau)} \cdot \frac{K}{Y} + \frac{\delta K}{Y}\right] \cdot (\dot{K}/K) - s_L \cdot (\dot{L}/L) \qquad (15)$$

If taxes on firms' earnings are proportional, so that τ is the average as well as the marginal tax rate, then $rK/(1-\tau)$ is equal in equilibrium to firms' earnings (net of depreciation but gross of the earnings tax). Hence, the bracketed term in equation (15) equals s_K, the income share of capital, if capital income is measured by firms' earnings (gross of earnings taxes) plus depreciation. The usual formula for the TFP growth rate in equation (5) therefore remains valid.

For a tax on output or sales, competitive firms satisfy $F_L = w/(1-\tau)$ and $F_K = R/(1-\tau)$, where R is again the rental price of capital and τ is the marginal tax rate on output. The growth-accounting formula in equation (4) therefore implies, after substitution for F_K and F_L,

$$g = \dot{Y}/Y - \left[\frac{R}{(1-\tau)} \cdot \frac{K}{Y}\right] \cdot (\dot{K}/K) - \left[\frac{w}{(1-\tau)} \cdot \frac{L}{Y}\right] \cdot (\dot{L}/L) \qquad (16)$$

If the tax on output is proportional, so that marginal and average tax rates coincide, the total revenue collected is τY. Output, Y, equals factor incomes plus the amount collected by the indirect tax:

$$Y = RK + wL + \tau Y$$

so that the total factor income, $RK + wL$, equals $(1-\tau) \cdot Y$. Hence, the bracketed terms on the right-hand side of equation (16) equal s_K and s_L, respectively. (Note that these shares are expressed in relation to factor income rather than gross domestic product.) It follows that the usual formula for the TFP growth rate given in equation (5) still holds.[5]

[5]The analysis is more complicated if firms are subject to non-proportional tax schedules (with respect to output or earnings). If marginal tax rates on firms are

The standard growth-accounting formula works, for example, with a proportionate value-added tax that attaches the same tax rate to value added by capital and labor inputs. However, the usual formula would be inaccurate if different tax rates applied to the value added by each factor. If firms pay the tax rate τ_K on RK and the rate τ_L on wL, then the growth-accounting formula in equation (4) leads to

$$g = \dot{Y}/Y - (\frac{1+\tau_K}{1+\tau}) \cdot s_K \cdot (\dot{K}/K) - (\frac{1+\tau_L}{1+\tau}) \cdot s_L \cdot (\dot{L}/L) \qquad (17)$$

where τ is the average of the tax rates, as given by

$$\tau = s_K\tau_K + s_L\tau_L$$

If, for example, $\tau_K > \tau_L$, then equation (17) indicates that the weight on $\dot{K}/K$ should be raised relative to that on $\dot{L}/L$ to compute g accurately.

3.3 Multiple Types of Factors

Suppose now that the production function is

$$Y = F(A, K_1, K_2, L_1, L_2) \qquad (18)$$

One interpretation of equation (18) is that K_1 and K_2 represent different types or qualities of capital goods, whereas L_1 and L_2 represent different types or qualities of labor. Then the usual growth-accounting exercise goes through in the manner of Jorgenson and Griliches (1967) if each type of factor is weighted by its income share. That is, $\dot{K}_1/K_1$ is weighted by R_1K_1/Y, and so on. The usual Solow residual generated from this

increasing, there is effectively a penalty on large firms. Hence, in the present setup with constant returns to scale, firms would be of infinitesimal size in equilibrium. Non-proportional tax schedules can be admitted in models in which the establishment of a firm requires a fixed cost and in which span-of-control or other considerations eventually create diminishing returns to firm size.

procedure accurately measures the contribution of technological progress to growth, g, as long as all factors are paid their social marginal products.

Problems arise if the factor categories cannot be distinguished in the data, for example, if $\dot{K}_1/K_1$ and $\dot{K}_2/K_2$ are each associated with the overall capital share, $(R_1K_1 + R_2K_2)/Y$. One source of this kind of problem is that newer, and typically better, types of capital goods might be aggregated with the older types. Similarly, different categories of labor may be aggregated in the data.

Another interpretation of equation (18) is that K_1 and L_1 represent factor employments in sector 1—say urban manufacturing—whereas K_2 and L_2 represent employments in sector 2—say rural agriculture. Changes may occur over time in sectoral composition, for example, as a shift from agriculture to industry. Such shifts cause no trouble for the growth accounting if the various growth rates of factor quantities—distinguished by their sector of location—are weighted by their income shares. However, errors occur if capital or labor is aggregated across sectors and if the growth of these aggregates is weighted by overall income shares of capital or labor, respectively.

To illustrate, suppose that the TFP growth rate is incorrectly estimated as

$$\tilde{g} = \dot{Y}/Y - \left(\frac{R_1K_1 + R_2K_2}{Y}\right) \cdot (\dot{K}/K) - \left(\frac{w_1L_1 + w_2L_2}{Y}\right) \cdot (\dot{L}/L) \qquad (19)$$

where $K = K_1 + K_2$ and $L = L_1 + L_2$. This estimate compares with the appropriate formula,

$$\hat{g} = \dot{Y}/Y - \left(\frac{R_1K_1}{Y}\right) \cdot (\dot{K}_1/K_1) - \left(\frac{R_2K_2}{Y}\right) \cdot (\dot{K}_2/K_2) - \left(\frac{w_1L_1}{Y}\right) \cdot (\dot{L}_1/L_1) - \left(\frac{w_2L_2}{Y}\right) \cdot (\dot{L}_2/L_2) \qquad (20)$$

Equation (20) correctly estimates the contribution to growth from exogenous technological progress—that is, $\hat{g} = g$— if all factors are paid their social marginal products.

The expression for $\tilde{g}$ in equation (19) can be shown from algebraic manipulation to relate to true TFP growth, as estimated accurately by equation (20), in accordance with

$$\tilde{g}-\hat{g} = (\frac{K_1}{K})\cdot(\frac{K_2}{K})\cdot\frac{K}{Y}\cdot(R_1-R_2)\cdot(\frac{\dot{K}_1}{K_1}-\frac{\dot{K}_2}{K_2})+(\frac{L_1}{L})\cdot(\frac{L_2}{L})\cdot\frac{L}{Y}\cdot(w_1-w_2)\cdot(\frac{\dot{L}_1}{L_1}-\frac{\dot{L}_2}{L_2}) \tag{21}$$

Hence, if $R_1 \neq R_2$ and $\dot{K}_1/K_1 \neq \dot{K}_2/K_2$ or if $w_1 \neq w_2$ and $\dot{L}_1/L_1 \neq \dot{L}_2/L_2$, then $\tilde{g} \neq \hat{g}$. Specifically, if $R_1 > R_2$, then $\dot{K}_1/K_1 > \dot{K}_2/K_2$ leads to $\tilde{g} > \hat{g}$ and similarly for labor.

With the interpretation of the factor types as quality classes, the result is that measured TFP growth overstates true TFP growth if the composition of factors is shifting over time toward types of higher quality (and such shifts are not allowed for in the estimation). This problem is the one emphasized and resolved subject to data limitations by Jorgenson and Griliches (1967).

One sectoral interpretation of the results involves the migration of labor from rural to urban areas. The urban wage rate, w_1, may exceed the rural wage rate, w_2, for various reasons, including minimum-wage legislation and requirements of union membership for the city jobs. In this case, a shift of labor from the rural to the urban sector represents a gain in economy-wide productivity. The term involving labor in equation (21) reflects the economic growth generated by this change in the sectoral composition of labor, for a given growth rate of aggregate labor, $\dot{L}/L$. This type of growth effect, applied to movements of labor from low-productivity agriculture to high-productivity industry, was discussed by Kuznets (1961, p. 61), who derived an expression analogous to equation (21).

From the perspective of growth accounting, the terms that involve sectoral shifts should appear somewhere in the calculations. If the changes in labor quantities in each sector are weighted by labor-income shares for each type of labor, then the growth contribution from the sectoral changes appears in the part accounted for by changes in factor quantities in equation (20). If the weighting is done instead in the manner of equation (19), then the contribution appears in the estimated TFP growth rate.

4 TFP Growth and R&D

Growth accounting is often viewed as a first step in explaining the TFP growth rate, g, as estimated in equation (5). For example, the research program summarized by Griliches (1973) focuses on R&D spending as a determinant of the TFP growth rate.[6] Recent theories of "endogenous growth" have implications for the modeling of the relationship between technological change and R&D outlays. The following sections explore these relationships for models that involve increases in the number of types of products and improvements in the quality of existing products.

4.1 Varieties Models

The product-varieties framework was applied to technological change by Romer (1990) and Grossman and Helpman (1991, Ch. 3). In a simple formulation, output, Y, is given from a Spence (1976)/Dixit and Stiglitz (1977) production function as

$$Y = AL^{1-\alpha} \sum_{j=1}^{N} x_j^{\alpha} \tag{22}$$

where A is an exogenous technology factor, L is labor input, x_j is the quantity employed of intermediate input of type j, N is the number of varieties of intermediate products that are currently known and used,

[6] Earlier contributors to this literature include Terleckyj (1958), Minasian (1962), Griliches (1964), and Mansfield (1965).

and $0 < \alpha < 1$. In some versions of this model, x_j is treated for simplicity as non-durable. However, durability of the intermediates can be admitted, in which case x_j represents the service flow from the j^{th} type of capital good.

The output stream, Y, can be consumed, used as intermediate inputs to production (on a one-for-one basis for each type of input), or allocated to R&D. In particular, in this model, measured output is gross not only of outlay on intermediates but also of R&D expenditures.

In the formulation considered in Barro and Sala-i-Martin (1995, Ch. 6), each of the j types of non durables is priced (by the monopoly holder of the rights to the production of intermediates of type j) at the monopoly level, which turns out to be $1/\alpha > 1$. In equilibrium, each intermediate is employed at the same level, x. Hence, equation (22) can be expressed as

$$Y = AL^{1-\alpha}N^{1-\alpha}X^{\alpha} \tag{23}$$

where $X = Nx$ is the total quantity of intermediate inputs. For the case of durable inputs, X corresponds to the flow of services from the aggregate capital stock.

Technological progress occurs through R&D outlays that raise N over time. Hence, the variable N represents the current state of the endogenously determined technology. In this model, the leading technology—that is, the one that employs all N varieties that have been discovered—is used by all producers. Therefore, this specification fits best for general-purpose technologies (David [1991], Bresnahan and Trajtenberg [1995]), which have broad application in the economy.

Competitive producers of output, Y, equate the marginal product of labor to the wage rate, so that

$$w = (1 - \alpha) \cdot (Y/L)$$

Hence, the share of labor income is, as usual,

$$s_L = wL/Y = 1 - \alpha \tag{24}$$

Competitive producers also equate the marginal product of each type of intermediate input to the (monopoly) price of intermediates, $1/\alpha$. This condition can be expressed as

$$1/\alpha = \alpha \cdot (Y/X)$$

Therefore, the share of income expended on the N intermediates is

$$s_x = (1/\alpha) \cdot (X/Y) = \alpha \tag{25}$$

For durable inputs, the flow $(1/\alpha) \cdot (X/Y)$ would correspond to the monopoly rentals charged for capital services.

The growth rate of output can be computed from equation (23) as[7]

$$\dot{Y}/Y = \dot{A}/A + (1-\alpha) \cdot (\dot{N}/N) + s_L \cdot (\dot{L}/L) + s_x \cdot (\dot{X}/X) \tag{26}$$

where the formulas for s_L and s_x from equations (24) and (25) were used.[8] Therefore, the usual approach for computing the TFP growth rate yields, in this model,

$$\hat{g} = \dot{Y}/Y - s_L \cdot (\dot{L}/L) - s_x \cdot (\dot{X}/X) = \dot{A}/A + (1-\alpha) \cdot (\dot{N}/N) \tag{27}$$

Hence, despite the monopoly pricing of the intermediate inputs, the Solow residual correctly measures the sum of the contributions to productivity growth from exogenous technological change, $\dot{A}/A$, and endogenous expansion of varieties, $\dot{N}/N$.

[7] The underlying model of changing N assumes $\dot{A}/A = \dot{L}/L = 0$. However, equation (26) is valid as long as the marginal products of L and each of the x_j are equated to their factor prices.

[8] This approach treats N as a continuous variable. Probably it is best to think of N as a metaphor for the overall state of the technology, rather than literally the number of intermediate products that have been discovered.

Note from equation (27) that the endogenous-growth part of the Solow residual reflects only the fraction $1-\alpha$ of the growth rate of the number of varieties, $\dot{N}/N$. The remaining part, $\alpha \cdot (\dot{N}/N)$, is picked up as part of the term $s_x \cdot (\dot{X}/X) = \alpha \cdot (\dot{N}/N + \dot{x}/x)$ on the left-hand side of equation (27). For a fixed quantity x of intermediates of each type, the discovery of new types of products at the rate $\dot{N}/N$ induces an increase in the aggregate of intermediates at the same rate. The contribution of this expansion of intermediates to growth—which involves the coefficient α, the income share of payments to intermediates—is attributed to growth of factor inputs, rather than to the underlying technological progress. In effect, part of the technological advance from discoveries of new types of intermediate goods is embodied in the intermediates that use the new technology.

In the simplest varieties model, $\dot{N}$ is proportional to the amount of output devoted to R&D, $\dot{N} = (1/\eta) \cdot (R\&D)$, where η is a cost parameter that represents the amount of R&D required to achieve a unit increase in N. (In the present framework, this R&D cost is assumed to be constant.) Hence, the growth rate of N is given by

$$\dot{N}/N = (R\&D)/\eta N$$

The term ηN is the capitalized value of all past R&D outlays—the number N multiplied by the reproduction cost, η, for each invention. Therefore, the measured TFP growth rate in equation (27) satisfies

$$\hat{g} = \dot{A}/A + (1-\alpha) \cdot (current\ R\&D\ flow)/(market\ value\ of\ past\ R\&D) \tag{28}$$

In the varieties model, the chosen quantity x is proportional to L, so that the value Y/L computed from equation (23) is proportional to N. Since the denominator of the final term on the right-hand side of equation (28) equals ηN, this final term ends up proportional to the ratio of $R\&D$ to per worker output, Y/L. Thus, $\hat{g}$ in equation (28) can be expressed as a linear function of the ratio $(R\&D)/(Y/L)$. This result is similar to specifications used by Griliches (1973) and Coe and Helpman (1995), among others, except that R&D outlays enter in the varieties model in relation to per worker output, Y/L, rather that the level of output, Y. The source of the difference is that knowledge of the varieties of products, N, is non-rival in the varieties framework. For this reason, the model features a scale benefit from increases in L. (If $R\&D$, Y, and L all rise in the same proportion, then g increases.)

The empirical literature described by Griliches (1973) uses a regression approach to assess the effect of an R&D variable on the TFP growth rate. Thus, as in regression approaches to growth accounting, the analysis can be confounded by reverse-causation problems. In this case, the difficulty is that R&D spending would respond to exogenous changes in productivity growth—the variable $\dot{A}/A$ in equation (28)—so that the estimated coefficient on the R&D variable would proxy partly for exogenous technological progress. Satisfactory instrumental variables to avoid this problem may not be available. Possible instruments include measures of government policies toward R&D, including research subsidies, legal provisions such as the patent system, and the tax treatment of R&D expenditures.

Within the theory that underlies equation (28), it might be possible to extend the usual growth-accounting procedure to assess the contribution from R&D. That is, a modified Solow residual could be computed that subtracts from the growth rate of output, $\dot{Y}/Y$, not only the contributions from the growth of factor inputs, $s_L \cdot (\dot{L}/L) + s_x \cdot (\dot{X}/X)$, but also the term

$(1-\alpha)\cdot(current\ R\&D\ flow)/(market\ value\ of\ past\ R\&D)$. However, the computation of this term entails knowledge not only of the labor share, $1-\alpha$, and the current flow of R&D spending, but, in addition, the measure of the cumulated stock (or capitalized value) of past R&D.

It should also be recalled that the underlying model contains a number of restrictive assumptions. First, the R&D outlays appear directly in the measure of gross output. Second, the technological change, $\dot{N}/N$, applies uniformly across the economy. Third, no technological forgetting applies.

4.2 Quality-Ladders Models

The other prominent model of technological change in the recent endogenous-growth literature is the quality-ladders formulation due to Aghion and Howitt (1992) and Grossman and Helpman (1991, Ch. 4). In this framework, technological progress consists of improvements in the quality of intermediate inputs (or, equivalently, reductions in the cost of providing inputs of given quality). The number of varieties of products is usually assumed to be fixed in this setting, although changes in this number could again be admitted.

One simple specification, explored in Barro and Sala-i-Martin (1995, Ch. 7), uses the production function

$$Y = AL^{1-\alpha}\sum_{j=1}^{N}(q^{\kappa_j}x_{j\kappa_j})^{\alpha} \tag{29}$$

where A is the exogenous level of technology, L is labor input, $0<\alpha<1$, and N is the fixed number of varieties of intermediates. The parameter $q>1$ is the proportionate spacing between rungs on a given quality ladder. Technological progress occurs through R&D outlays that allow movements up the quality ladder, one step at a time. The variable κ_j is the highest quality-ladder position currently achieved in sector j. The variable $x_{j\kappa_j}$ is the quantity employed of the j^{th} type of non-durable intermediate.

The key element of the quality-ladders framework is that different quality grades of intermediate inputs within a given sector are modeled as perfect substitutes. Higher ranked inputs are simply better than lower ranked ones. For this reason, lower quality intermediates of type j (at the rungs $\kappa_j - 1, \kappa_j - 2, ...$) are driven out of the market in equilibrium. This technological obsolescence—or creative destruction—distinguishes the quality-ladders model from the varieties framework. In that framework—explored in the previous section—no technological obsolescence occurred, and new varieties of products worked along side the old ones to produce goods. (To some extent, this result depended on the additive separability of the quantities x_j in equation [22].)

Units of $x_{j\kappa_j}$ are again priced at the monopoly level, $1/\alpha > 1$, in each sector. Given the way that the quantities $x_{j\kappa_j}$ are determined (to equate the marginal product of each intermediate to the monopoly price), the production function in equation (29) can be rewritten as

$$Y = AL^{1-\alpha}X^{\alpha}\, Q^{1-\alpha} \tag{30}$$

where $X \equiv \sum_{j=1}^{N} x_{j\kappa_j}$ is the total spending on intermediates and Q is an aggregate quality index, given by

$$Q \equiv \sum_{j=1}^{N} q^{\kappa_j \alpha/(1-\alpha)} \tag{31}$$

Equation (30) implies that the standard growth-accounting approach would yield in this model

$$\hat{g} = \dot{Y}/Y - s_L \cdot (\dot{L}/L) - s_x \cdot (\dot{X}/X) = \dot{A}/A + (1-\alpha) \cdot (\dot{Q}/Q) \tag{32}$$

where $s_L = wL/Y$ and $s_x = (1/\alpha) \cdot (X/Y)$. Therefore, in this model, the Solow residual measures the sum of exogenous technological progress,

$\dot{A}/A$, and the growth rate of overall quality, $\dot{Q}/Q$, weighted by the labor share, $1-\alpha$.[9] This result is similar to equation (27) from the varieties model, except that the measure of technological change is $\dot{Q}/Q$, rather than $\dot{N}/N$. Again, a portion of the contribution from technological change (the part $\alpha \cdot \dot{Q}/Q$) is embodied in the growth of inputs ($\dot{X}/X$), and only the remainder appears in the Solow residual.

Some new results arise from the relation of $\dot{Q}/Q$ to R&D expenditures. In the version of the quality-ladders model explored in Barro and Sala-i-Martin (1995, Ch. 7), $\dot{Q}$ is proportional to aggregate R&D spending. The growth rate of Q can be expressed as

$$\dot{Q}/Q = c \cdot (current\ R\&D\ flow)/(market\ value\ of\ past\ R\&D) \quad (33)$$

where $0 < c < 1$ is a constant. In contrast to the varieties model, the constant c is less than one because of the obsolescence of the old types of intermediates in the sectors that experience quality enhancements. The constant c is higher the larger the ratio of the productivity of a newly discovered grade of intermediate input to the productivity of the next lowest grade, which just became obsolete. If this ratio is higher, then creative destruction is more creation than destruction and, hence, the contribution of the current R&D flow to the overall quality index, Q, is attenuated to a lesser extent. In the model, the key determinant of the productivity ratio is the parameter q, the proportionate spacing between quality grades.[10] A higher value of q implies a higher value of c.

[9] This analysis treats Q as a continuous variable. In fact, Q moves discretely over time corresponding to the effects of the discrete changes in the κ_j in equation (31). The continuous formulation is a reasonable approximation if the number of sectors is large and the stochastic changes in the various κ_j have a substantial amount of independence.

[10] The relation is $c = 1 - q^{-\alpha/(1-\alpha)}$, where $q > 1$ is the spacing between steps on the quality ladder.

The quality index, Q, can be viewed as a measure of the R&D capital stock. However, it is incorrect in this model to follow the common practice by which this stock is constructed. In the usual perpetual-inventory approach, the change in the R&D capital stock equals current R&D spending—the counterpart to gross investment—less depreciation on the existing R&D capital stock. The last term, often modeled as a constant fraction of the existing stock, is thought to correspond to obsolescence of old technologies. In the quality-ladders framework, the correct procedure is to discount current R&D expenditure by the factor $c < 1$ to allow for the contemporaneous obsolescence of lower quality intermediate inputs. Then this discounted R&D spending enters one-to-one as the net investment flow that changes the R&D capital stock (that is, the quality index, Q). The depreciation rate on this stock is zero, because no technological forgetting takes place in the model.

The growth-accounting formula can be written from equations (32) and (33) as

$$\hat{g} = \dot{A}/A + c \cdot (1-\alpha) \cdot (current\ R\&D\ flow)/(market\ value\ of\ past\ R\&D) \quad (34)$$

This result parallels equation (28), except for the presence of the coefficient $c < 1$. Thus, in the quality-ladders model, the contribution of the variable $(current\ R\&D\ flow)/(market\ value\ of\ past\ R\&D)$ to TFP growth is less than one-to-one partly because of the multiplication by the labor share, $1 - \alpha$, and partly because of the obsolescence coefficient, c. Since the coefficient c would not be directly observable, a non-regression approach to assessing the growth effects from R&D seems not to be feasible within the quality-ladders framework.

As in the varieties model, the market value of past R&D is proportional to output per worker, Y/L. Hence, g can again be expressed (from equation [34]) as a linear function of the ratio $(R\&D)/(Y/L)$. The effect of R&D on the TFP growth rate can therefore be assessed from a regression approach using this form of an R&D variable. In principle, the results could be used to estimate the obsolescence coefficient, c. However, this approach requires satisfactory instruments for the R&D variable. Possible candidates again include government policies with respect to R&D, including subsidies, legal provisions, and tax rules.

5 Conclusions

Standard growth-accounting exercises generate a Solow residual, which is typically viewed as a measure of technological progress. Recent theories of endogenous growth allow for a sharper perspective on this residual. Specifically, the residual can be clearly interpreted within settings that allow for increasing returns and spillovers or in models in which technological progress is generated by purposeful research. These interpretations provide guidance for explaining the residual in terms of R&D outlays, public policies, and other factors.

Two general conclusions are that standard growth-accounting exercises provide useful information within the context of modern theories of endogenous growth and that the recent theories can be used to extend the usefulness of traditional growth accounting. Hence, the older and newer approaches to economic growth are complementary.

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Table 1

Estimates of TFP Growth Rates

OECD	**1947-73**	**1960-73**	**1973-89**
Country	**TFP growth rate**	**TFP growth rate**	**TFP growth rate**
Canada	0.018	0.011	0.003
France	0.030	0.023	0.014
Germany	0.037	0.026	0.009
Italy	0.034	0.040	0.006
Japan	0.040	0.058	0.011
Netherlands	0.025	—	—
United Kingdom	0.019	0.019	0.007
United States	0.014	0.008	0.003

Latin America, 1940-1990		**East Asia, 1966-1990***	
Country	**TFP growth rate**	**Country**	**TFP growth rate**
Argentina	0.005	Hong Kong	0.023
Brazil	0.008	Singapore	0.002
Chile	0.014	South Korea	0.017
Colombia	0.008	Taiwan	0.026
Mexico	0.011		
Peru	-0.006	*Hong Kong value is for 1966-91.	
Venezuela	0.001		

Notes: OECD estimates for 1947-73 are from Christenson, Cummings, and Jorgenson (1980). OECD estimates for 1960-73 and 1973-89 are from Dougherty and Jorgenson (1997, Table 3). Latin American estimates are from Elias (1990), updated with unpublished notes from Victor Elias. East Asian estimates are from Young (1995, Tables V-VIII).

Table 2

Primal and Dual Estimates of TFP Growth Rates

Country	**Primal Estimate**	**Dual Estimate**
Hong Kong, 1966-1991	0.023	0.027
Singapore, 1972-1990	-0.007	0.022
South Korea, 1966-1990	0.017	0.015
Taiwan, 1966-1990	0.021	0.037

Notes: These estimates are from Hsieh (1998, Table 1). The primal estimates are computed from data on growth rates of quantities of factor inputs, using factor income shares as weights. The dual estimates are computed from data on growth rates of prices of factor inputs, using the same factor income shares as weights. The lack of coincidence for the primal and dual estimates of TFP growth rates is discussed in the text.