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**Solow vs. Solow:
Notes on Identification and Interpretation
in the Empirics of Growth and Development***

by

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ABSTRACT

Most empirical studies of long run growth refer to one of the two seminal contributions by Robert Solow (1956, 1957). His work shows that in order to estimate the relative roles of factor accumulation and technology in development, an a priori identification assumption is needed about the nature of technical change. This specific assumption differs across the two Solow papers. I show that starting with the identification assumption made in Solow (1956), one should expect to find that differences in technology rather than differences in factor accumulation explain most if not all of the observed long-run differences in output per worker. The opposite interpretation appears to prevail in parts of the recent literature on the empirics of growth.

1. Introduction

Understanding the long run growth rate of an economy is of central importance to national policy makers, and understanding the vast international differences in the level of output per worker is of central importance for devising effective development policies. Most empirical studies in these fields refer to one of the two seminal contributions by Robert Solow (1956, 1957), which discuss the role of factor accumulation and technical change in long-run growth and development. His work shows that in order to estimate the relative roles of factor accumulation and technology in development, an a priori identification assumption is needed about the nature of technical change. This specific assumption differs across the two Solow papers.

The remarkable comeback of non-parametric accounting studies in the empirics of growth and development highlights that the subtle though quantitatively important methodological difference between Solow (1956) and Solow (1957) is not always recognized. Following Solow (1957), recent growth accounting studies have been used to measure a possible acceleration of the long run growth rate in the US and other advanced economies since the mid 1990s.¹ Following Solow (1956), development accounting studies have been used to identify the relative roles of factor accumulation and technology in explaining international differences in output per worker.² Unfortunately, a clear-cut empirical distinction between the relative contributions of factor accumulation and technical change (or technology differences across countries) cannot be achieved by conventional methods of growth accounting. This problem has been known in the literature for long, but it has consistently been ignored in most of the recent discussion. Non-parametric accounting methods can only identify what a given concept of technical change implies for the interpretation of observed growth rates or levels of development but they cannot identify whether the a priori chosen concept is correct in the sense that it reflects the true nature of technical change.

In principle, parametric estimation methods could be used to identify the potential factor augmenting bias of technical change. But in practice, such a solution is marred by empirical

¹ Examples include Gordon (2000), Jorgenson and Stiroh (2000), and Oliner and Sichel (2000).

² Examples include Klenow and Rodriguez-Clare (1997), and Hall and Jones (1999).

problems. The main empirical problems are the often missing robustness of non-linear regression techniques which is required to estimated flexible functional forms, and the potential endogeneity of standard explanatory variables which requires appropriate instruments in order to achieve unbiased regression coefficients. That is, an econometric approach may require a priori restrictions to guarantee the consistency of the parameter estimates with economic theory and, therefore, brings back the same identification problem that plagues non-parametric methods. Most surprising is, however, that cross-country regression analyses that claim to be in line with the Solow (1956) model have modeled the level of technology as part of the regression constant. The seminal paper in this line of research is Mankiw et al. (1992)³. By default, their modeling strategy does not allow for one of the basic insights of the Solow growth model (1956), namely that long run differences in output per worker should be due to differences in technology.

The next section presents some stylized facts and highlights the methodological ambiguities that surround every empirical study of growth and development. Section 3 shows that different assumptions about the factor bias of technical change necessarily result in quantitatively different assessments of the relative roles of factor accumulation and technology in growth and development. Reconsidering what has been called the neoclassical revival in growth economics, Section 4 clarifies why empirical results that show a large contribution of technology differences to explaining income differences actually support the Solow growth model (Solow 1956), contrary to what has sometimes been said in the literature.

2. Stylized Facts and the Identification Problem

Leaving aside any statistical problems of measuring output and factor input, the standard methodology used in the empirics of growth and development suggests that an observed difference in output per unit of labor input – either over time or across countries - can result from two sources: from a movement along a production function, or from a shift of the production function. An upward movement along a production function reflects an increase in factor accumulation. An upward shift of the production function reflects a change in

³ This paper has generated a large empirical literature. For detailed references to this literature, see, e.g., <http://www.bris.ac.uk/Depts/Economics/Growth/refs/augsol.htm>, and <http://www.bris.ac.uk/Depts/Economics/Growth/refs/levels.htm>.

"technology", which can be interpreted in broader terms than just including technical change, especially in a cross-country context.⁴

However, the notion of technical change proves to be an elusive concept when it comes to empirical estimation. In the growth accounting literature, it is often neglected that there is no way to estimate the *size* of the rate of technical change from a given set of data without implementing an identifying assumption that determines *how* the underlying production function might shift. Since identifying assumptions may reasonably differ, interpreting productivity growth often means different things to different people. Figure 1 tries to highlight the basic problem in the context of some stylized facts of growth and development.

Points A and B are assumed to be generated by production functions with diminishing returns. Both points may represent observed combinations of output per hours worked (labor productivity y) and capital per hours worked (capital intensity k), either at different points in time or across countries. The question is how much of the observed increase in labor productivity from $y(A)$ to $y(B)$ can be explained in terms of increased factor accumulation (as a movement along a given production function) and how much can be explained in terms of technical change (as a shift of the production function to a higher level).

Three stylized facts of growth and development provide helpful restrictions. First, the capital output ratio appears to be fairly constant on average, for individual countries in the long run and also across countries. For instance, average labor productivity has grown about as fast as average capital intensity in the United States in the 20th century, which implies a constant capital output ratio (see, e.g., Mankiw 2000). And in cross-country data, there is a statistically significant correlation between the log levels of labor productivity and capital intensity,

⁴ For instance, countries obviously differ, among other things, by geographic and climatic conditions, disease ecologies, and institutional frameworks. Most of these factors appear to be fairly persistent over time; some, like climate and geography, do not change at all in economically relevant time. All of these factors can be expected to impact on output per worker, either directly or indirectly through their effects on factor accumulation and population growth. Such a broad concept of "technology" has recently been proxied by variables such as frost frequency (Masters and McMillan 2001), malaria prevalence (Sachs 2001, 2003), and institutional infrastructure (Hall and Jones 1999, Acemoglu et al. 2001), where the proxy variables may be considered as identifying international differences in agricultural technology, health technology, and institutional technology.

pointing to a constant capital output ratio on average. At a minimum, the international variation in the capital output ratio appears to be small relative to the variation in output per worker and the variation in capital per worker (Hall and Jones 1999). In Figure 1, a constant capital output ratio shows up as the slope of the straight line through the origin.

Second, the shares of capital and labor in factor income have remained fairly constant over time in industrialized countries (Gust and Marquez 2000), and they appear to be fairly constant across countries as well (Gollien 2002). With a constant capital output ratio and constant factor shares, it follows as a third stylized fact that the rate of return to capital has remained more or less constant in industrialized countries over the long run, and does not differ systematically across countries. In Figure 1, the constant rate of return to capital shows up as the identical slope of the straight lines through A and B , which represent tangents to two production functions in the $y-k$ space. The intersection of each tangent with the y -axis identifies the real wage w as a function of the capital intensity. As Figure 1 is drawn, the relation between the real wage and labor productivity is held constant, which reflects the stylized fact of a constant labor share.⁵

Hence given the stylized facts of growth and development with regard to factor shares, the capital output ratio, and the rate of return to capital, at least part of the increase in labor productivity would have to be interpreted as due to a shift of the production function. But since the shift of the production function cannot be directly observed, it is principally impossible to know from data on labor productivity and capital intensity alone which part of the change in labor productivity is due to a change in technology and which part is due to a change in factor accumulation. This identification problem is well known for more than a quarter century at least (Nelson 1973) and has been discussed in great detail in theory (Diamond et al. 1978) but, as Hulten (2000) notes in passing, has generally been ignored in the applied productivity literature.

⁵ In Figure 1, $w(A)$ and $w(B)$ are fixed at 70 percent of $y(A)$ and $y(B)$, which approximately equals the size of labor's share in factor income.

3. Accounting for Growth with Alternative Technology Assumptions

In terms of Figure 1, the basic methodological question is *how* a production function through A should be shifted to end up as a production function through B . For instance, there could be a vertical upward shift, a horizontal leftward shift, or a shift along the straight line through the origin. Under certain additional conditions to be discussed below, shifts of the production function along these lines would be neutral with regard to the functional distribution of income, i.e., they would be compatible with the observed constancy of factor shares.⁶ However, the three distribution-neutral shifts of the production function would imply rather different interpretations of the relative roles of factor accumulation and technical change in a decomposition of labor productivity.

A most general form of the production function would specify output (Y) as a function of capital (K), labor (L), and technology such that

$$(1) \quad Y = F(B(t)K, A(t)L) ,$$

where technical change is assumed to be factor augmenting, with factors A and B growing over time. For $A(t) = 1$, technical change is said to be purely capital augmenting, for $B(t) = 1$, it is said to be purely labor augmenting, and for $A(t) = B(t)$, it is said to be both capital and labor augmenting.

Up to now the growth accounting literature has mainly relied on a concept of technical change with $A(t) = B(t)$. This concept is called Hicks-neutral and is defined as a shift of the production function that leaves unchanged the capital intensity k for any constant factor price relation w/r .⁷ Hicks-neutral technical change appears to conform most naturally to the notion of neutrality because it implies a vertical upward shift of the production function along a constant capital intensity in a diagram like Figure 1. However, it should be noted that the term "neutral" as defined above actually refers to constant factor shares, not necessarily to a constant capital intensity.

⁶ For an early textbook discussion of distribution-neutral shifts of the production function see, e.g., Allen (1967).

⁷ For recent surveys of the literature, see Barro (1999) and Hulten (2000).

Since constant factor shares appear to be a stylized fact in time series and in cross country data, it is probably no coincidence that the Cobb-Douglas production function with constant returns to scale and a unit elasticity of substitution has been widely used in the applied growth literature. In addition, this specific functional form guarantees the existence of a steady state for a production function like (1) independent from the specific parameter values for $A(t)$ and $B(t)$.⁸ Hicks-neutral technological change can be incorporated into a Cobb-Douglas production function as

$$(2) \quad Y = C(t)K^{\alpha}L^{(1-\alpha)} ,$$

where $C(t) = A(t) = B(t)C$, and α is capital's share in factor income. Using small letters to indicate per capita terms, equation (2) can be rewritten in growth rates as

$$(3) \quad \Delta y = \Delta C(t) + \alpha \Delta k ,$$

where Δ indicates a rate of change over time. Equation (2) is the standard formula used in the literature to account for the sources of labor productivity growth, where the term $\alpha \Delta k$ is called capital deepening and the term $\Delta C(t)$, which accounts for the rate of Hicks-neutral technical change, is called total factor productivity growth. For instance, if average labor productivity grows at 2 percent and capital intensity also grows at 2 percent, which roughly describes the long run growth experience of the United States, using a capital share in factor income of one third implies that the contribution of capital deepening would be estimated to be 2/3 percentage points, with a residual contribution of total factor productivity growth (of Hicks neutral technical change) of 4/3 percentage points. Hence by employing Hicks-neutrality as the identifying assumption in this specific example, 66.6 percent of the observed increase in labor productivity would be attributed to a shift of the production function, and 33.3 percent would be attributed to a movement along the production function.

A different identifying assumption should produce a different quantitative result for the relative roles of factor accumulation and technical change. For instance, the concept of Solow

⁸ For a textbook discussion, see, e.g., Allen (1967); for a more recent treatment, see, e.g., Barro and Sala-i-Martin (1995).

neutral technical change refers to the case $A(t) = 1$ and is defined as a shift of the production function that leaves unchanged the labor output ratio for any constant real wage. A constant real wage at constant labor productivity again satisfies the condition of constant factor shares. This specific concept of technical change has been held to be more appropriate than the concept of Hicks neutrality for the case of developing countries (Fei and Ranis 1963). But also for G7 countries in 1960-97, Boskin and Lau (2000) find, based on the econometric estimation of an aggregate meta-production function, that technological change may indeed be represented as "generalized Solow neutral".

Like Hicks neutrality, Solow neutrality would (only) be consistent with steady state growth for the special case of a Cobb-Douglas production function, which can always be rewritten in a way that is consistent with a constant capital output ratio in the presence of growth. But the implied contributions of factor accumulation and technical change would differ under the two neutrality assumptions, even in the case of a Cobb-Douglas production function. With Solow neutrality for the Cobb-Douglas case, output equals

$$(4) \quad Y = (B(t)K)^\alpha L^{(1-\alpha)} ,$$

so it follows that

$$(5) \quad \Delta y = \alpha \Delta B(t) + \alpha \Delta k .$$

Comparing equations (5) and (3), it is tempting to infer that the contribution of total factor productivity to growth, which is represented by the whole first term on the right side of equation (5), does not seem to depend on the identifying assumption. Hence it is often concluded that when using a Cobb-Douglas production function, it does not matter for an assessment of the relative roles of factor accumulation and total factor productivity which specific form of distribution-neutral technical change is employed.

In my view, such an interpretation is misleading. As it is used in the literature, the term total factor productivity, as indicated by its appropriate name, is invariably tied to the concept of Hicks neutral technical change. If technical change turns out to be Solow neutral rather than Hicks neutral, the concept of total factor productivity can no longer be reasonably applied.

This is because Solow neutrality is defined for a constant labor output ratio, not for a constant capital intensity as in equation (6). Using Solow neutrality as the identifying assumption, the appropriate accounting equation would thus follow as

$$(6) \quad \Delta y = \Delta B(t) + \Delta k - \frac{1-\alpha}{\alpha} \Delta y \quad ,$$

where y in the third term on the right-hand-side equals the inverse of the labor output ratio. Hence by definition, the concept of Solow neutrality gives a larger weight to the contribution of technical change in a decomposition of labor productivity growth than Hicks neutrality, since

$$(7) \quad \Delta B(t) = \frac{1}{\alpha} \Delta C(t) \quad .$$

With $\alpha = 1/3$ as before and Solow neutrality as the identifying assumption, the contribution of technical change to labor productivity growth would be estimated to be three times as large as in the case of Hicks neutrality. At face value, there is no way to decide which of the two estimates of the contribution of technical change is more plausible. Following Solow (1956), however, one would conclude that Hicks neutrality and Solow neutrality are both misleading approaches when applied in the empirical analysis of long run growth.

One reason is that, as mentioned before, Hicks neutrality and Solow neutrality are only consistent with steady state growth under the specific assumption of a Cobb-Douglas production function. The other reason is that the variables to be held constant in these concepts of technological change, namely the capital intensity and the labor output ratio, are actually not constant but change over time (and differ across countries) in a systematic way. Given the stylized facts of growth and development as discussed in the previous section, a concept of technological change that holds constant the capital output ratio should provide a more promising starting point for empirical analyses of growth and development.

The concept of Harrod neutral technological change, employed in Solow (1956), satisfies both conditions. It is consistent with a steady state for the case of a general production

function⁹ and it holds constant the capital output ratio. That is, Harrod neutral technological change is defined as a shift of the production function that leaves unchanged the capital output ratio for any constant rate of return to capital. Harrod neutral technological change is labor augmenting in the sense that it is equivalent to an increase in the labor force. Hence Harrod neutrality assumes that a shift of the production function causes changes in capital intensity in order to maintain a constant capital-output ratio in the presence of a rising labor force. In this interpretation, changes in capital intensity would result because of the change in technology and, therefore, should be counted as endogenous. Comparing two steady states, all of the observed difference in labor productivity would accordingly be counted as being entirely due to the contribution of exogenous technical change.

With Harrod neutrality in the Cobb-Douglas case, output equals

$$(8) \quad Y = K^{\alpha} (A(t)L)^{(1-\alpha)} ,$$

so holding the capital output ratio constant it follows that

$$(9) \quad \Delta y = \Delta A(t) + \frac{\alpha}{(1-\alpha)} \Delta(k/y) ,$$

which is the basic equation used in the development accounting studies by Klenow and Rodriguez-Clare (1997) and Hall and Jones (1999). It follows by definition that

$$(10) \quad \Delta A(t) = \frac{1}{(1-\alpha)} \Delta C(t) = \frac{\alpha}{1-\alpha} \Delta B(t) ,$$

which shows that Harrod neutrality gives a larger weight than Hicks-neutrality and a smaller weight than Solow neutrality to the contribution of technical change to growth. With a capital share of 1/3 as before, equation (10) states that by using Harrod neutrality as the identifying assumption, the contribution of technical change to labor productivity growth would be estimated to be 50 percent larger than under Hicks neutrality and 50 percent smaller than under Solow neutrality.

⁹ For a recent textbook discussion, see, e.g., Barro and Sala-i-Martin (1995).

My accounting exercises are meant to demonstrate that it is not possible to decide on the basis of non-parametric methods which concept of technical change is the correct one. Since the specific factor-augmenting properties of technological change cannot be directly observed, they have to be imposed as an a priori assumption. Theory and empirics do suggest, however, that Harrod neutrality appears to be the most convenient concept of technical change in studies of long run growth. Nevertheless, most growth accounting studies still use Hicks-neutrality as the identifying assumption. Starting from Solow (1956), growth accounting studies would give a substantially larger weight to the contribution of technical change to labor productivity growth. And for samples with a more or less constant capital output ratio, which could be considered as representing steady state behavior across units of observation, one should in fact expect to find that almost all of the observed differences in labor productivity (over time or across countries) are due to differences in technology.

4. The Neoclassical Revival and Its Critics Reconsidered

After the advent of endogenous growth theory in the mid 1980s (Romer 1986, Lucas 1988), the empirical study by Mankiw et al. (1992, henceforth MRW) is usually held to represent one of the basic cornerstones of a “neoclassical revival”¹⁰ in empirical growth economics. The MRW paper reports cross country regression results, which show that international differences in factor accumulation are statistically significantly correlated with international differences in output per worker. Abstracting from all detail and focusing on the simplest case with just two factors of production,¹¹ MRW start from equation (8) and use an equation like (see also equation (9))

$$(11) \quad \ln y_i = \ln A(t) + \frac{\alpha}{(1-\alpha)} \ln(k/y)_i + \varepsilon_i$$

¹⁰ This term was coined by Klenow and Rodriguez-Clare (1997) and refers specifically to the papers by Mankiw et al. (1992), Mankiw (1995), Barro et al. (1995), and Young (1995); see also Easterly and Levine (2001).

¹¹ MRW augment the Solow growth model by a third factor of production, namely human capital. Their empirical results are meant to support the augmented Solow model, not the textbook Solow model, but this does not make a difference for the point to be discussed below.

to run an OLS regression in log levels across a sample of countries $i = 1 \dots n$, with ε as an i.i.d. error term. Assuming a constant rate of technical change, the technology term is considered as part of the regression constant, thereby imposing the restriction that there are no systematic differences in technology across countries. The regression coefficient on their proxy variable for the capital output ratio is estimated to be statistically significant and of a size which implies a factor share of capital of about 1/3 (at least in the specification which includes a measure of human capital), which quantitatively confirms a priori expectations. Therefore, MRW claim to provide strong empirical support in favor of the (augmented) Solow growth model.

Klenow and Rodriguez-Clare (1997, henceforth KRC) criticize the MRW approach and claim that the cross-country data do not support the Solow growth model. Again abstracting from all detail, KRC use a variant of equation (9) as a non-parametric accounting equation in levels and estimate the technology term as a residual:

$$(12) \quad \ln A(t)_i = \ln y_i - \frac{\alpha}{(1-\alpha)} \ln(k/y)_i \quad .$$

Since the international variation in the capital output ratio is small relative to the international variation in output per worker, they find, somehow by default, a large contribution of the residual (of international differences in Harrod neutral technology) to international differences in output per worker. KRC interpret their accounting result as providing strong empirical evidence against the restriction imposed in the MRW approach, namely that technology does not systematically differ across countries. Therefore, KRC conclude that research needs to be re-focused on models that emphasize differences in technology rather than differences in factor accumulation.

The puzzling aspect in this debate is that the neoclassical growth model has been interpreted by these two studies as a model that emphasizes differences in factor accumulation as an explanation for differences in output per worker. This interpretation appears to persist in the literature on the empirics of growth, at least according to a recent overview by Easterly and Levine (2001), but it appears to be in conflict with the basic insight of the Solow growth model (Solow 1956). This is most obvious by looking again at Figure 1. Imposing the restriction that there are no systematic differences in technology across countries, the MRW

regression approach approximates points A and B by a single production function.¹² But the Solow growth model holds that the steady state difference in output per worker between points A and B should result from a shift of the production function rather than from a movement along a production function.

KRC use a more plausible approach to estimate the Solow growth model by allowing for variation in the level of technology across countries. Yet because their empirical evidence is in obvious conflict with the MRW evidence, and the MRW findings are presumed to confirm the Solow growth model, KRC interpret their findings as empirical evidence against the Solow growth model. In my view, this is not justified. Nevertheless, KRC are right to argue that what is needed is a better understanding of the factors behind the observed international differences in the level of the residual variable called technology.¹³

Recent contributions by Hall and Jones (1999), Acemoglu et al. (2001), and Sachs (2001, 2003) can be interpreted as first steps in this direction. These studies point to country specific factors such as institutional frameworks or natural endowments like climate, geography, and disease ecology as the major determinants of international income differences. Abstracting from the ongoing discussion on the relative importance of institutions and endowments, the impact of these variables on labor productivity can be estimated in principle by a modified cross-country regression equation like equation (11).

One possibility to capture the potential productivity effects of endowments and institutions would be to model the technology term of equation (11) as a broad concept of technology that allows for country-specific factors, as informally suggested by Solow (2001). That is, Harrod neutral technology $A_i(t)$ can be assumed to grow for each individual country i with the same constant rate g over time t , but at different levels which are determined by various factors X_i such that

¹² The relatively good fit of the MRW regression arises because they use the log investment share in GDP and the log of the growth rate of the labor force (conditioned by a rate of technological change of 2 percent and a depreciation rate of 3 percent) instead of the log of the capital output ratio, which is of course not exactly constant across countries.

¹³ This point is also emphasized by Prescott (1998).

$$(13) \quad A_i(t) = A(0) e^{gt} e^{\phi_k X_{ik}} ,$$

where $A(0)$ stands for the initial level of a narrow concept of technical knowledge which is the same for all countries, and X_k may capture factors $k=1...I$ such as institutions and endowments that differ across countries but remain fairly stable over time. Equation (13) suggests that persistent differences in X across countries would explain persistent differences across country-specific production functions, which in turn would shift over time due to the common constant rate g .

With this modification of the technology term and by imposing the alternative restriction that the capital output ratio is part of the regression constant, equation (11) can be rewritten as

$$(14) \quad \ln y_i = \ln A(0) + gt + \frac{\alpha}{(1-\alpha)} \ln(k/y) + \phi X_i + \varepsilon_i ,$$

which reproduces the basic structure of the regression equations used by Hall and Jones (1999), Acemoglu et al. (2001), and Sachs (2003). That is, by imposing a cross-country restriction on the factor accumulation term rather than on the technology term, these studies reproduce the non-parametric accounting result of KRC with a parametric methodology, namely that international differences in a broad concept of technology account for international differences in output per worker. Notwithstanding all sorts of empirical estimation problems, it appears that this result is much closer to the basic message of the Solow growth model than the results presented by MRW.

5. Conclusion

Two seminal papers by Robert Solow continue to influence empirical research on growth and development. Following Solow (1957), a large literature has attempted to account for the relative contributions of technical change and factor accumulation to growth in output per worker. What has been known for long but has rarely been discussed recently is that non-parametric accounting methods require an a priori identification of the factor bias of technological change. Neoclassical growth theory following Solow (1956) and empirical evidence on a relatively constant capital output ratio both suggest that Harrod neutrality is the

most convenient identifying assumption to begin with in empirical analyses of long run growth. However, traditional growth accounting studies usually employ Hicks neutrality as the identifying assumption. By default, one would estimate a contribution of technical change to growth and development that is about 50 percent higher with Harrod neutrality than with Hicks neutrality.

Hence by estimating the Solow growth model in a cross-country context, one should expect to find a large contribution of technology differences in explaining international differences in the level of development. The opposite interpretation prevails in parts of the applied literature. Studies showing a large contribution of factor accumulation have been held to support the Solow growth model, and studies showing a large contribution of technology have been held to reject the Solow growth model. In my view, such an interpretation neglects the subtle differences in the identifying assumptions between Solow (1956) and Solow (1957), which imply substantially different roles of factor accumulation and technical change in the empirics of growth and development. This insight is not new but obviously ignored in most recent applied work.

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Figure 1 — Stylized Facts About Growth and Development: From A to B

