A RE-EXAMINATION OF SOLOW'S GROWTH MODEL WITH APPLICATIONS TO CAPITAL MOVEMENTS

Neantro Saavedra Rivano

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1. Introduction and summary

The main purpose of this paper is to re-examine the
neo-classical Solow's growth model. A very simple formalism
underlying this model is developed (section 2) and shown to
have several uses. First, it allows an easy generalization
of Solow's model to the case of differentiated saving
propensities (section 3). Second, two-country models can be
treated more simply (section 4). And finally, some generally
accepted results on the long-run benefits of free capital
mobility can be properly interpreted and understood. In
particular, it is shown that under reasonable assumptions,
in the context of a two-country model, and starting from an
autarkic long-run equilibrium, freeing the movements of
physical capital may diminish in the long run the welfare of
one of the countries and even shrink the per-capita world
capital stock.

2. The simple model

Let us recall, for convenience, the conventional neo-
classical (Solovian) setting of a one-sector growing
economy. A single good is produced using capital $K$ and labor
$L$ in a way described by a linear homogeneous production
function $F(K, L)$. Letting $k = K/L$ and

$$f(k) = F(K/L, l),$$

the usual (Inada) conditions on the production function can
be stated as follows:

- $f(0) = 0$
- $f'(k) > 0$
- $f(k) - kf'(k) > 0$
- $\lim_{k \to 0} f'(k) = 0$
- $\lim_{k \to +\infty} f'(k) = +\infty$
- $f''(k) < 0$

It is further assumed that a constant fraction $s$ of income
(identical to the product, up to this point) is saved, and
that labor grows at a constant rate $n$. The accumulation
equation, expressed in per-capita terms, is easily found to

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be

\[ k = sf(k) - nk \]

(1)

This is a rather simple differential equation in the state variable \( k \). It has a unique equilibrium solution \( \hat{k} \), which is easily shown to be globally stable. The straightforward method of finding the steady-state value of the capital-labor ratio is simply to equate to zero the right-hand side of (1)

\[ sf(k) = nk \]

This can be also done graphically by finding the intersection (other than the origin) of the graph of the concave function \( sf(k) \) with the straight line \( nk \).

The method of solution we will adopt instead is less direct, but it will serve us well in what follows. It consists of two steps. The first may be interpreted as solving a version of this model for a small open economy. The second is the specialization from this enlarged case to the original closed economy case. It turns out that this procedure uncovers some interesting features of the Solow model and allows also for easier generalizations.

2.1. A growing small open economy

Let us rewrite the accumulation equation (1) as

\[ \dot{k} = sy - nk \]

where per-capita income \( y \) substituted per-capita output \( f(k) \), and decompose now income according to factor payments:

\[ y = rk + w \]

(2)

where \( r \) is the profit rate, \( w \) the wage rate. Assume now that the profit rate is exogenously given, while the wage is related to it through the factor-price frontier. The resulting accumulation equation is

\[ \dot{k} = sw - (n-sr)k \]

(3)

and it should be interpreted as that of a small open economy facing a given world profit rate. Notice that capital \( k \), owned by nationals, which is fixed in the short run, differs in general from capital employed domestically and entering the production function, so that there will be imports or exports of physical capital according to whether the former is larger or smaller than the latter. The latter, denoted by \( \hat{k} \), is determined by the exogenously given profit rate from the profit-maximizing relation.
the inverse functional relation will be denoted \( k(r) \).

Of course, fixing \( r \) is equivalent to fixing \( k \) and also to fixing the wage rate \( w \); note in addition the following useful though well-known relation

\[
\frac{dw}{dr} = -k(r) \quad (4)
\]

The growth model described by (3) is linear and has in particular the interesting feature that its steady-state equilibrium solution can be determined explicitly as a function of the given parameters, especially among them the world profit rate \( r \):

\[
k(r) = \frac{sw(r)}{n-sr} \quad (5)
\]

Of course, a necessary and sufficient condition for the existence of an economically meaningful long-run equilibrium is that denominator of the preceding expression be positive

\[
r ( n/s ) \quad (6)
\]

The equilibrium solution is then unique and globally stable. From now on it will always be assumed that the profit rate is in the range defined by this inequality.

Of even greater interest are the properties of the function \( k(r) \) that gives the steady-state value of the capital-labor ratio as depending on the world profit rate and which can be summarized in the following proposition

**Proposition 1.** a) The function \( k(r) \) is U-shaped, attaining its minimum value at \( r_0 \) characterized by

\[
sw ( k(r_0) ) = n k ( r_0 )
\]

b) At its minimum \( r_0 \)

\[
k(r_0) = k( r_0 )
\]

c) \( k(r) \) is larger (resp. smaller) than \( k(r) \) if and only if \( r \) is larger (resp. smaller) than \( r_0 \).

In addition, the derivative of \( k(r) \) can be computed explicitly as
For a proof see the Appendix. The situation is pictured in figure 1. The results of these proposition may be seen from a different perspective if one recalls that the datum of \( r \) is equivalent to that of capital domestically employed \( \kappa \), so that the steady-state value of \( k \) can be alternatively seen as a function of \( \kappa \), denoted also \( k(\kappa) \). One sees then immediately, from the preceding proposition, that, as a function of \( \kappa \); a) \( k \) is also a U-shaped function, that attains its minimum at \( \kappa_0 \approx r(\kappa_0) \); b) at its minimum, \( k = \kappa_0 \); and c) \( k(\kappa) \) is larger (resp. smaller) than \( \kappa \) if and only if \( \kappa \) is smaller (resp. larger) than \( \kappa_0 \). Figure 2 illustrates these results.

2.2. The closed-economy solution

It is clear that the long-run equilibrium solution \( \hat{r} \) to Solow's original model (1) corresponds to the autarkic particular solution of (3), obtained when there are no exports nor imports of physical capital or, in other terms, when

\[
k(\kappa) = \kappa
\]

This is equivalent to

\[
k(r) = \kappa(r)
\]

where, as before, \( \kappa(r) \) is the inverse function of \( r = f'(r) \). From the above proposition and subsequent comments, it follows that \( \hat{r} = \kappa_0 \), the point at which \( k(\kappa) \) attains its minimum. As in the long run per-capita income is proportional to the capital-labor ratio, the proposition can be interpreted as stating that any deviation from autarky (be it by importing or exporting capital) will improve the welfare of the economy and, indeed, that the larger the deviation from autarky the larger the gains in the capital-labor ratio, and thus in welfare. In short, a country will benefit from opening itself to international capital movements in the long run as well as in the short run.

That the long-run part of this last statement is not as safely established as the short-run part (see MacDougall (1960) for the latter) will be seen in the next section. At this point, however, it is interesting to note the following asymmetry in the preceding result. While imports of capital in any amount will increase necessarily the steady-state capital-labor ratio, there are limits to the part of capital owned by nationals that can be exported.
This is because imports of capital correspond to a lowering of \( r \) while exports of capital amount to increasing \( r \), which is constrained by inequality (6).

3. A Kaldorian generalization

Following Kaldor (1957) we will consider now the case of differentiated saving propensities. It will be assumed that a constant proportion \( s_L \) of wage income together with a constant proportion \( s_K \) of profit income is saved. It is expected that the saving propensity out of wages is smaller than that out of profits, although this is not a necessary restriction in what follows. The accumulation equation is easily seen to become

\[
k' = s_L w + s_K r k - nk \tag{8}
\]

where, as before, the profit rate is exogenous and the wage rate is related to it through the factor-price frontier.

3.1. The generic case

We will consider in the first place the generic case when the saving propensity out of wages is positive. The steady-state value of the capital-labor ratio, as a function of the world profit rate \( r \), is again explicitly obtained from the linear differential equation (8)

\[
k(r) = \frac{s_L w}{n - s_K r} \tag{9}
\]

The necessary and sufficient condition for existence of this long-run equilibrium, which ensures its uniqueness and global stability, is

\[
r < \frac{n}{s_K} \tag{10}
\]

The results in proposition 1 are generalized as follows

**Proposition 2.**

a) The function \( k(r) \) is U-shaped, attaining its minimum value at \( r_0 \) characterized by

\[
s_K f(k(r_0)) = nk_0
\]

b) At its minimum

\[
s_K k(r_0) = s_L k(r_0)
\]

\[1\] We are not unaware of the controversy sparked by this "Kaldorian" hypothesis on savings (for an account of this, see for instance, Hahn and Matthews 1964). Nevertheless, we will adopt it as a convenient way of reflecting the impact of income distribution on saving behavior.
c) $k(r)$ is larger (resp. smaller) than $s_L$ if and only if $r$ is larger (resp. smaller) than $r_m$.

In addition, the derivative of $k(r)$ can be computed explicitly as

$$k'(r) = \frac{s_L k(r) - s_L k(r)}{n - s_L k(r)} \quad (11)$$

For a proof see the Appendix. The situation is pictured in figures 3 and 4, for the case when the saving propensity out of wages is smaller than that out of profits (the other case being similar). Notice that figure 4 illustrates the results taking capital domestically employed $K$, whose datum is equivalent to that of $r$, as the dependent variable. As it is pictured: a) $k(r)$ is a U-shaped function, attaining its minimum at $k_0 = k(r_0)$; b) at its minimum, $s_L k = s_L k'$; and c) $k(r)$ is larger (resp. smaller) than $s_L / s_K$ if and only if $K$ is smaller (resp. larger) than $k_0$.

As proposition 2 shows and figures 3,4 illustrate, the steady-state value of the capital-labor ratio attains its minimum in autarky only in the very special case of equal saving propensities. Otherwise, the minimum is reached elsewhere. For example, if $s_L < s_K$, a movement away from autarky will increase the per-capita capital stock in the case of lending but will decrease it in the case of borrowing. The intuitive reason for the decrease in the latter case is clear: an influx of capital will depress the rate of profit, thus altering the distribution of income to the benefit of labor; savings arising in a larger proportion out of profits, as assumed, the economy will leave its steady-state path for one where the per-capita capital stock decreases.

A similar behavior is observed for per-capita income. At the steady state, per-capita income is

$$y(r) = w(r) + rk(r) \quad (12)$$

so that

$$y'(r) = k(r) - k(r) + rk'(r) \quad (13)$$

At the autarkic point $k = K$, both $y'$ and $k'$ have the same positive sign (we assume always $s_L < s_K$); but at the minimum point defined by $s_L k = s_L k'$, where $k' = 0$ and $k < K$, we have that $y'$ is negative. This means that, although lending leads also to a decrease in per-capita income, the minimum value of income is reached at a lower level of lending than the minimum value of the capital-labor ratio is.

3.2. The Marxian singular case.

If the saving propensity out of wages is zero, the accumulation equation (8) becomes.
\[ k = (n - s_k r) k \]  
(14)

There is no function \( k(r) \) in this singular case, instead the value of the profit rate is fixed:
\[ r = n/s_k \]  
(15)

which necessarily fixes the capital-labor ratio in production as well
\[ f'(k_0) = n/s_k \]

In the autarkic case, \( k = k_0 \), while in the small open-economy case, \( k \) becomes arbitrary. A movement away from autarkic long-run equilibrium increases income if the country is a lender, decreases it if the country is a borrower. Indeed, \( y = kr + w \), so that, with \( r, w \) fixed, income is a linear function of \( k \) and the country is a lender (resp. borrower) whenever \( k \) is larger (resp. smaller) than \( k_0 \).

4. Two-country models

4.1. The setting.

We shall deal simultaneously with two economies (labelled by the numbers 1,2), obeying specifications similar to those in section 3 above. The accumulation rule will be given by
\[ k^i = \sum_{i=1}^2 w_i + s_{k_i} r_i k_i - nk_i \quad i = 1,2 \]  
(16)
as in (3). The same rate of population growth is assumed everywhere, but neither the saving propensities nor the production functions need be the same across countries.

Under capital immobility (autarky), the two economies are totally independent, the equations in (16) being solved separately in the manner indicated before. On the other hand, under perfect capital mobility capital flows instantaneously across borders so as to equalize the rate of profit at all times. Because of the interdependence implied by a common rate of profit, the equations in (16) constitute a system that must be solved simultaneously.

We are interested in the comparison of the long-run equilibria corresponding to these two capital mobility regimes. Specifically, the experiment to be carried out is the following. Starting from the long-run autarkic equilibrium, allow capital to flow unimpeded across countries so that, under the new accumulation rule, a new long-run equilibrium will be attained. The question then is to determine if both economies benefit or not in the long
run from this transition, as measured in terms of per-capita capital owned and income.

4.2. Analysis of the steady states.

Equating to zero the right-hand side of (16), the following conditions on the steady states of this two-country world are obtained (recall (9))

\[ k_i = \frac{S_i W_i}{n - SK_i r_i} \quad i = 1, 2 \quad (17) \]

In the autarkic case each of these two expressions, together with the respective conditions \( r_i = f'_i(k_i) \), yields the long-run values \( k_i \) of the per-capita capital stock. In the case of perfect capital mobility, we need specify the dependence of the common rate of profit \( r \) on the per-capita capital stocks of both countries. If \( k_1, k_2 \) are the two countries' relative factor endowments at a given moment, let \( k \) be total world capital normalized by the population of country 1:

\[ k = k_1 + \lambda k_2 \quad (18) \]

where \( \lambda \equiv L_2 / L_1 \) is the constant labor force ratio. Under a regime of perfect capital mobility, capital is allocated in production across countries such that

\[ k = k_1 + \lambda k_2 \]
\[ f'_1 (k_1) = f'_2 (k_2) \]

The common profit rate \( r \) thus established at each moment depends uniquely on the world factor ratio \( k \) and not on the distribution of its ownership \( E \). It turns out that the inverse functional relation is easier to describe:

\[ k_w(r) = k_1(r) + \lambda k_2(r) \quad (19) \]

where \( k_1(r) \) is the inverse function of \( f'_1(k_1) \) defined in 2.2. and \( k_w(r) \) denotes the world factor ratio associated with a given international profit rate \( r \).

While \( k_w(r) \) should be interpreted as the normalized world stock demand for capital associated with a given profit rate \( r \), we also have the normalized long-run world stock supply for capital associated with \( r \)

\[ k_w(r) = k_1(r) + \lambda k_2(r) \quad (20) \]

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2 This relies crucially, of course, on the one-good assumption of our model.
where $k_j(r)$ was defined in (17). The steady-state value $r$ of the world profit rate, from which the values of all other variables can be determined, is then obtained from the equation

$$k_w(r) = k_w(r)$$

(21)

It is worth recalling that the autarkic long-run value $r^*_j$ of the profit rate in each country is obtained from

$$k_j(r) = k_j(r)$$

as was shown in section 3 above.

As for the solution of (21), we have the following

**Proposition 3.** For $r < \min \left( n/s_1, n/s_2 \right)$, equation (21) has a solution, and any such solution lies in the interval between $r^*_1$ and $r^*_2$.

See the Appendix for a proof. We will always suppose that the solution is unique, the situation is then pictured in figure 5.

A variety of situations appear that will depend on the values of the saving propensities in the two countries and on the values of the autarkic profit rates. Some of these will be described now.

### 4.3. Ruffin's case

In an elegant paper, Ruffin (1979) shows that, if each country saves a constant proportion of its income, the transition from long-run autarkic equilibrium to a regime of perfect capital mobility will be mutually advantageous in the long run. We can establish Ruffin’s result very easily within our framework. Indeed, it was proved in section 2 (under the assumption of a uniform saving propensity) that any non-autarkic long-run equilibrium results, for each country, in a welfare improvement (as measured by per-capita income or capital stock) over the autarkic steady-state.

### 4.4. ‘North-South’ case

Suppose, as in Findlay (1980), that country 1 (the ‘North’) has a uniform saving propensity $s_1$, while in country 2 (the ‘South’) the propensity to save out of wages is zero so that only a fraction $s_2$ out of profit income is saved for accumulation purposes. We shall assume, in addition, that the autarkic long-run profit rate is higher in the South than in the North, so that after a regime of capital mobility is established, capital will flow from the North to the South. As in the preceding case, the North will benefit from this transition, in the sense that both its per-capita income and capital owned will be higher in
the new long-run equilibrium. On the other hand, since the South becomes a borrower, its per-capita income and capital owned will decrease, as was seen in section 3.2. above. More remarkable is the fact that the fall in \( k_2 \) must always exceed the rise in \( k_1 \), so that in effect the world economy, as measured by \( k = k_1 + \lambda k_2 \), contracts. To prove this assertion, observe in the first place that the long-run value of the Southern rate of profit is the same under both capital mobility regimes (see (15)) and thus capital-labor ratios must also coincide

\[
\hat{k}_2 = \hat{k}_2
\]

On the other hand, the Northern rate of profit increases after the transition to a regime of capital mobility, and the capital labor-ratio diminishes accordingly:

\[
\hat{k}_1 < \hat{k}_1
\]

Since, in the long run, capital mobility thus reduces \( k_1 \), but leaves \( k_2 \) and \( \lambda \) unchanged, \( k_w = k_1 + \lambda k_2 = k \) must decline:

\[
\hat{k} < \hat{k}
\]

4.5. A more general asymmetry.

We propose to show that some of the preceding results can be maintained even if the propensity to save out of wages \( s' \) in the South is nonzero, albeit smaller than the propensity to save out of profits \( s \). To simplify matters, let us assume that both countries share the same production function \( f \), that \( \lambda \leq 1 \), and that the Northern uniform saving propensity equals the Southern propensity to save out of profit.

The analysis of the steady states outlined in section 4.2. becomes particularly simple and can be illustrated in Figure 6. Given the assumptions just made, in particular \( s' < s \), \( k_2(\hat{r}) \) is multiple of \( k_1(\hat{r}) \) and lies below it. While \( \hat{r}_1 \) is determined by the intersection of \( f'(\hat{r}) \) and \( k_1(\hat{r}) \), which occurs at its minimum, \( \hat{r}_0 \) is necessarily larger. In addition, as it follows from proposition 3, the long-run world profit rate \( \hat{r} \) lies in between \( \hat{r}_1 \) and \( \hat{r}_2 \). It follows then that while the North benefits in the long run from the transition to perfect capital mobility, the South will see its per-capita capital stock diminish and in general also its per-capita income.

Of even more interest is the fact that in some cases the world capital stock will shrink, i.e.

\[
k_w(\hat{r}) < k_1(\hat{r}_1) + k_2(\hat{r}_2)
\]

This happens, for instance, if the production function is of the Cobb-Douglas type.
\[ f(k) = k^a \]

with \( a = 0.2 \) and the values for the other parameters are:
\( \varepsilon = 0.4, \varepsilon' = 0.1, n = 0.02 \). In this case, \( k_w(F) = 54.2 \), \( k_1(r_1) = 42.3 \) and \( k_2(r_2) = 13.5 \).

It could not be determined, however, whether the world average per-capita income might also decrease in the transition to perfect capital mobility in this case.

5. Concluding remarks.

This article has re-examined Solow's one-sector growth model with the objective of applying it to the discussion of some commonly accepted propositions on the benefits of perfect capital mobility in the context of a two-country growing world. Adopting the conventional assumption of constant saving propensities, it was found that a situation of mutual per-capita income gains for both countries is rather exceptional. Not only may borrowing countries easily lose but, globally, the world may, in some instances, become worse off as a consequence of free capital movements. These results also help to understand some previous results of Burgstaller and Saavedra-Rivano (1984) and of Saavedra-Rivano (1982).

Appendix.


Proposition 1 being clearly a particular case of proposition 2, we will only prove the latter. Simple differentiation with respect to \( r \) of \( k(r) \), as expressed in (9), gives easily

\[ k'(r) = \frac{s_k k(r) - s_L k(r)}{n - s_k r} \]

which is the last assertion in proposition 2. Next, from the expression (9) for \( k(r) \) one immediately finds that

\[ s_k k(r) - s_L k(r) = s_L \frac{s_k f(k(r)) - n k(r)}{n - s_k r} \]

whence the remainder of proposition 2 follows at once.
A2. Proof proposition 3.

Let us assume, without loss of generality, that \( r_1 < r_2 \). Observe also that the restriction on the values of \( r \) in the body of proposition 3, which is nothing more than a restatement of the restriction assumed immediately after inequality (6), serves to ensure that \( k_1(r) \) and \( k_2(r) \) are always positive. In order to prove the proposition, let us note that as a consequence of proposition 2, \( k_1(r) - k_1(r) = k_2(r) - k_2(r) \) is negative for \( r < r_1 \) and positive for \( r > r_1 \), while similarly \( k_2(r) - k_2(r) \) is negative for \( r < r_2 \) and positive for \( r > r_2 \). We thus conclude that their sum \( k(r) - k(r) \) is negative for \( r < r_1 \) and positive for \( r > r_2 \), whence the proposition follows immediately by continuity.

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Figure 3 \((s_L < s_K)\)

Figure 4 \((s_L < s_K)\)
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