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CATCH-UP, GROWTH AND CONVERGENCE IN THE OECD

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ABSTRACT

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This paper analyses the sources of post-war growth and convergence in the OECD using an extension of Mankiw, Romer and Weil's (1992) model in which the rate of technical progress is determined endogenously by the level of R&D spending and a process of technological catch-up. The results indicate that the impact of R&D investment on growth has been significant. Technological catch-up is found to be very fast and seems to have played an important role in OECD convergence during the first half of the sample period. The exhaustion of this effect, moreover, may help explain the slowdown of growth and convergence after the mid-1970s, and suggests that further convergence will require an important investment effort on the part of poorer countries. Finally, there is evidence that the neoclassical convergence effect is also operative but its contribution to convergence in output per worker has been minor.

JEL Classification: O30, O40
Keywords: growth, convergence, catch-up

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NON-TECHNICAL SUMMARY

What determines the relative growth performance of different economies? Economists have long held that the immediate answer to this question lies mostly in factor accumulation. Traditional neoclassical models emphasized the role of investment in physical capital. More recently, the literature on endogenous growth marks a shift to a broader concept of capital which includes human and technological capital as well. The key message, however, remains unchanged: countries that save and invest more tend to grow faster and have higher income levels in the long run. Controlling for investment rates, the theory also identifies two mechanisms which, potentially at least, tend to favour poorer countries, thereby generating a tendency for what is often called convergence. If technology displays diminishing returns to reproducible factors, the return on investment will be higher in capital-poor countries which will therefore grow faster than richer ones with the same investment rate and may, in addition, be able to attract foreign investment. Second, countries that are less technologically advanced may find it possible to grow quickly by adopting foreign technologies at a relatively low cost.

This paper quantifies the contribution of these various mechanisms to economic growth and income convergence in the OECD countries during the period 1963–88. As a framework, I develop a descriptive growth model which incorporates simultaneously the main immediate determinants of growth, i.e. the accumulation of physical and human capital and technical progress fuelled by R&D investment and technological diffusion across countries. The model extends some recent work in this area, notably by Dowrick and Nguyen (1989), Barro and Sala (1990, 1992) and Mankiw, Romer and Weil (MRW 1992), and tries to provide a comprehensive framework for the analysis of a number of growth and convergence mechanisms that have often been studied separately in the literature. Starting from MRW's model of growth through the accumulation of physical and human capital, I partially endogenize the rate of technical progress by allowing it to be a function of R&D investment and a measure of technological backwardness. The resulting model incorporates both the 'neoclassical convergence effect' due to the existence of diminishing returns to reproducible factors, emphasized by Barro and Sala (1992) and MRW (1992), and the technological catch-up effect analysed by Dowrick and Nguyen (1989), making it possible to attempt to separate the two.

Starting from the theoretical model I derive a convergence equation which allows us to express the growth rate of income per capita as a function of the level of the same variable, investment rates in physical, human and

technological capital, and the initial technological gap between each country and an exogenous technological frontier. As in MRW or Barro and Sala, the coefficient of initial income in this equation yields an estimate of the strength of a neoclassical convergence effect that reflects the degree of returns to scale in reproducible factors. The present specification, however, also provides estimates of the speed of technological diffusion and of the contribution of R&D investment to productivity growth.

After constructing a suitable proxy for the initial technological gap, the equation is estimated using panel data for 21 OECD countries during the period 1963–88, controlling for cyclical shocks. The results tend to confirm those of previous empirical studies. Investment in physical, human and technological capital has a significant positive effect on growth, and the estimated values of the parameters of the production function are not out of line with those reported in the literature (although the coefficient of physical capital is slightly higher and that of human capital slightly lower than those reported by MRW). Both convergence mechanisms (neoclassical and catch-up) seem to be operational. The estimated value of the neoclassical convergence coefficient, which is close to the 2% figure that has become standard in the literature, implies slightly decreasing returns in reproducible factors and, by itself, would induce slow convergence towards a steady state determined by investment rates. The speed of technological diffusion, however, seems to be very rapid. The estimated catch-up parameter is over 10% a year, implying that the half-life of the process of technological convergence (towards a long-run level of relative technical efficiency which is determined by the intensity of R&D investment) is less than a decade.

The estimated model, together with the underlying data, is then used to quantify the immediate sources of post-war growth and convergence in the OECD countries. For each of six subgroups of this sample (North America; Australia and New Zealand; EFTA; the richer EEC countries; the poorest four EEC countries; and Japan) I calculate the contribution to growth of factor accumulation, R&D investment, neoclassical convergence, technological catch-up and cyclical perturbation. As expected, the joint impact of the two convergence factors (neoclassical convergence and technological catch-up) strongly favours the poorer countries, particularly at the start of the period, but the size of this effect decreases rapidly over time. The cross-sectional behaviour of investment rates, however, is not particularly conducive to convergence, as some of the higher income groups present above-average rates of factor accumulation and *vice versa*. Differences in investment rates, however, seem to account for much of the differential performance within the top and bottom of the distribution (i.e. Japan vs. the poorer EEC countries, and North America vs. Australia and New Zealand).

One of the clearest conclusions to emerge from the analysis is that the catch-up effect seems to have played an extremely important role in income dynamics during the post-World War II period. Technological diffusion is by far the largest source of growth differentials in early subperiods, accounting for up to four points in the case of Japan, but drops to less than one point towards the end of the sample. On the whole, this factor seems to account for most of the observed decline in income dispersion during the first part of the sample period. The exhaustion of catch-up opportunities, moreover, may help explain the slowdown of growth and convergence in more recent years, although cyclical factors have undoubtedly played a role as well.

To conclude, the paper emphasizes that the existence of forces promoting convergence is not sufficient to guarantee the elimination of existing income differentials, even in the long run. Using the estimated parameters, we compute each country's level of relative income in a long-run equilibrium (under the assumption that investment rates remain constant at their observed levels in the 1980s) and find that predicted long-run income dispersion is significantly higher than that observed in 1988. Although unpleasant, this prediction may not be unreasonable. In fact, it is compatible with the experience of recent years, which have been characterized by the halt of the convergence trend, and also with the rapid decrease of inequality observed during the first part of the sample period. My results, then, are consistent with Abramovitz's (1987) view that post-war convergence was driven to a large extent by a process of rapid technological catch-up. With this process pretty much exhausted, however, we now find ourselves in a situation in which the only road to convergence is an important increase in the investment effort of the poorer countries.

1.- Introduction

What determines the relative growth performance of different economies? Economists have long held that the immediate answer to this question lies mostly in factor accumulation. Traditional neoclassical models emphasized the role of investment in physical capital. More recently, the literature on endogenous growth marks a shift to a broader concept of capital which includes human and technological capital as well. The key message, however, remains unchanged: countries which save and invest more tend to grow faster and have higher income levels in the long run. Controlling for investment rates, the theory also identifies two mechanisms which, potentially at least, tend to favour poorer countries thereby generating a tendency for what is often called convergence. If technology displays diminishing returns to reproducible factors, the return on investment will be higher in capital-poor countries which will therefore grow faster than richer ones with the same investment rate and may, in addition, be able to attract foreign investment. Secondly, countries which are less technologically advanced may find it possible to grow fast by adopting foreign technologies at a relatively low cost.

An extensive empirical literature -- stretching back at least to the pioneering growth accounting studies of Solow (1957) and Denison (1962)-- has attempted to test the relevance and quantify the contribution of these various growth mechanisms. In recent years, this line of research has attracted a good deal of attention, in large part as a response to new theoretical developments in growth economics and to an increasing awareness of the 'practical' importance of the subject. Recent papers by Dowrick and Nguyen (1989), Barro and Sala i Martin (1990, 1992), Mankiw, Romer and Weil (MRW, 1992) and Lichtenberg (1992), among others, have investigated the sources of growth and convergence, using explicitly formulated growth models as a framework for empirical analysis.

The present paper builds on this work and seeks to extend it. Section 2 develops a descriptive growth model which tries to incorporate simultaneously the main immediate determinants of growth, i.e. the accumulation of physical and human capital and technical progress. The model extends some recent work in this area and tries to provide a comprehensive framework for the analysis of a number of growth and convergence mechanisms which have often been studied separately in the literature. Starting from MRW's model of growth through the accumulation of physical and human capital, I partially endogenize the rate of technical progress by allowing it to be a function of R&D investment and a measure of technological backwardness. The resulting model incorporates both the "neoclassical convergence effect" due to the existence of diminishing returns to reproducible factors, emphasized by Barro and Sala (1992) and MRW (1992), and the technological catch-up effect analyzed by Dowrick and Nguyen (1989), making it possible to attempt to separate the two.

In Section 3, a convergence equation derived from the model is estimated using pooled OECD data. The results, together with the underlying data, are used in Sections 4 and 5 to try to tell a coherent story about post-war growth and convergence in this sample. For each of six groups of OECD countries, I calculate the contribution to growth of factor accumulation, R&D investment, neoclassical convergence and technological catch-up. The results suggest that the contribution to growth of R&D investment and technological catch-up has been substantial. The latter factor, moreover, accounts for most of the income convergence observed during the first half of the sample period and its gradual exhaustion helps explain both the growth slowdown and the halt in the convergence process observed after the mid 1970s.

2.- The Mechanics of Growth and Convergence

The predictions of theoretical models concerning the prospects for income convergence across countries depend crucially on two technological assumptions: the existence, or inexistence, of increasing returns to reproducible factors, including the stock of technical knowledge or "technological capital," and the degree to which useful knowledge is a public good across countries.

Traditional neoclassical models, based on the assumptions of decreasing returns to capital and free access by all countries to a common stationary technology, predict that growth cannot be sustained permanently but have optimistic implications from the point of view of convergence. In the absence of technical progress, decreasing returns imply that the marginal product of capital will fall with the accumulated stock, reducing both the incentive to save and the contribution of a given volume of investment to output growth. As a result, growth will gradually slow down and, under standard assumptions, will eventually stop. The same logic explains the convergence prediction: poorer countries will have a greater incentive to save and a higher rate of growth for a given rate of investment. Hence, they will gradually reduce the distance which separates them from their wealthier neighbours. Moreover, this result will be reinforced by open-economy considerations, as factor flows and trade will both contribute to factor price equalization.

The introduction of exogenous technical progress in this framework allows for sustained growth but does not modify the convergence result, provided we maintain the assumption that technology is a pure public good in the sense that all countries have access to the same stock of useful knowledge. In fact, for the convergence prediction to survive, it is enough to assume that this is true in the long run. In this line, a potentially important factor in the convergence process is the technological *catch-up* effect emphasized by Abramovitz (1979, 1986) and other authors. According to this hypothesis, the possibility of imitating at low cost technologies developed elsewhere should allow poor countries to grow faster than rich ones, other things equal.

The considerations we have just outlined have traditionally served to justify a certain optimism regarding the long-run perspectives of the less developed countries. Even a quick look at the data, however, shows that the evolution of the world income distribution has not confirmed such expectations. The dispersion of income per capita in broad samples has increased throughout the post-WWII period, and a cross-section regression of growth rates over this period on initial income per capita yields a positive coefficient, suggesting that rich countries have grown faster, on average than poor ones.1 These facts, together with the historically upward trend of average growth rates, have inspired the search for alternatives to the traditional neoclassical model, giving rise in recent years to the endogenous growth literature.2 Building on the work of authors like Arrow (1962)

[1] See for example Parente and Prescott (1993) or de la Fuente (1995).
[2] See for example Romer (1986) and Lucas (1988).

and Uzawa (1965), this literature has explored the implications of increasing returns and the determinants of the rate of technical progress, reaching predictions which are in some cases very different from those of the traditional models.

Romer (1986), for example, has shown that the existence of aggregate scale economies can invert the neoclassical predictions of a falling growth rate and convergence across countries. With increasing returns in reproducible factors,[3] the return on investment is an increasing function of the accumulated stock. As a result, the growth rate will increase with time and with the level of income. In the same line, Lucas (1988), Grossman and Helpman (1991) and Romer (1990) show that positive growth rates may be sustained indefinitely in models in which the rate of technical progress is determined endogenously and reflects private investment decisions in human or technological capital, provided such activities are not subject to diminishing returns due, for example, to the existence of learning effects. In these models, moreover, permanent differences in growth rates may arise as a result of differences across countries in economic policies, market size, or factor endowments.

Most of the recent empirical work on these issues has focused on the degree of returns to scale to reproducible factors as the determinant of the speed of income convergence. Romer (1987a) tests the hypothesis that the rising dispersion of per capita incomes may be due to the existence of increasing returns using a convergence equation derived from a production function which allows for external effects from capital accumulation. Although Romer cannot reject the hypothesis that the aggregate production function exhibits constant returns in capital and labour, his estimate of the coefficient of capital (which is roughly twice this factor's observed share in national income) is consistent with the existence of important externalities and implies slow income convergence. Other authors, however, find the existence of externalities of the required size implausible and argue that Romer's estimates are probably biased by the endogeneity of his regressors and the omission of some important variables. Thus, if technical

[3] With a positive rate of population growth, the existence of increasing returns in all factors (including labour) also allows for sustained growth of income per capita. In this case, however, the rate of growth of per capita income is an increasing function of the rate of population growth, a result which seems quite implausible, since practically all empirical studies find a significant negative relationship between the rates of growth of population and income per capita.

progress or the accumulation of human capital, in addition to directly increasing productivity, lead to higher investment in physical capital (to incorporate new technologies to production processes, for example), the omission of these variables would tend to exaggerate the impact of investment on growth.[4] To explore this possibility, Barro and Sala (BS, 1990, 1992), Mankiw, Romer and Weil (MRW, 1992) and other authors estimate different variants of the neoclassical growth model which incorporate human capital as an input in the production function. Their results suggest that the accumulation of both physical and human capital has played an important role in growth and are consistent with slow convergence towards steady states which may differ across countries reflecting underlying differences in investment rates.

One common feature of this work is that the finding of a negative partial correlation between growth and initial income is interpreted as evidence of decreasing returns in reproducible factors. There is, however, a second possibility (which does not exclude the first): if income per capita is correlated with the level of technological development, the estimated coefficient of initial income in growth regressions may be capturing, at least in part, a technological catch-up effect.

In fact, one of the earliest studies in the convergence literature, due to Dowrick and Nguyen (DN, 1989), incorporates an extreme form of this hypothesis. DN construct an extension of the standard neoclassical model (without human capital) in which the rate of technical progress is determined in part by the speed of technological diffusion. In their specification, the technological catch-up effect is proportional to the ratio of each country's per capita output to that of the leading country (the US). The resulting convergence equation is very similar to the one estimated by MRW, but the interpretation of some of its coefficients is quite different. In particular, the negative coefficient of initial income is interpreted by the authors as evidence of a strong catch-up effect which, according to their calculations explains most of the observed reduction in income disparities within the OECD.

[4] In addition to the studies cited in the text, see Benhabib and Jovanovic (1991). In more recent work (1989a, 1990b), Romer himself seems to have come to the conclusion that the high coefficient of physical capital found in his earlier paper was due in part to the correlation of investment with omitted factors.

In the light of the previous discussion, a potential objection to DN's conclusions is that their catch-up coefficient may reflect in part the effect of diminishing returns rather than technological diffusion. Clearly, the reverse criticism also applies to the studies by BS or MRW, casting some doubt on the accuracy of their estimates of the returns to scale parameter. One of the objectives of this paper is to try to disentangle the effects of the two convergence mechanisms identified by the literature. To this end, in Part a of this section I will develop an extension of MRW's model with human capital in which the rate of technical progress is a function of R&D expenditure and each country's distance from a "technological frontier" which shifts upward at an exogenous rate. In Section 2b, I derive a convergence equation suitable for empirical work from a log-linear approximation to the model. As in MRW or Barro and Sala, the coefficient of initial income in this equation yields an estimate of the strength of a neoclassical convergence effect which reflects the degree of returns to scale in reproducible factors. My specification, however, also provides estimates of the speed of technological diffusion and of the contribution of R&D investment to productivity growth.[5] The results will then be used in Section 3 to explore the immediate sources of the differential growth performance of various groups of OECD countries.

2.a.- A descriptive growth model

This section develops a simple descriptive model which builds on some recent work in the growth literature. The model is closely related to those proposed by Dowrick and Nguyen (1989), Barro and Sala i Martín (1990) and Mankiw, Romer and Weil (1992), but differs from them in that it explicitly incorporates the possibility of increasing returns and partly endogenizes the rate of technical progress. To simplify the exposition, I will assume for the time being that there is a single type of capital, introducing the distinction between physical and human capital in the empirical part of the paper.

Let us assume technology can be adequately described by an aggregate production function of the form

[5] Lichtenberg (1992) extends the model proposed by MRW to incorporate R&D investment. In his specification, however, technological capital is treated in the same way as physical or human capital and does not affect the rate of technical progress, which is taken as exogenous.

(1) $Y = \Phi K^{\alpha}(AL)^{1-\alpha} = \Phi ALZ^{\alpha}$

where A is an index of labour-augmenting technical progress and K denotes a broad capital aggregate which includes both human and physical capital. The variable Z = K/AL denotes the capital/labour ratio in efficiency units. To incorporate the possibility of increasing returns in the simplest possible way, we will assume that the term Φ, although perceived as exogenous by individual agents, is in fact a function of the form $\Phi = \bar{Z}^{\mu}$, where $\bar{Z}$ is average capital intensity (which coincides with Z in a symmetric equilibrium).[6]

Under these assumptions, output per worker is given by

(2) $Q = AZ^{\alpha+\mu}$

where $\alpha+\mu$ measures the degree of returns to scale in reproducible factors (i.e. in the various forms of capital, but not in labour) taking into account capital's indirect contribution to productivity through possible externalities.

By assumption, growth of output per worker must be the result of the accumulation of productive factors or the outcome of technical progress. Taking logarithms of (2) and differentiating with respect to time, we see that the rate of growth of output per capita $Q'/Q = g_Q$,[7] can be written as the sum of two terms which reflect, respectively, the rate of technical progress and the accumulation of reproducible factors:

(3) $g_Q = g_a + (\alpha+\mu)\, g_z$.

It remains to specify the immediate determinants of g_a and g_z. Let us start with the second factor. Denoting by s the fraction of GDP invested in physical or human capital, and by δ the rate of depreciation, the increase in the aggregate capital stock, K', is given by the difference between investment and depreciation, that is,

[6] This specification is basically the one proposed by Romer (1986) to capture the possibility that capital accumulation may generate positive spillovers. A possible justification is provided in Romer (1987b). If there are fixed entry costs, a larger capital stock will allow an increase in the number of firms and a finer division of labour. Increased specialization, particularly by producers of intermediate goods, could then improve overall efficiency.

[7] We will use the notation $x' = dx/dt$ for the derivative of x with respect to time. The growth rate of x will be denoted by $g_x = x'/x$.

(4) $K' = sLQ - \delta K$.

Since $Z = K/AL$, the growth rate of the stock of capital per efficiency unit of labour, g_Z, is the difference between $g_k = K'/K$ and the sum of the rates of technical progress and growth of the labour force. Using (2) and (4), it is easy to see that

(5) $g_Z = g_k - g_a - n = sZ^{\alpha+\mu-1} - (n+g_a+\delta)$

where $Z^{\alpha+\mu-1}$ is the average product of capital taking into account the externality.

Finally, we have to specify the determinants of the rate of technical progress, g_a. We will assume that g_a is an increasing function of the fraction of GDP invested in R&D (θ) and of the opportunities for technological catch up, measured by the log difference ($b = \ln X/A$) between a "technological frontier" denoted by X and the country's own technological index, A:

(6) $g_a = \gamma\theta + \varepsilon b$.

The parameters ε and γ measure, respectively, the speed of diffusion of new technologies across countries and the productivity of R&D. We will also assume that best-practice technology shifts out at a rate g_x which we will take as exogenous from the perspective of each given country and assume constant for simplicity.

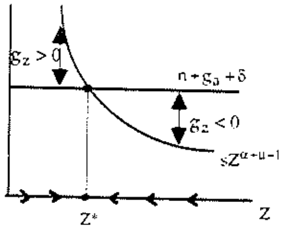
To analyze the dynamics of the system in an informal way, it will be convenient to consider capital accumulation and technical progress separately. Let us start by studying the evolution of the stock of capital per efficiency unit of labour, which is described by equation (5). Assuming for now that the rate of technical progress, g_a, is an exogenous constant, we can draw both terms on the right-hand side of (5) as functions of Z. As shown in Figure 1, the rate of factor accumulation, g_Z, is the difference between the product of the investment rate and the average product of capital, $sZ^{\alpha+\mu-1}$, and the constant $(n+g_a+\delta)$.[8]

[8] The figure ignores the fact that the rate of technical progress, g_a will be changing over time, causing a vertical displacement of the horizontal line. It can be shown, however, that the "whole system" is stable. Asymptotically, the horizontal line stops shifting as g_a converges to the constante value g_x and Z converges to Z^* as shown in the figure.

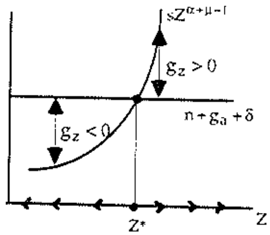
The behaviour of the dynamical system described by (5) depends crucially on the value of $\alpha+\mu$. When $\alpha+\mu < 1$, that is, when the neoclassical assumption of decreasing returns holds, the return on investment, given by $Z^{\alpha+\mu-1}$, is a decreasing function of the stock of capital. The growth rate decreases with Z and becomes negative for Z sufficiently large. (See Figure 1a). Hence, the system is stable, and the stock of capital per efficiency unit of labour converges to its stationary value, Z*, characterized by

$$g_Z = 0 \;\Rightarrow\; (7)\; Z^* = \left(\frac{s}{n+g_a+\delta}\right)^{1/(1-\alpha-\mu)}.$$

Figure 1: Dynamics of factor accumulation



a.- Decreasing returns to capital



b.- Increasing returns

When the external effects associated with the accumulation of capital are sufficiently strong that $\alpha+\mu > 1$, the situation is very different, as shown in panel b of Figure 1. Since the return on investment is now an increasing function of the stock of capital per efficiency unit of labour, the rate of accumulation increases with Z instead of falling. Hence, Z grows when it is larger than Z* and falls when it is smaller, moving farther and farther away from the steady state, which must now be interpreted as a threshold for growth rather than as a long-run equilibrium.

The implications of these results for convergence are clear. Given two countries identical except in their initial capital stocks (i.e. with access to the same technology and similar rates of investment and population growth), the evolution of their stocks of capital and therefore of their relative incomes depends crucially on the existence or inexistence of increasing returns to scale in reproducible factors.

Under the assumption of decreasing returns, the stock of capital per worker (and hence average productivity) will converge to a common value. With increasing returns, on the other hand, the advantage of the initially richer country will increase over time.

To analyze the impact of technical progress on growth and convergence it will be convenient to work explicitly with two countries, f and l, (follower and leader). Let us define the technological distance between leader and follower by

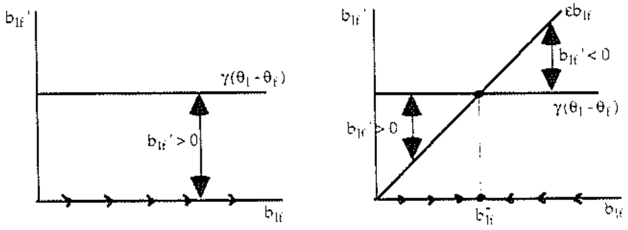
$$b_{lf} = a_l - a_f = b_f - b_l$$

where b_l and b_f denote the technological distance between each of these countries and the best-practice frontier. Observe that the evolution of relative technological backwardness, b_{lf}, satisfies the equation

$$(8)\ b_{lf}' = a_l' - a_f' = \gamma(\theta_l - \theta_f) + \varepsilon(b_l - b_f) = \gamma(\theta_l - \theta_f) - \varepsilon b_{lf}.$$

Figure 2 shows the dynamics of this equation under two assumptions on the value of ε. When there is no technological diffusion (ε = 0), the leading country (which by assumption invests more in R&D) always has a higher rate of productivity growth. As a result, b_{lf}' is always positive and the technological distance between leader and follower, b_{lf}, grows without bound as shown in Figure 2b.

Figure 2: Evolution of the technological distance between leader and follower



a.- No technological diffusion b.- Catch-up with technological diffusion

When ε > 0, on the other hand, the line εb_{lf} is positively-sloped and cuts the horizontal line $\gamma(\theta_l - \theta_f)$ at a finite value of b_{lf} we will denote by b_{lf}^*. Under this assumption, the model is stable: b_{lf}' is positive (that is the technological gap increases over time) when b_{lf} is below its stationary value, b_{lf}^*, and negative (b_{lf} decreases) otherwise (see Figure 2b). Hence, the technological gap converges to a finite value, b_{lf}^*, defined by

$$b_{lf}' = 0 \quad \text{fi} \quad (9) \quad b_{lf}^* = \frac{\gamma(\theta_l - \theta_f)}{\varepsilon} .$$

In the long run, the (logarithm of the) ratio of the productivity indices of the two countries converges to a constant value which is directly proportional to the difference between their rates of investment in R&D, and inversely proportional to the speed of technological catch-up.

In summary, each of the processes we have considered (factor accumulation and technical progress) may or may not induce divergence in per capita incomes. If the technology displays increasing returns in capital ($\alpha+\mu > 1$), the rate of return on investment increases with the stock of capital, and the system displays "explosive" behaviour. Over time, growth accelerates in each given country, and income differences across nations increase without bound. On the other hand, when $\alpha+\mu < 1$ the return on investment falls with accumulation and this implies that stocks of capital per worker (and hence per worker income levels) tend to converge across countries, provided they share the same technology. Similarly, the evolution of relative technical efficiency may adopt two quite different patterns. If there is no international technological diffusion ($\varepsilon=0$), the country which invests more in R&D will always have a higher rate of productivity growth. If there is a diffusion effect, however, the technological distance between the two countries will tend to stabilize at a point at which the advantage derived from the possibility of imitation is just sufficient to offset the lower R&D investment of the follower.

Considering the two factors jointly, we can distinguish between two cases. When the technology exhibits increasing returns in capital ($\alpha+\mu > 1$) or there is no technological diffusion ($\varepsilon = 0$), the model is unstable and the growth paths of the two countries diverge. If there are decreasing returns and technological diffusion ($\alpha+\mu < 1$ and $\varepsilon > 0$), however, the model is stable. Asymptotically, the rates of growth of the two countries converge to the world rate of technical progress, g_x, and the ratio of their per capita incomes approaches a strictly positive constant value whose logarithm is given by:[9]

$$(10)\ (q_l - q_f)^* = \frac{\gamma(\theta_l-\theta_f)}{\varepsilon} + \frac{\alpha+\mu}{1-\alpha-\mu} \ln\left(\frac{s_l(n_f+g_x+\delta)}{s_f(n_l+g_x+\delta)}\right),$$

where $q = \ln Q$.

This expression shows that long-run income disparities can be attributed to differences in levels of investment in physical and technological capital. The first term, $\frac{\gamma(\theta_l-\theta_f)}{\varepsilon}$, is the ratio of the indices of total factor productivity in the two countries ($\ln A_l/A_f$). Hence, long-run differences in productivity levels depend on the ratio of the technological investment coefficients of the two countries and decrease with the speed of technological diffusion. Finally, the last term, which measures relative capital intensity, is a function of the rates of investment and population growth.

Under plausible technological assumptions, then, the model predicts what, following Barro and Sala (1990), we will call *conditional convergence.* There is convergence in the sense that each country approaches a long-run equilibrium in which its income, expressed as a fraction of the sample average, remains constant over time at a level determined by its investment effort. Notice, however, that if fundamentals (i.e. investment rates or their determinants) differ across countries, this is perfectly compatible with the indefinite persistence of a substantial degree of inequality.

In a long-run equilibrium, all economies grow at a rate equal to the world rate of technical progress. During the transition to the steady state, however, growth rates can differ across countries. This transitional growth component may be expressed as a function of the distance between a country's current position in terms of factor intensity in efficiency units (Z) and relative technical efficiency (b) and the steady-state values of these two variables. Notice that the rate of technical progress is not necessarily largest in those countries with the lowest levels of total

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9 Recall that output per worker is given by $Q = AZ^{\alpha+\mu}$. Taking the logarithm of this expression and using (7) and (9), we obtain equation (10).

factor productivity, or highest R&D investment, but rather in those which are furthest below their long-run level of relative technical efficiency. Similarly, differences in growth rates reflect in part each country's investment effort, which determines the location of the steady state. Controlling for investment rates, however, it is not necessarily those countries with the lowest stock of capital per worker which grow fastest, but those which have low factor endowments relative to their level of technological attainment.

2.b.- A Convergence Equation

Appendix 1 shows how a convergence equation suitable for empirical work can be derived from the model developed above. Essentially, I construct a log-linear approximation to the model around a steady state and use it to derive an equation describing the evolution of income per capita. The equation which describes the evolution of the index of technological efficiency is then solved and the solution is substituted into the law of motion of income per capita. The end result is a single equation which gives the growth rate of income per capita as a function of the level of the same variable, investment rates, and the initial technological gap. Adding human capital to the model (with coefficient β in the production function and the same rate of depreciation as physical capital) and letting s_k and s_h denote the rates of investment on physical and human capital, respectively, the convergence equation can be written,

$$(11)\ q_{it}' = g_x + \lambda x_o + \lambda g_x t - \lambda q_{it} + \frac{\lambda(\alpha+\mu)}{1-\alpha-\mu-\beta}\ln\frac{s_{kit}}{n_i+g_x+\delta} + \frac{\lambda\beta}{1-\alpha-\mu-\beta}\ln\frac{s_{hit}}{n_{it}+g_x+\delta} + $$
$$+\lambda\frac{\gamma\theta_i-g_x}{\varepsilon}[1+(\eta-1)e^{-\varepsilon t}] + \lambda[(x_o-a_{lo})+(a_{lo}-a_{io})](\eta-1)e^{-\varepsilon t}$$

where i is a country subindex and the neoclassical convergence coefficient, λ, is given by

$$(12)\ \lambda = (1-\alpha-\mu-\beta)(n+\delta+g_x).$$

According to equation (11), the growth rate of output per worker in country i at time t, q_{it}', is an increasing function of the rates of investment in physical, human and technological capital (s_k, s_h and θ) and of the initial gap with respect to best-practice technology, $(x_o - a_o)$, which we write as the sum of the gap with respect to the leader $(a_{lo} - a_{io})$ and the distance between the leader and the technological frontier, $(x_o - a_{lo})$, and decreases with the log of the contemporaneous level of income, q_{it}. The parameter λ, which depends on the degree of decreasing returns to human and physical capital, measures the speed of convergence of income per efficiency unit of labour towards its steady-state value. A positive value of λ can be taken as evidence of decreasing returns in reproducible factors and, therefore, of the operativeness of the neoclassical convergence mechanism, although in terms of output per efficiency unit of labour, and not necessarily per worker.

Equation (11) also captures the impact of the technological catch-up process, whose speed is measured by the coefficient ε. The parameter $\eta = \frac{\varepsilon}{\delta+n+g_x}$ will be greater than one when the speed of technological diffusion is relatively high. In this case, the coefficient of the initial technological gap, $\lambda(\eta-1)e^{-\varepsilon t}$ is positive but the contribution of the catch-up factor decreases with time and converges to zero. That is, countries which are technologically backwards at the beginning of the period tend to grow faster, but their advantage decreases gradually as each country approaches its own stationary level of relative technical efficiency, as determined by its rate of R&D investment.

3.- Estimation and empirical results

I estimate a version of equation (11) using pooled data for a sample of 21 OECD countries during the period 1963-88. Since the sample period is subdivided into five-year intervals, we have five observations per country. The income variable is output per worker corrected for differences in purchasing power and measured in constant dollars. As a proxy for the rate of investment in human capital, I have used university enrollment, expressed as a fraction of the labour force, while investment in technological capital is measured by total R&D expenditure (private+public) as a fraction of GDP.

Table 1: Definition and sources of the variables

q_{it}' = Average annual rate of growth of real output (GDP) per worker in each subperiod. Source: Summers and Heston (S-H), 1991, PWT.5.

q_{it} = logarithm of real output per worker at the beginning of each subperiod (in 1985 dollars, measured in international prices). (S-H, 1991).

s_k = investment in physical capital (private+public) as a fraction of GDP. Average of the annual observations for each subperiod. (S-H, 1991).

s_h = university enrollment as a fraction of the labour force in 1960, 65, 70, 75 and 80. The figure for 1960 is associated with the period 1963-8, etc. (Source, UNESCO).

θ = R&D expenditure (private+public) as a fraction of GDP. Average of the values corresponding to 1963, 65, 70, 75 and 80.[10] (Source: UNESCO)

dU = change in the unemployment rate over each subperiod. (Source: OECD)

Table 1 describes the construction and sources of the variables used in the empirical analysis. Two aspects of our choice of variables deserve some discussion. First, we have used university enrollment (rather than secondary enrollment or the sum of secondary and tertiary enrollments) for the following reason. On the whole, there is relatively little variation across the countries in the sample in terms of their secondary enrollment rates (secondary schooling is mandatory in all of them). As a result, the impact of educational investment on productivity will be difficult to detect. Moreover, much of the variation observed in the available data is rather suspicious. Some countries present very substantial and rapid changes in enrollment rates which raise questions about the homogeneity of the data. Moreover, the low enrollment rates attributed to several countries in Central Europe seem to indicate that these figures do not include students enrolled in vocational training programmes conducted by enterprises (a rather common system in these countries). Hence, we have preferred to use data on tertiary enrollments, which seem to be more homogeneous across countries and over time,

[10] For some countries data are not available for all years. Before computing the mean, missing values have been estimated in the following manner. First, we calculate the average R&D expenditure for those countries which have data for all years. Available figures for other countries are then normalized by the average of the first group. The (relative) value assigned to the missing observations is the average of the values for adjacent years or, if this is not possible, that of the closest available year.

and should therefore give a more reliable image of the educational effort of the different countries.

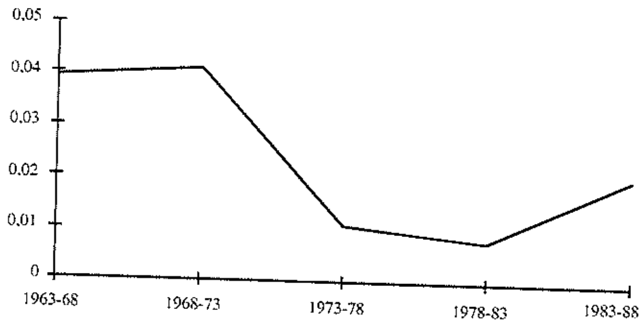
Secondly, our measure of technological investment is average R&D expenditure (as a fraction of GDP) over the entire sample period, rather than within each 5-year subperiod, as in the case of human and physical capital. In part, this choice is made for convenience, for the assumption that θ_i remains constant over time considerably simplifies the equation to be estimated which would, otherwise, include a relatively complicated lag structure. On the other hand, given the likely existence of long and variable lags between R&D investment and its impact on output growth, it seems more reasonable to work with a measure of average effort during a relatively long period than to try to uncover a contemporaneous correlation between the two variables.

In the estimation of equation (11), two important problems arise. The first one is that, since initial technological backwardness (a_{lo} - a_{io}) is not directly observable, one needs to construct some proxy for it. Among the available data, there are three variables which should contain some information about the degree of technical sophistication at the beginning of the period: the fraction of the population holding a university degree in 1960, the number of scientists and engineers employed in R&D activities as a fraction of the labour force in 1965, and average product per worker at the beginning of the sample period. None of these indicators is, however, the ideal variable. Moreover, since each of them is highly correlated with some other explanatory variable (the initial income level, the university enrollment rate, or the level of R&D expenditure), their use as regressors is likely to result in a multicollinearity problem. For both these reasons, I have chosen to construct an indicator of the initial technological gap based on an average of three indices which measure the initial position of each country relative to the US in terms of these three variables. The ordering induced by this index seems quite reasonable, with the exceptions of of Japan, which is ranked forth, tied with Canada, and Austria (which appears below Italy and Ireland, followed only by Greece, Spain and Portugal). (See the last column of Table 3). Since the case of Japan is of particular interest, and this is the only country which is not analyzed as part of a larger group in the following section, I will attempt to estimate a correction factor for this country's initial gap below.

The second problem is how to control for cyclical factors or, more generally, for the possibility of period-specific shocks, without losing the capacity to detect the catch-up effect. Figure 1, which shows the average OECD growth rate in each subperiod, illustrates the problem. The decline of the average growth rate during the period could be an indication of the gradual weakening of the catch-up effect, but it probably reflects the impact of cyclical factors as well and, in particular, the coincidence of recessive periods and adverse supply shocks in the second half of the sample period. A simple way to control for these factors would be to use a specification with fixed effects by subperiod. The period dummies, however, would also capture the catch-up effect and their coefficients would be difficult to interpret in terms of the underlying model. On the other hand, if we do not control at all for period-specific shocks, we may exaggerate the intensity of the catch-up process.

As a compromise, I have included dummies (D3 and D4) for the two more clearly recessive periods (1973-78 and 1983-88), attributing the rest of the decline of the growth rate, after controlling for other factors, to the gradual exhaustion of catch-up opportunities. (This effect should be picked up by the term $\lambda[(x_o - a_{lo}) + (a_{lo} - a_{io})]\ (\eta-1)e^{-\varepsilon t}$ in equation (11)). As an alternative strategy, I have also tried to control for cyclical factors more directly by including the change in the unemployment rate over each subperiod as a regressor. As we will see below, both approaches yield quite similar results.

Figure 1: Average growth rate in the OECD



I have imposed some restrictions on the parameters of the model. Following what has become standard practice in the literature, I assume that the annual depreciation rate is 3% and the rate of technical progress (at the frontier) is 2% per annum. I have also restricted the convergence coefficient, λ, and the parameter η to be equal for all countries, even though the model suggests that both these parameters should vary with the rate of population growth. The baseline equation is, then, of the form:

$$(13)\quad q_{it}' = \Gamma_o + \lambda^*0.02^*t - \lambda\, q_{it} - \Gamma_k \ln \frac{s_{kit}}{n_{it}+0.05} + \Gamma_h \ln \frac{s_{hit}}{n_{it}+0.05} +$$
$$\lambda \frac{\gamma\theta_i - 0.02}{\varepsilon}\left(1+\left(\frac{\varepsilon}{n+0.05}-1\right)e^{-\varepsilon t}\right) + \lambda\big((x_o - a_{lo}) + (a_{lo} - a_{io})\big)\left(\frac{\varepsilon}{n+0.05}-1\right)e^{-\varepsilon t}$$

where $\Gamma_o = g_x + \lambda x_o$ is a constant and n denotes the average rate of growth (across all countries and subperiods) of the labour force (approximately 1% per year). Different specifications will also contain various period dummies and/or the change in the rate of unemployment (dU).

The results, obtained by non-linear least squares, are presented in Table 2. The first three equations contain dummies for recessive subperiods but not the change in unemployment. In equation [1], I have tried to estimate the leader's gap with respect to the technological frontier, $x_o - a_{lo}$, as an additional parameter. Since the results are not precise at all, I repeat the estimation after imposing values of this parameter which may be reasonable. In equation [2] it is assumed that $x_o - a_{lo} = 0$ (i.e. that the US makes use of best-practice technology), while in [3] the assumption is that initial "pure" labour productivity in this country is 30% below its theoretical maximum (i.e. $x_o - a_{lo} = 0.30$). As can be seen in the Table, the results are quite similar in both cases.

In equations [4] through [7], I impose the assumption that the US technological gap is 0.30 and include a dummy for Japan in the initial gap term, which is now of the form

$$(0.3 + \Gamma_{Jap}{}^*DJAPAN + (a_{lo} - a_{io})).$$

Table 2: Estimation of the convergence equation

	[1] coef.	(t)	[2] coef.	(t)	[3] coef.	(t)
constant	0.269	(5.34)	0.207	(4.82)	0.215	(5.02)
D3	-0.0155	(5.41)	-0.0165	(5.37)	-0.0162	(5.33)
D4	-0.0178	(5.87)	-0.0194	(6.04)	-0.0191	(6.01)
λ	0.03	(5.89)	0.0229	(5.34)	0.0238	(5.56)
Γ_k	0.028	(5.33)	0.0259	(4.69)	0.0261	(4.78)
Γ_h	0.0123	(3.65)	0.00782	(2.42)	0.00886	(2.72)
ε	0.0643	(5.83)	0.102	(8.46)	0.0977	(9.64)
γ	0.0112	(2.40)	0.0267	(4.78)	0.0244	(4.85)
$x_o - a_{lo}$	17.47	(0.37)	[0.00]		[0.30]	
DJAPAN						
dU						
R^2	0.733		0.699		0.706	
$\alpha+\mu$	0.347		0.475		0.450	
β	0.153		0.143		0.153	

	[4] coef.	(t)	[5] coef.	(t)	[6] coef.	(t)	[7] coef.	(t)
constant	0.168	(3.94)	0.16	(3.99)	0.158	(4.00)	0.1365	(4.36)
D2							0.0163	(6.90)
D3	-0.016	(5.62)			-0.011	(3.43)		
D4	-0.019	(6.20)			-0.011	(3.04)		
λ	0.0185	(4.29)	0.018	(4.39)	0.0175	(4.36)	0.0158	(4.97)
Γ_k	0.0247	(4.70)	0.022	(4.18)	0.0239	(4.79)	0.0241	(5.59)
Γ_h	0.0078	(2.51)	0.0076	(2.58)	0.0074	(2.57)	0.0118	(4.77)
ε	0.106	(7.99)	0.123	(8.31)	0.113	(7.95)	0.1397	(8.96)
γ	0.0208	(3.34)	0.0216	(3.23)	0.0196	(3.08)	0.0203	(3.09)
$x_o - a_{lo}$	[0.30]		[0.30]		[0.30]		[0.30]	
DJAPAN	2.265	(2.63)	1.81	(2.86)	2.15	(2.88)	1.784	(3.74)
dU			-0.31	(7.15)	-0.189	(3.51)	-0.263	(7.30)
R^2	0.735		0.731		0.766		0.822	
$\alpha+\mu$	0.526		0.520		0.540		0.495	
β	0.165		0.180		0.168		0.242	

- *Note:* Parameter values shown inside brackets have been imposed, not estimated.
- The reported values of $\alpha+\mu$ and β are computed as follows. From the point estimate of λ and our maintained assumption that $g+\delta = 0.05$, we recover an estimate of $\alpha+\mu+\beta$ using the formula $\lambda = (1-\alpha-\mu-\beta)(n+g+\delta)$ and the average value of n (1%) across countries and subperiods. To recover each coefficient, we use the fact that $\Gamma_k = \frac{\lambda(\alpha+\mu)}{1-\alpha-\mu-\beta}$ and $\Gamma_h = \frac{\lambda\beta}{1-\alpha-\mu-\beta}$, which implies that $\frac{\Gamma_k}{\Gamma_h} = \frac{\alpha+\mu}{\beta}$.

Hence, the coefficient of DJAPAN, which is always significant and positive, gives us a correction factor for our estimate of Japan's initial technological lag. This correction is quite significant, as it moves Japan from close to the top to the bottom of the distribution in terms of the initial level of technological development.

Equations [4] to [7] contain various combinations of period dummies and/or the change in unemployment over each subperiod.[11] Both sets of variables are significant in all specifications, although the cross-equation pattern of coefficients suggests that both variables are partly picking up the same effects. Most of the other coefficients are quite stable across specifications, although the estimate of the catch-up parameter, ε, is somewhat sensitive to the set of dummies included. For obvious reasons, technological convergence appears to be faster when we include a dummy for the second subperiod (which presents above-average growth rates) and slowest when we control for the recessive subperiods towards the end of the sample. In all cases, however, the catch-up coefficient, ε, is highly significant and very large (over 10% per year), suggesting that the process of technological diffusion takes place very rapidly.[12, 13]

The remaining variables are significant and have the expected sign in all specifications. The convergence coefficient, λ, which is around 2% per year, indicates the existence of decreasing returns in physical and human capital and is close to the values reported in other studies. As for the coefficients of the aggregate production function (recovered from the estimates of λ, Γ_k and Γ_h), my estimate of

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11 If labour were homogeneous, a 1% increase in the rate of unemployment should induce roughly a 1% decrease in growth of output per worker. Hence, we could expect the coefficient of dU to be close to -1. The estimated value of this coefficient, however, is much lower. One possible explanation is that least productive workers are laid off first.

12 That is, one half of the deviation of the technological gap from its steady-state value would be eliminated in less than 7 years. At this rate, most of the impact of the catch-up effect would be exhausted after three decades.

13 The catch-up coefficient could be biased upward if our proxy for the initial technological gap (which implies a ratio close to 10 between the initial productivity indices of the US and Portugal) exaggerates the existing technological difference between the leader and other countries. To explore this possibility, I have tried to estimate a correction factor (which would enter the equation multiplying the term $(a_{lo} - a_{io})$ in equation (11)). The point estimate of this factor is larger than one (indicating that if anything our index underestimates initial productivity differences) but has a very large standard error (1.12). When we impose a correction factor of 0.5, the estimated catch-up rate increases slightly instead of decreasing. This suggests that the result of a very high rate of technological diffusion is robust to scale errors in the measurement of the initial technological gap.

the exponent of physical capital ($\alpha+\mu \cong 0.5$) is above this factor's observed share in national output, suggesting that there may indeed be some externalities associated with the accumulation of physical capital. This coefficient is also higher than the one obtained by MRW for the OECD countries with cross-section data (although lower than Romer's), while that of human capital ($\beta \cong 0.16$) is below the value reported by MRW. On the other hand, both coefficients are typically within one standard error of those reported by MRW.[14] Finally, the coefficient of the R&D variable, γ, is always positive and significant.

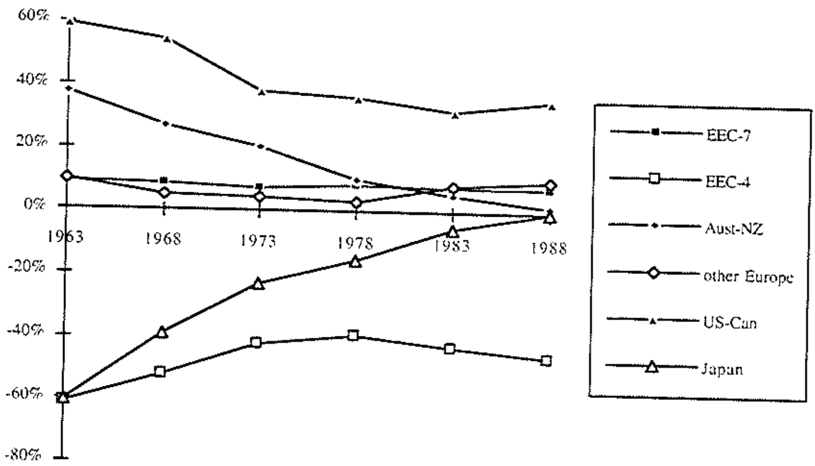
These results tend to confirm those of previous empirical studies. As Lichtenberg (1992), I find that R&D investment has a significant positive effect on growth. The estimated values of the parameters of the production function are not out of line with those reported in the literature and both convergence mechanisms (neoclassical and catch-up) seem to be operational, although the second one appears to be quantitatively more important. The estimated size of the neoclassical convergence coefficient is within the usual range of values found in the literature. Ex ante, this may be a bit surprising, for it may be expected that once we allow the catch-up effect to pick up part of the observed convergence the coefficient on initial income should go down. In fact, this turns out to be the case: the "neoclassical convergence" coefficient increases when we add R&D investment as a regressor, and goes down again to roughly the initial level when we introduce the catch-up effect. (See Appendix 3 for a more detailed discussion of this issue).

4.- Growth and Convergence in the OECD, 1963-88

In this section, I will use the model estimated above to analyze the immediate determinants of OECD growth and convergence during the post-war period. For this purpose, I will split the OECD sample into six (relatively homogeneous) groups of countries: the core EEC countries (EEC7); the four poorer EEC countries (EEC4); the rest of Western Europe ("EFTA"); North America; Australia and New Zealand; and Japan.

14 MRW's point estimate of the coefficient of physical (human) capital is 0.38 (0.23), with a standard error of 0.13 (0.11).

Figure 2: Evolution of relative income for subgroups of the OECD



Notes:
- Relative income is average (log) income per worker in deviations from the contemporaneous sample average of log income; this is approximately equal to the % deviation from the (geometric) sample mean of income per worker.
- Country groups: EEC7 = Belgium, Holland, Italy, W. Germany, France, UK and Denmark; EEC4 = Spain, Ireland, Greece and Portugal; US and Canada; Japan; Australia and New Zealand; Other Europe = Austria, Finland, Sweden, Switzerland and Norway.

Figure 2 shows the evolution of relative income, defined as log income per worker in deviations from the contemporaneous OECD average, in each group during the period 1963-88. While the two sets of richer European countries maintain a stable relative position, slightly above the sample average, throughout the period, there are important differences in performance within the top and bottom groups of the distribution, particularly in the second half of the sample. period Starting from similar levels of relative income, Japan converges rapidly towards the sample mean while the EEC4 countries, after a promising start, lose ground after 1978. At the upper end of the distribution, both North America and Australia-New Zealand see their income advantage erode, but while the decline of the second group continues throughout the period, North America's relative position stabilizes in the second half of the period. On the whole, there is clear income convergence during the 1960s and early 1970s, but income differentials largely stabilize, and even increase in some cases, after the mid 1970s.

To investigate the immediate sources of the differential performance of these various groups, I will use the model developed in Section 2 to decompose each country's growth rate into six factors which reflect, respectively, the contributions of factor accumulation (physical and human capital accumulation and population growth), R+D investment, technological catch-up, the neoclassical convergence effect, a cyclical component which is proportional to the change in the unemployment rate, and an error term. (See Appendix 2 for details). All computations are made using the parameter estimates shown in equation [5] of Table 2, i.e. a specification with a Japanese dummy and the change-in-unemployment variable but no period dummies.

As a reference, I will use a fictional country endowed with the (contemporaneous sample) average rates of factor accumulation (including R&D), average income per worker and the average technological gap. The contribution of each of these factors to a country's relative performance will be mesured by the corresponding component of its growth rate, expressed in differences with the value predicted by the model for our hypothetical average economy.

Figures 3 and 4 summarize, respectively, the impact on growth of the two convergence factors (neoclassical convergence and technological catch-up effects) and the contribution to relative performance of factor accumulation, including R&D investment. As expected, the joint impact of the convergence factors strongly favours the poorer countries, particularly at the start of the period, but the size of this effect decreases rapidly over time. The cross-sectional behaviour of investment rates, however, is not particularly conducive to convergence, as some of the higher-income groups present above-average rates of factor accumulation and viceversa. Differences in investment rates, however, seem to account for much of the differential performance within the head and tail groups (i.e. Japan vs. EEC4 and North America vs. Australia and New Zealand). Figure 5 displays the estimated cyclical effects, which on average seem to have been most favourable to North America, the EFTA countries and Japan. Figure 6 shows that the error terms remain quite considerable, particularly in the second subperiod, where the model

Figure 3: Sum of neoclassical convergence and catch-up effects

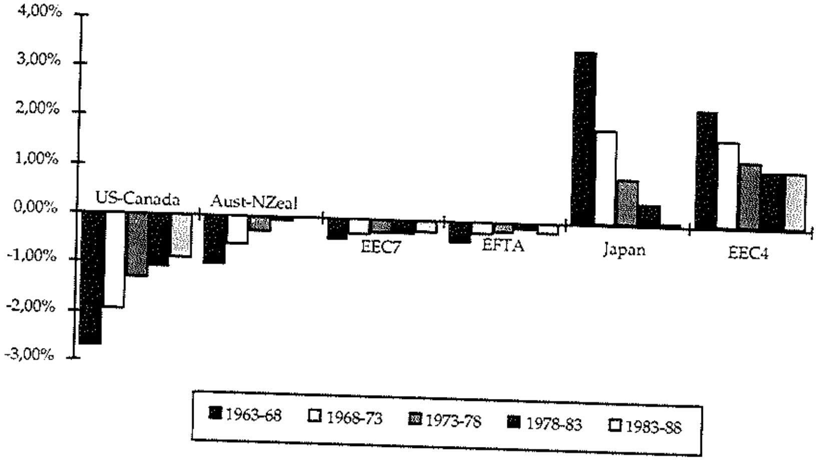


Figure 4: Sum of R&D and factor accumulation effects

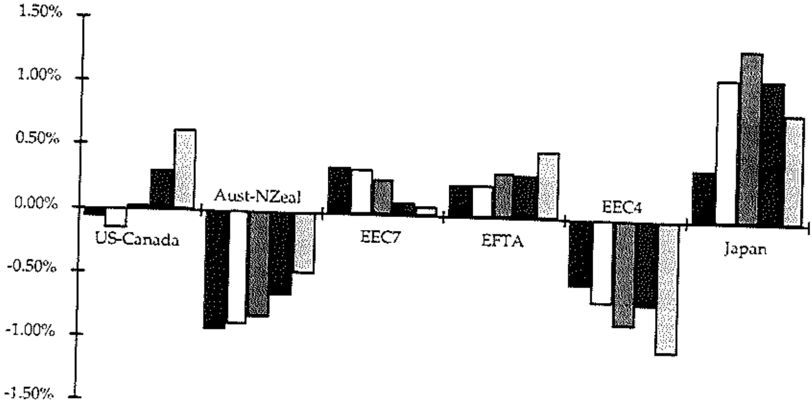


Figure 5: Comparative performance in terms of dU (cyclical component)

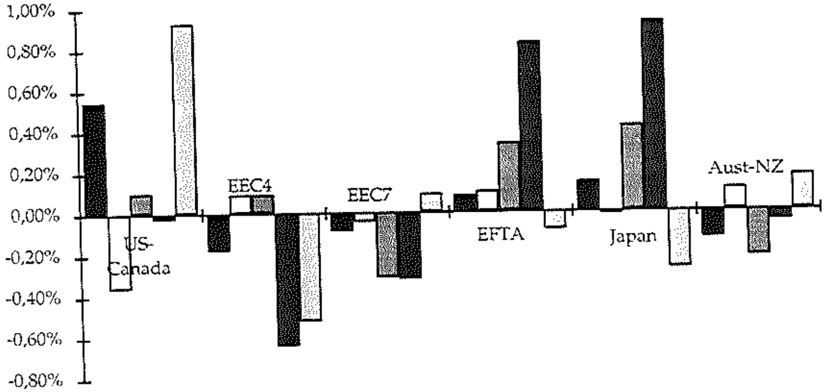


Figure 6: Error terms (actual-predicted)

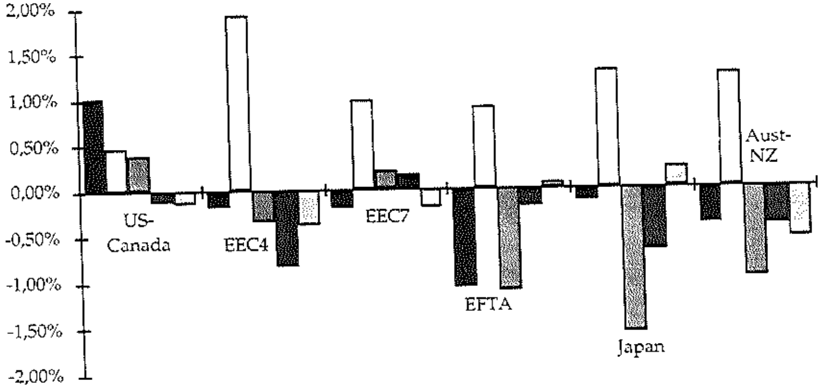


Figure 7: Souces of growth differentials, North America (US andCanada)

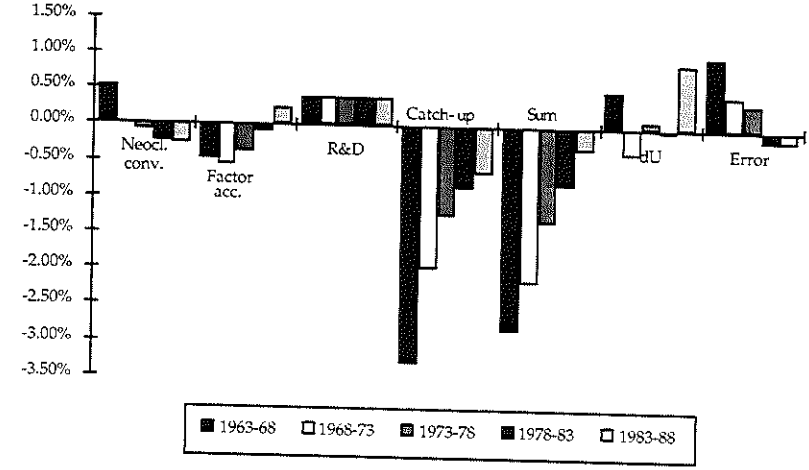
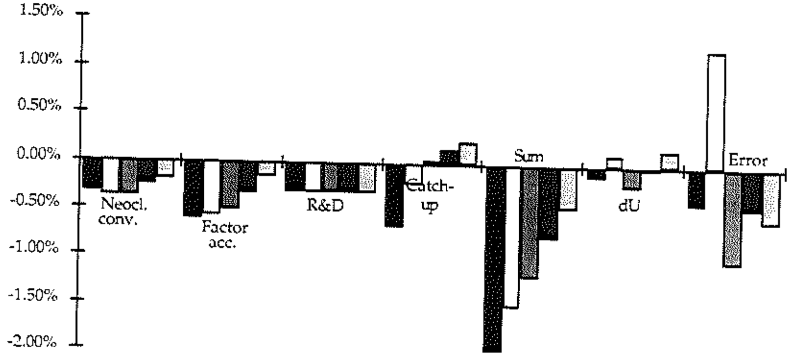


Figure 8: Souces of growth differentials, Australia and New Zealand



- *Note:* "Sum" is the sum of the terms that precede it (i.e. neoclassical convergence, factor accumulation, R&D and catch-up).

Figure 9: Souces of growth differentials, EEC7

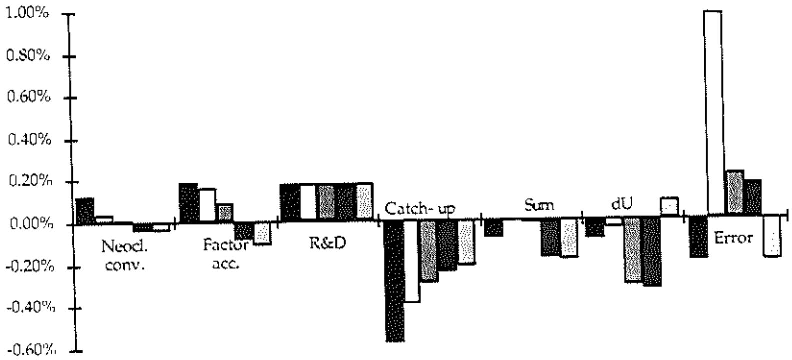


Figure 10: Souces of growth differentials, EFTA

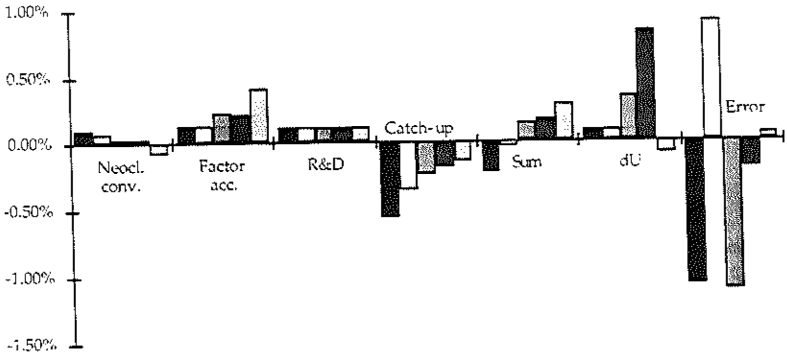


Figure 11: Souces of growth differentials, EEC4

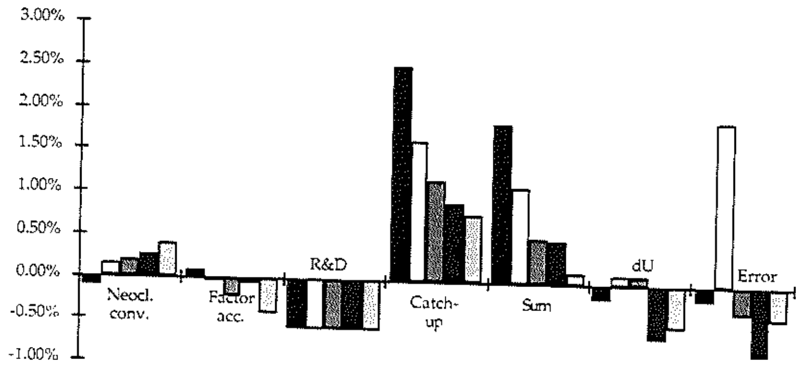
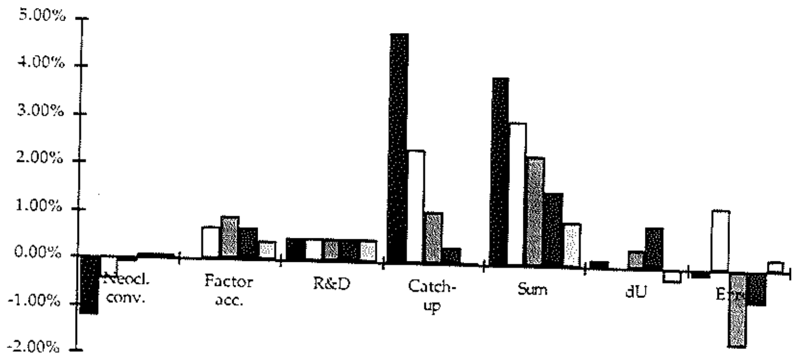


Figure 12: Souces of growth differentials, Japan



generally underpredicts growth performance.[15] The pattern of decreasing positive residuals for the US and Canada suggests that we may have overestimated their initial technological lead.

Figures 7-12 contain a more detailed breakdown of the sources of growth for each group of countries. The case of Japan deserves some discussion and serves also to illustrate some of the limitations of the analysis. As noted, the results displayed in Figure 12 are obtained using a specification which corrects our initial (and surprisingly low) estimate of Japan's initial technical gap. The resulting figure is consistent with the conventional view that Japanese growth has been fueled both by a rapid catch-up process and by extremely high rates of factor accumulation. In the absence of the correction, however, the picture that emerges is quite different: the catch-up contribution would now be negative and the main source of the Japanese miracle would be a strong neoclassical convergence effect. In other words, if we take our uncorrected estimate of the Japanese technical gap at face value, Japan appears in the early 1960s as a quite technologically sophisticated and extremely capital-poor country (particularly in terms of factor endowments per efficiency unit of labour). As a result, high investment rates, and an extremely high rate of return on investment, would account for the Japanese miracle.

One of the clearest conclusions to emerge from the analysis is that the catch-up effect has played an extremely important role in income dynamics during the post-WWII period. Technological diffusion is by far the largest source of growth differentials in early subperiods, accounting for up to 4 points in the case of Japan, but drops to less than a point towards the end of the sample. In contrast, the other growth factors account for less than half a point in most cases, but they tend to be more stable over time. On the whole, this factor seems to account for most of the observed decline in income dispersion during the first part of the sample period. The exhaustion of catch-up opportunities, moreover, may help explain the slowdown of growth and convergence in more recent years, although cyclical factors have undoubtedly played a role as well.

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15 Prediction errors are, on average, considerably smaller when equation [7] in Table 2 is used as the basis for the growth decomposition. As noted above, however, this specification tends to yield an artificially high catch-up parameter.

The contribution of the neoclassical diminishing-returns effect to income convergence seems to have been much smaller than that of technological diffusion. It is worth noting that in some cases this effect, whose size depends on the capital/labour ratio *in efficiency units*, has actually worked in favour of rich countries or against poor ones (eg. EEC4, Japan and North America in the first subperiod). One implication of the small size of the estimated neoclassical convergence effect is that technology-adjusted factor endowment ratios (i.e. capital/labour ratios measured in efficiency units), and therefore rates of return on capital and pressures for capital flows, have probably not been very different across countries over most of the period.

6.- Perspectives for future convergence

The existence of diminishing returns and technological diffusion is consistent with the long-run persistence of important income differentials if investment rates differ across countries. Our empirical results suggest that both these convergence mechanisms are operative, but this does not necessarily imply that we should expect a further reduction of inequality in the future. In particular, if technological diffusion is as rapid as our results indicate, most of the potential for income convergence inherent in initial differences in total factor productivity will have been exhausted by now. Further convergence will require higher rates of factor accumulation in poorer countries.

To explore the implications of the model for future convergence prospects, we will use the parameters estimated in the previous section to calculate the relative income of each country in a long-run equilibrium under the assumption that investment rates in physical, human and technological capital remain indefinitely constant at their observed values during the last subperiod in our sample (1983-88). Factor accumulation rates are shown in Table 3 together with 1988 income levels and estimated long-run income, both measured in log deviations from the corresponding sample mean.

Without attributing too much importance to the specific value obtained for each country, the long-run ordering induced by the model seems to be reasonable. Countries such as Japan, Switzerland and Germany, characterized by high levels of investment in physical, human and technological capital occupy the first places of the table, displacing the US. On the other hand, the perspectives for the poorer countries are not particularly good. Were investment levels to remain constant at their current values, for example, the long-run income levels of Spain and Ireland would be close to 40% below the OECD average, with Greece and Portugal lagging even further behind.

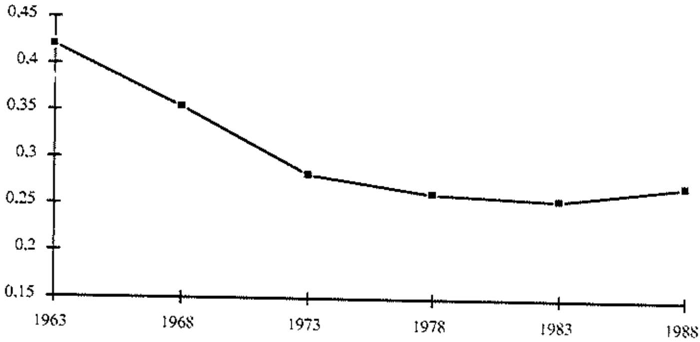
Table 3 : Investment rates and long-run relative income

	s_k	*univ*	θ	n	y_{rel} *SS*	y_{rel} *ss*	*ss-SS*	a_{lo}-a_{io}
Switzerland	30.15%	2.68%	3.08%	0.43%	0.306	0.632	0.326	0.54
Finland	27.88%	4.98%	1.57%	0.66%	-0.007	0.506	0.513	1.35
Japan	27.22%	4.27%	2.77%	0.85%	0.003	0.506	0.503	0.8
Norway	30.63%	4.08%	1.62%	0.82%	0.212	0.493	0.281	1.28
W. Germany	21.72%	4.38%	2.72%	0.26%	0.074	0.369	0.295	1.35
Austria	26.93%	4.37%	1.27%	0.55%	-0.019	0.361	0.380	1.71
USA	17.75%	11.14%	2.73%	1.02%	0.434	0.267	-0.167	0.00
Canada	23.60%	7.63%	1.41%	1.16%	0.286	0.248	-0.038	0.82
France	21.83%	4.61%	2.25%	0.73%	0.108	0.127	0.019	1.28
Italy	22.55%	4.96%	1.13%	0.60%	0.181	0.084	-0.097	1.55
Sweden	18.29%	3.97%	2.88%	0.37%	0.039	-0.008	-0.047	0.87
Belgium	18.26%	4.82%	1.75%	0.46%	0.121	-0.131	-0.252	0.92
Australia	24.64%	4.82%	1.13%	1.66%	0.157	-0.184	-0.341	0.92
Netherlands	17.89%	6.66%	2.06%	1.16%	0.141	-0.200	-0.341	1.06
Denmark	19.99%	3.99%	1.25%	0.52%	-0.103	-0.201	-0.098	0.58
N. Zealand	21.74%	5.88%	0.76%	1.61%	-0.12	-0.330	-0.210	1.31
UK..	17.33%	3.08%	2.22%	0.34%	0.015	-0.356	-0.371	1.29
Spain	20.50%	5.17%	0.55%	1.13%	-0.177	-0.370	-0.193	2.14
Ireland	22.99%	4.39%	0.82%	1.63%	-0.449	-0.405	0.044	1.53
Greece	18.39%	3.51%	0.33%	0.47%	-0.461	-0.563	-0.102	1.80
Portugal	20.44%	2.11%	0.32%	0.85%	-0.743	-0.844	-0.101	2.46
average	22.42%	4.83%	1.65%	0.82%				
std. deviation	4.03%	1.85%	0.85%	0.42%	0.271	0.395		
coeff. of var.	0.18	0.38	0.51	0.51				

- *Note*: investment rates (s_k, *univ* and θ) correspond to the period 1983-88; y_{rel} *SS* is observed relative income in 1988 (deviation from the sample mean of log income per worker, approximately equal to the % deviation of income from the geometric sample mean); y_{rel} *ss* is steady-state relative income, computed using the parameters estimated in equation [5] of Table 2; a_{lo}-a_{io} my estimate of the log of the technological distance from the leader at the beginning of the period.

Without attributing too much importance to the specific value obtained for each country, the long-run ordering induced by the model seems to be reasonable. Countries such as Japan, Switzerland and Germany, characterized by high levels of investment in physical, human and technological capital occupy the first places of the table, displacing the US. On the other hand, the perspectives for the poorer countries are not particularly good. Were investment levels to remain constant at their current values, for example, the long-run income levels of Spain and Ireland would be close to 40% below the OECD average, with Greece and Portugal lagging even further behind.

Figure 13: Dispersion of output per worker in the OECD



Note: coefficient of variation of log output per worker.

The model also predicts a significant increase in income dispersion within the sample. Table 3 shows that the considerable variation across countries in investment rates would induce, in a long-run equilibrium, a level of inequality higher than the one observed in 1988. Although unpleasant, this prediction may not be unreasonable. In fact, it is compatible with the experience of recent years which, as shown in Figure 13, have been characterized by the halt of the convergence trend, and also with the rapid reduction of inequality observed during the first part of the sample period. The results reported in the last section are consistent with Abramovitz's (1987) view that post-war convergence was driven to a large extent by a process of rapid technological catch-up. With this process pretty much exhausted, however, we now find ourselves in a situation in which the only road to convergence is an important increase in the investment effort of the poorer countries.

7.- Conclusion

I have developed a simple model which tries to capture the main immediate determinants of growth and the principal mechanisms which tend to favour "real convergence" among countries. The model is estimated using postwar OECD data. The results suggest that both convergence mechanisms identified in the literature are indeed operative. Other things equal, poorer countries tend to grow faster than richer ones because diminishing returns to reproducible factors imply that investment will be more productive at the margin, and because their technological backwardness provides the opportunity for rapid growth through the adoption of more advanced technologies developed elsewhere.

Using the estimated model as a framework, I have analyzed the sources of growth and convergence within the OECD. Technological diffusion seems to have played a crucial role in this process, accounting for the lion's share of the reduction in income disparities observed during the first half of the period. The exhaustion of catch-up opportunities, moreover, may help explain the slowdown of growth and convergence in more recent years, although cyclical factors have undoubtedly played a role as well. Finally, I have emphasized that the existence of forces promoting convergence is not sufficient to guarantee the elimination of existing income differentials, even in the long run. Real convergence, therefore, requires a greater investment effort on the part of the poorer nations.

On the whole, the model developed and estimated in this paper seems to do reasonably well at explaining some of the main features of the post-war growth and convergence experience of the developed countries. A number of important questions, however, remain open. First, large unexplained residuals remain even after controlling for cyclical factors. A second, and perhaps more important limitation of the analysis is that it is purely descriptive in nature. In a growth accounting fashion, I have attempted to decompose income growth into a number of factors which reflect the effects of factor accumulation and the convergence mechanisms identified by the theory. Further research is needed, however, on the driving forces behind these accumulation decisions and on the impact on them of various policy variables.

APPENDIX

1.- Derivation of the convergence equation

This section shows how the convergence equation estimated in Section 3 of the paper is derived. As discussed in the text, the evolution of the stock of capital per efficiency unit of labour is described by the equation

$$\text{(A.1)}\quad Z' = sZ^{\alpha+\mu} - (n+\delta+g_a)Z$$

and the rate of technical progress is given by

$$\text{(A.2)}\quad g_a = a' = \gamma\theta + \varepsilon b$$

where $b = x - a = \ln (X/A)$ denotes the "technological gap" between each country and the best-practice frontier. We have assumed that best-practice technology improves at a constant exogenous rate, $x' = g_x$. Hence, $b' = x' - a'$ and

$$\text{(A.3)}\quad b' = x' - a' = g_x - \gamma\theta - \varepsilon b.$$

Following standard practice, we will proceed by constructing a log-linear approximation to the system formed by (A.1) and (A.3) around its steady state. Setting $b' = 0$ in (A.3), the steady-state value of the technological gap b is given by[16]

$$\text{(A.4)}\quad \bar{b} = \frac{g_x - \gamma\theta}{\varepsilon}.$$

Notice that $b' = 0$ implies $x' = a'$ and hence $g_a = g_x$. Substituting this expression in (A.1) and setting $Z' = 0$, the steady-state value of Z is given by

$$\text{(A.5)}\quad \bar{Z} = \left(\frac{s}{n+\delta+g_x}\right)^{1/(1-\alpha-\mu)}.$$

---

[16] Notice that the long-run technological gap may be negative if R&D is high enough; it may be better to think of x as "average" rather than "best-practice" technology.

Substituting (A.2) into (A.1) and dividing both sides of this equation by Z, the growth rate of Z is given by

$$\frac{Z'}{Z} = sZ^{\alpha+\mu-1} - (n+\delta+\gamma\theta+\varepsilon b).$$

Letting z = ln Z, this expression can be written

$$\text{(A.6)}\quad z' = se^{(\alpha+\mu-1)z} - (n+\delta+\gamma\theta+\varepsilon b) \equiv F(z, b).$$

Evaluating the partial derivatives of the function F() at the steady state, we obtain

$$\bar{F}_z = -(1-\alpha-\mu)(n+\delta+g_x) \equiv -\lambda \quad \text{and} \quad \bar{F}_b = -\varepsilon.$$

Hence, (A.6) can be approximated by the log-linear equation

$$\text{(A.7)}\quad z' = -\lambda\,\tilde{z} - \varepsilon\tilde{b}$$

where tildes denote deviations from the steady state (e.g. $\tilde{z} = z - \bar{z}$) and

$$\bar{z} = \frac{1}{1-\alpha-\mu}\ln\frac{s}{n+\delta+g_x}.$$

Next, we rewrite equation (A.7) in terms of (the log of) income per worker. Since (taking logs of the per capita production function) $q = a + (\alpha+\mu)z$, we have:

$$q' = a' + (\alpha+\mu)z' = a' - \lambda(\alpha+\mu)(z-\bar{z}) - \varepsilon(\alpha+\mu)\tilde{b} = a' - \lambda(q-a) + \lambda(\alpha+\mu)\bar{z} - \varepsilon(\alpha+\mu)\tilde{b}$$

$$\Rightarrow \text{(A.8)}\quad q' = a' + \lambda a - \lambda q + \lambda(\alpha+\mu)\bar{z} - \varepsilon(\alpha+\mu)\tilde{b}.$$

It remains to incorporate the behaviour of the technological variables in equation (A.8). Solving (A.3), the time path of b is given by

$$\text{(A.9)}\quad \tilde{b}_t = \tilde{b}_o e^{-\varepsilon t} \quad \text{or} \quad b_t = b_o e^{-\varepsilon t} + \bar{b}\,(1-e^{-\varepsilon t})$$

where $\tilde{b} = b - \bar{b}$. Asymptotically, the technological gap of a given country converges to a constant value, $\bar{b}$, which is a decreasing function of R&D spending and the speed of technological diffusion across countries.

Substituting (A.9) into (A.2) and using (A.4), we see that the rate of technical progress at time s is given by

$$\text{(A.10)}\quad a_s' = \gamma\theta + \varepsilon b_s = \gamma\theta + \varepsilon(\bar{b} + \tilde{b}_s)) = g_x + \varepsilon \tilde{b}_o e^{-\varepsilon s}.$$

Asymptotically, the rate of technical progress converges to the exogenous rate of displacement of the technical frontier, g_x. If the initial technical gap, is above its steady-state value (i.e. if $\tilde{b}_o > 0$), the rate of productivity growth decreases over time as imitation opportunities are gradually exhausted. Finally, we integrate equation (A.10) from 0 to t to obtain the time path of the productivity index:

$$\text{(A.11)}\quad a_t = a_o + g_x t + \tilde{b}_o(1-e^{-\varepsilon t}) = a_o + x_o - x_o + g_x t + (b_o - \bar{b})(1-e^{-\varepsilon t})$$

$$= x_o + g_x t + (b_o - \bar{b})(1-e^{-\varepsilon t}) - (x_o - a_o).$$

Substituting (A.9), (A.10) and (A.11) into (A.8), we arrive at our final convergence equation,

$$\begin{aligned}
\text{(A.12)}\quad q_t' &= a_t' + \lambda a_t - \lambda q_t + \lambda(\alpha+\mu)\bar{z} - \varepsilon(\alpha+\mu)\tilde{b}_t = \\
&= g_x + \varepsilon \tilde{b}_o e^{-\varepsilon t} + \lambda\left(a_o + g_x t + \tilde{b}_o(1-e^{-\varepsilon t})\right) - \lambda q + \lambda(\alpha+\mu)\bar{z} - \varepsilon(\alpha+\mu)\tilde{b}_o e^{-\varepsilon t} \\
&= g_x + \lambda g_x t - \lambda q_t + \lambda(\alpha+\mu)\bar{z} + \lambda\tilde{b}_o\left((1-e^{-\varepsilon t}) + \frac{\varepsilon(1-\alpha-\mu)}{\lambda}e^{-\varepsilon t}\right) + \lambda a_o + \lambda x_o - \lambda x_o \\
&= g_x + \lambda g_x t - \lambda q_t + \lambda(\alpha+\mu)\bar{z} + \lambda\tilde{b}_o[1+(\eta-1)e^{-\varepsilon t}] + \lambda x_o - \lambda(x_o - a_o)
\end{aligned}$$

where $\frac{\varepsilon(1-\alpha-\mu)}{\lambda} = \frac{\varepsilon(1-\alpha-\mu)}{(1-\alpha-\mu)(\delta+n+g)} = \frac{\varepsilon}{\delta+n+g} \equiv \eta$. Finally, recall that

$$\tilde{b}_o = b_o - \bar{b} = (x_o - a_o) - \frac{g-\gamma\theta}{\varepsilon}.$$

Using this expression, we have

$$q_t' = g_x + \lambda x_o + \lambda g_x t - \lambda q_t + \lambda(\alpha+\mu)\bar{z} + \lambda \frac{\gamma\theta - g_x}{\varepsilon}[1+(\eta-1)e^{-\varepsilon t}] + (x_o - a_o)\lambda(1+(\eta-1)e^{-\varepsilon t}) - \lambda(x_o - a_o)$$

$$\text{(A.13)}\quad q_t' = g_x + \lambda x_o + \lambda g_x t - \lambda q_t + \lambda(\alpha+\mu)\bar{z} + \lambda \frac{\gamma\theta - g_x}{\varepsilon}[1+(\eta-1)e^{-\varepsilon t}] + \lambda(x_o - a_o)(\eta-1)e^{-\varepsilon t}$$

where the gap relative to best-practice technology can be written as the sum of the gap relative to the leader and the leader's gap.

$$x_o - a_o = (x_o - a_{lo}) + (a_{lo} - a_o).$$

When we introduce human capital separately, the same procedure will yield equation (11) in the text.

2.- Decomposition of the growth rate differential

Rewriting equation (A.8) in the form

$$\text{(A.8')}\quad q' = [a' - \varepsilon(\alpha+\mu)\tilde{b}] - \lambda(q - a) + \lambda(\alpha+\mu)\bar{z},$$

we see that the rate of growth of output per worker, q', depends on the rate of technical progress, a', and the deviations of income per efficiency unit of labour, $q - a = (\alpha+\mu)z$, and the technological gap, b, from their steady-state values. Using this expression, we can decompose the growth rate of output per capita into the sum of three components:

- The first term $(a' - \varepsilon(\alpha+\mu)\tilde{b})$ summarizes the impact of technical progress. Productivity growth raises output directly, but it also has an indirect effect of the opposite sign: as depreciation or population growth, it tends to 'dilute' the capital stock, reducing the rate of growth of output per efficiency unit of labour. We will see below that this term may be further split into two components, one reflecting the catch up effect and the other the impact of R&D.

- We will refer to the second term, $-\lambda(q - a)$, as the "neoclassical convergence" effect. Equation (A.8') shows that output growth is a decreasing function of income per efficiency unit of labour. Hence, the growth rate tends to fall with income per capita but increases with the level of technological development. As a result, this effect tends to benefit countries which are *relatively* capital poor (i.e. have low endowments of capital *per efficiency unit* of labour) and not necessarily the poorer countries. (This observation also has some relevance for the direction of capital flows).[17]

- Finally, the steady-state term, $\lambda(\alpha+\mu)\bar{z}$ can be taken as an indicator of the contribution to growth of "factor accumulation" and population growth.

Using (A.2) and (A.4), we can write the technological component of growth in the form

$$\text{(A.14)}\quad a^{\cdot} - \varepsilon(\alpha+\mu)\tilde{b} = \gamma\theta + \varepsilon b_t - \varepsilon(\alpha+\mu)\tilde{b}_t = \gamma\theta + \varepsilon b_t - \varepsilon(\alpha+\mu)(b_t - \bar{b})$$

$$= \gamma\theta + \varepsilon(1-\alpha-\mu)b_t + \varepsilon(\alpha+\mu)\bar{b} = \gamma\theta + \varepsilon(1-\alpha-\mu)b_t + \varepsilon(\alpha+\mu)\frac{g_x - \gamma\theta}{\varepsilon}$$

$$= \varepsilon(1-\alpha-\mu)b_t + [(1-\alpha-\mu)\gamma\theta + (\alpha+\mu)g_x]$$

We will refer to the first term in the last expression as the "catch-up" component, and to the second one as the R&D component of technical progress. (Notice that the constant exogenous component, $(\alpha+\mu)g_x$, disappears when we take differences across countries).

Table A.1 contains the information used to construct the figures in the text.

[17] To compute a_t we need to estimate x_o; this term can be recovered from the independent term of the estimated equation, $\Gamma_o = g_x + \lambda x_o$, under the maintained assumption that $g_x = 0.02$.

Table A.1: Sources of growth differentials

		neoclassical convergence	*factor accumulat.*	*R&D*	*catch-up*	*dU*	*error*
US-Canada	*1963-68*	0.54%	-0.47%	0.39%	-3.29%	0.54%	1.02%
	1968-73	-0.02%	-0.55%	0.39%	-1.96%	-0.36%	0.47%
	1973-78	-0.09%	-0.37%	0.39%	-1.24%	0.10%	0.39%
	1978-83	-0.24%	-0.09%	0.39%	-0.85%	-0.03%	-0.13%
	1983-88	-0.28%	0.23%	0.39%	-0.64%	0.92%	-0.14%
EEC4	*1963-68*	-0.12%	0.08%	-0.61%	2.51%	-0.18%	-0.18%
	1968-73	0.14%	-0.05%	-0.61%	1.64%	0.09%	1.92%
	1973-78	0.19%	-0.22%	-0.61%	1.17%	0.09%	-0.34%
	1978-83	0.26%	-0.07%	-0.61%	0.91%	-0.64%	-0.83%
	1983-88	0.39%	-0.44%	-0.61%	0.78%	-0.52%	-0.39%
EEC7	*1963-68*	0.12%	0.18%	0.18%	-0.58%	-0.09%	-0.20%
	1968-73	0.04%	0.16%	0.18%	-0.40%	-0.04%	0.97%
	1973-78	0.01%	0.09%	0.18%	-0.30%	-0.32%	0.21%
	1978-83	-0.04%	-0.08%	0.18%	-0.24%	-0.33%	0.17%
	1978-83	-0.04%	-0.11%	0.18%	-0.22%	0.09%	-0.20%
EFTA	*1963-68*	0.10%	0.13%	0.11%	-0.57%	0.08%	-1.08%
	1968-73	0.08%	0.13%	0.11%	-0.36%	0.10%	0.90%
	1973-78	0.04%	0.23%	0.11%	-0.25%	0.34%	-1.12%
	1978-83	0.03%	0.22%	0.11%	-0.19%	0.82%	-0.20%
	1983-88	-0.08%	0.40%	0.11%	-0.15%	-0.09%	0.06%
Japan	*1963-68*	-1.26%	-0.05%	0.46%	4.82%	0.15%	-0.14%
	1968-73	-0.47%	0.66%	0.46%	2.40%	-0.02%	1.28%
	1973-78	-0.11%	0.90%	0.46%	1.09%	0.42%	-1.60%
	1978-83	0.09%	0.66%	0.46%	0.38%	0.93%	-0.69%
	1983-88	0.09%	0.39%	0.46%	-0.01%	-0.29%	0.23%
Aust-NZeal	*1963-68*	-0.35%	-0.62%	-0.32%	-0.68%	-0.13%	-0.41%
	1968-73	-0.38%	-0.58%	-0.32%	-0.22%	0.11%	1.23%
	1973-78	-0.38%	-0.52%	-0.32%	0.02%	-0.22%	-1.01%
	1978-83	-0.26%	-0.35%	-0.32%	0.16%	-0.05%	-0.43%
	1983-88	-0.21%	-0.17%	-0.32%	0.23%	0.17%	-0.58%

3.- Some exploratory growth regressions

Table A.2 reports the results of some exploratory growth regressions which make use of the explanatory variables used in the text. The specification used is of the form

$$\text{(A.15)}\ q_{it}' = g_x + \lambda x_o + \lambda^{*}0.02^{*}t - \lambda q_{it} + \Gamma_k \ln \frac{s_{kit}}{n_i + g_x + \delta} + \Gamma_h \ln \frac{s_{hit}}{n_{it} + g_x + \delta}$$
$$+ (\Gamma_{du}\, dU + \Gamma_{RD}\, \theta + \Gamma_{gap}\, GAP0 + \Gamma_{gapt}\, GAP^{*}t + \Gamma_{RDT}\, \theta^{*}t)$$

where t is a time trend and GAP0 is our estimate of the initial technological gap relative to the US . We start out with the equation shown in the first line of (A.15) and add the remaining regressors one by one, incorporating a correction factor for Japan in the way discussed in the notes to Table A.2. Equation [7] in the table is an approximation to the convergence equation estimated in the text in the text, and yields similar results. Notice that the inclusion of interaction terms between the initial technological gap (and R&D investment) and a trend allow us to capture the "catch-up exhaustion effect" discussed in the text.

Some of the cross-equation changes in parameter estimates are noteworthy. First, the human capital variable has a negative coefficient (Γ_h) in equations [1] through [5]. The coefficient, however, becomes positive and significant once we allow for the catch-up exhaustion effect. Hence, the reason for the counterintuitive sign of Γ_h seems to be the following. University enrollment rates are the only variable with a significant (positive) trend in equations [1] to [5]. Since growth rates, after after controlling for other factors, tends to decrease over the period, the contribution of educational investment appears to be negative. Once we "explain" the decline in the growth rate through the catch-up term, however, the sign of the coefficient is reversed.

Secondly, notice the behaviour of the neoclassical convergence coefficient as we include additional regressors. In equations [1] and [2], which control only for investment rates in human and physical capital, the estimated value of λ is close to the standard 2% found in the literature. When we control for R&D investment and/or the initial technological gap (equations [3] to [5]), the estimated speeed of convergence increases by around 25%. Once we allow for catch-up exhaustion, however, λ falls again to values close to 2% in equations [6] and [7].

Finally, notice that the initial technological gap variable, by itself, is not significant and has the "wrong" sign (equations [4] and [5]). When an interaction term with a trend is included, however, both terms are highly significant and have the expected sign. This indicates that the advantage conferred by the initial technological gap has been diminishing over the period, as expected.

Table A.2: Some exploratory growth regressions

	[1]	[2]	[3]	[4]	[5]	[6]	[7]
constant	0.183	0.169	0.231	0.222	0.236	0.150	0.170
	(3.29)	(3.57)	(4.35)	(3.12)	(3.28)	(2.56)	(2.86)
λ	0.0201	0.0184	0.0256	0.0232	0.0253	0.0165	0.0187
	(3.75)	(4.03)	(4.75)	(3.37)	(3.56)	(2.83)	(3.15)
Γ_k	0.01963	0.0214	0.0211	0.0192	0.0195	0.0203	0.0218
	(2.56)	(3.27)	(3.30)	(2.96)	(3.00)	(3.89)	(4.19)
Γ_h	-0.00757	-0.0063	-0.0063	-0.0076	-0.0072	0.0081	0.109
	(2.60)	(2.52)	(2.57)	(3.05)	(2.90)	(2.80)	(3.32)
dU		-0.337	-0.311	-0.307	-0.302	-0.348	-0.357
		(6.22)	(5.75)	(5.56)	(5.45)	(7.80)	(8.01)
θ			0.0054		0.0031	0.0034	0.0064
			(2.38)		(1.13)	(1.68)	(2.42)
Gap0				-0.0053	-0.0034	0.0195	0.0188
				(1.30)	(0.78)	(4.57)	(4.28)
*Gap0*t*						-0.0012	-0.0011
						(6.78)	(6.02)
θ*t							-0.0003
							(1.78)
DJAPAN				0.0108	0.0086		
				(1.50)	(1.16)		
CJAPGAP						1.70	1.48
						(3.12)	(2.65)
R^2	0.384	0.556	0.580	0.587	0.592	0.738	0.746

- *Notes:*
- t-statistics in parentheses below each coefficient
- DJAPAN is the coefficient of a Japanese dummy when it is included in the equation in an additive fashion. CJPAGAP is a correction factor for Japan's initial technological gap and is given by the coefficient of a Japanese dummy ($\Gamma_{cjapgap}$) when the equation includes a catch-up term of the form

$$\Gamma_{gap}\ (GAP0 + \Gamma_{cjapgap}{*}DJAPAN) + \Gamma_{gapt}\ (GAP0 + \Gamma_{cjapgap}{*}DJAPAN){*}t$$

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