Growth with Technical Change and Human Capital: Transition Dynamics Versus Steady State Predictions*

Chris Papageorgiou
Department of Economics
Louisiana State University
Baton Rouge, LA 70803
cpapa@unix1.sncc.lsu.edu

Fidel Perez-Sebastian
Department of Economics
Universidad Pública de Navarra
31006 Pamplona, Spain
fidel.perez@unavarra.es

September, 1999

Abstract

This paper studies the steady-state and transitional dynamics predictions of an R&D-based growth model and evaluates their performance in explaining income disparities across countries. We find that even though steady-state conditions do slightly better at predicting schooling enrollment and investment rates, transitional dynamics predictions, better fit the cross-country output per worker data. These results suggest that the traditional view of a world in which nations move along their distinct balanced-growth paths is as likely as the one in which countries move along adjustment paths toward a common (very long-run) steady state. In addition, the model provides a reduced form empirical specification that incorporates capital input and R&D-effort measures. Therefore, we can compare the performance of the standard neoclassical growth model to that of an R&D-based growth model with human capital and imperfect competition, like ours. This stands in contrast to the prevalent view that reduced form regressions cannot discriminate between neoclassical and R&D-based growth frameworks.

JEL Classification Numbers: O33, O41, O47.

*We thank Craig Burnside, Jordi Caballe, Emilio Domínguez, Theo Eicher, Theodore Palivos, John Williams, and seminar participants at the 4^{th} International Conference of the Society of Computational Economics, University of Cambridge, England, 1998, and the Midwest Macro Conference, University of Pittsburgh, Fall 1999, for helpful comments and suggestions.

1 Introduction

In growth literature it is common practice to study cross-country income disparities under two maintained assumptions: First, that countries have distinct long-run growth paths, and therefore cross-country disparities can be studied using steady-state analysis. Second that income disparities can arise from transitions back to the steady state, thus understanding cross-country income differences requires the use of transitional dynamics analysis.

Since Mankiw, Romer and Weil (1992) (MRW) seminal contribution, empirical work on economic growth has primarily adopted the former assumption focusing on estimating reduced form steady-state specifications. The lack of absolute convergence exhibited by the international data seems to support this practice.[1] Theoretical growth models are also primarily focused on balanced-growth path analysis. Sala-i-Martin (1996) claims that the main reason to concentrate on steady states is that they are easier to analyze than transitional dynamics, and therefore makes them spring boards on which to advance richer explanations of growth.

Even though the literature has embraced steady-state analysis, it is widely accepted that income disparities are most likely due to some combination of steady-state differences and transition towards the long-run path.[2] It is then important to ask the question: How much of the dispersion in per capita income can be explained by steady-state differences and how much by countries being away from their steady-state paths? The main goal of this paper is to study the steady-state and transitional dynamics predictions of a growth model, and evaluate their performance in explaining income disparities across countries. To the best of our knowledge this is the first attempt in the literature to assess the importance of steady-state and transitional paths.

We, first, develop a model of economic growth that contains three main engines: technological progress, physical capital accumulation, and human capital formation. We argue that a successful model of economic growth and development is one in which *both* technological progress and human capital accumulation are necessary engines, and the endogenous outcome of the economic system.[3]

[1] In addition, Easterly and Kremer (1993) finds growth rates to be highly unstable over time while country characteristics are stable. They interpret their finding as one describing a world scenario in which countries are near their steady-state relative income levels.

[2] Barro and Sala-i-Martin (1995, Ch. 11) report estimates of regional σ-convergence within countries that allows for a large role for transitional dynamics. King and Rebelo (1993) also emphasize the important role of adjustment paths in explaining growth experiences.

[3] Recent theoretical and empirical advancements in economic growth literature suggest that *technological progress* and *capital input accumulation* are primary determinants of economic growth. The majority of growth models, however, focus on only one of these engines at a time. Ak-based models, e.g. Lucas (1988), Jones and Manuelli

In our model, technological progress is enhanced through innovation and imitation, and human capital through formal schooling. Modeling schooling (human capital) is a challenging task because the model will ultimately be taken to the data. Therefore we have to a look for a specifications of human capital that matches up with the existing cross-country data on education (average years of schooling as in, e.g. Barro and Lee (1993), and Nehru, Swanson, and Dubey (1995)). Our choice for the schooling technology follows the Mincerian approach (Mincer 1974) that has recently been revived by Bils and Klenow (1998).

Second, we employ cross-country data to evaluate the model's performance in explaining the growth process. We begin by estimating a MRW-type empirical specification implied by the model. Next, we study dynamics. The main innovation here is the characterization of the transitional dynamics by simulating the model and formally comparing its predictions to the data, as suggested by Klenow and Rodríguez-Clare (1997a). Finally, given the widespread use of steady-state conditions as a template on which to build empirical tests of alternative growth theories, we compare our transitional dynamics results to the steady-state results.

Our main finding is that both steady-state conditions and transitional dynamics seem to be able to describe the cross-county data equally well. Comparing between them, steady-state conditions do slightly better at predicting schooling enrollment and investment rates. Transitional dynamics predictions, however, fit the cross-country output per worker data better. Overall, these results suggest that a world in which nations move along their balanced-growth paths is as likely as a world in which countries move along adjustment paths toward a common (very long-run) steady state.

In addition, the model provides a reduced form empirical specification that incorporates capital input and R&D-effort measures. Therefore, we can compare the performance of the standard neoclassical growth model to that of an R&D-based growth model with human capital and imperfect competition, like ours. This stands in contrast to the prevalent view that reduced form regressions cannot discriminate between neoclassical and R&D-based growth frameworks (Barro and Sala-i-Martin (1995), and Jones (1996)). The steady-state regression results are in favor of the R&D-based growth model. In particular, including the R&D measure significantly improves the fit of the empirical specification. In a large sample of countries, all production factors enter

(1990), and Rebelo (1991), imply that sustainable growth is the outcome of reproducible inputs such as physical and human capital. Research and Development (R&D)-based models, e.g. Romer (1990), Grossman and Helpman (1991), Aghion and Howitt (1992), Jones (1995) and Young (1998), suggest that technological progress, rather than any accumulable input, is the primary engine of growth. Exceptions are Eicher (1996) and Restuccia (1997).

significantly. However, variations in output per worker across OECD nations are mainly explained by technological differences, whereas capital input disparities arise as the key explanatory factor among non-OECD countries.

Simulating the transitional dynamics using standard technologies and parameterizations, we find that the model generates output growth patterns very similar to the ones displayed by the Japanese and Korean experiences. In particular, we find that the model generates almost linear adjustment paths with growth rates that do not pick at the beginning of the development path but do so later on, like the patterns shown by the Japanese and Korean experiences.

Our paper is related to other work both in its scope and its methodological approach. Dinopoulos and Thompson (forthcoming) and Jones (1996) also analyze income disparities using MRW-type regressions. But their empirical specifications do not incorporate R&D components. There is a small but rapidly growing literature that investigates the relationship between human capital accumulation and technological progress, and their combined effect on economic growth. Eicher (1996) develops a rich model in which both human capital and technological innovation are endogenous. This paper, however, is only concerned with steady-state predictions. Restuccia (1997) develops a dynamic general equilibrium model with schooling and technology adoption. But the primary concern of the paper is how schooling and technology adoption may be amplifying the effects of productivity/policy differences on income disparity. Our paper is similar to Bils and Klenow (1998), Jones (1997, 1998), Hall and Jones (1999), and Jovanovic and Rob (1998), in that it uses the Mincerian approach to model schooling. Other work which is closer to the approach (using calibration and taking the implications of growth models to the data) rather than the scope of our paper include Christiano (1989), King and Rebelo (1993), Chari, Kehoe, and McGrattan (1996), Jovanovic and Rob (1998), and Perez-Sebastian (forthcoming). Finally, other growth models with multi-sector transitional dynamics include Caballe and Santos (1993), Mulligan and Sala-i-Martin (1993), Ortigueira and Santos (1997), and Eicher and Turnovsky (1997).

The rest of the paper is organized as follows. Section 2 presents the basic model. In this section, we establish the economic environment and examine the steady-state properties of the model. Section 3 provides estimates of a reduced form specification derived from the steady-state conditions of the model. These estimates serve as a first measure of fit that will be compared, later on, to the transitional dynamics predictions. The transitional dynamics analysis is presented in Section 4. Using calibration techniques, this section performs the simulation exercises and examines the stability of the system. Section 5 concludes discussing the main findings of our work, and directions for future research. Data sources are described in the Appendix.

2 The Basic Model

In this section we present the basic model. First, we outline the economic environment under which households and firms operate. Then we solve the socially optimal problem.

2.1 Economic environment

We consider a model economy that contains households and firms. Each household consist of identical agents that are involved in four types of activities: consumption goods production, intermediate goods manufacturing, human capital investment, and R&D effort. Population growth is in this economy exogenous and equal to n. Consumption goods are produced in a perfectly competitive environment in which prices and the variety of intermediate goods are taken as given. The intermediate-goods sector consists of monopolistic producers of differentiated products. Agents invest portions of their time to acquire formal education, provided by the schooling sector. Finally, the R&D activity is the source of technological progress in the model. In particular, agents spend part of their time learning new designs, which become new varieties of intermediate goods. When a design is learned, an intermediate-goods producer acquires the perpetual patent over the design. This allows the firm to manufacture the new variety, and practice monopoly pricing.

In what follows, we concentrate on the centrally planned economy (the social planner's problem), using social production functions in which externalities are internalized.[4] Our model economy is characterized by the following three equations: First, the production function takes the form

$$Y_t = (h_t L_{Yt})^{1-\alpha} \left[\sum_{i=0}^{A_t} x_{it}^{\alpha\gamma} \right]^{\frac{1}{\gamma}} \quad , \quad 0 < \alpha < 1 \ , \quad \gamma > 0 \ , \tag{1}$$

where Y_t is output and L_{Yt} is the portion of labor allocated to output production at period t; h_t is the per capita human capital (or per capita skill level) at t; $(1-\alpha)$ is the share of skilled labor; x_{it} is the amount of intermediate goods variety i at t; and A_t is the economy's technological level or, put in other words, the mass of producer durable types that have been already learned by date t. If $\gamma < 1$, intermediate goods are complementary; they are substitutes if $\gamma > 1$.

[4]We focus on the command optimum because historically governments do intervene in the economy. In addition, we calibrate the model to the Japanese and Korean output data. These countries are documented as having interventionist governments (see, e.g., Pack and Saggi (1997)). Finally, command optimum simplifies exposition.

Second, the R&D equation that determines technological progress is given by

$$A_{t+1} - A_t = \mu A_t^{\phi} \left(h_t L_{At}\right)^{\lambda} \left(\frac{A_t^*}{A_t}\right)^{\psi}, \quad \phi < 1, \ \ 0 < \lambda \leq 1, \ \ \psi \geq 0, \ \ A_t^* \geq A_t, \tag{2}$$

where L_{At} is the portion of labor employed in the R&D sector at time t; A_t^* is the worldwide stock of existing technology at t, which grows exogenously at rate g_{A^*}; μ is a parameter that determines the rate by which a new variety arrives; ϕ represents an externality due to the stock of existing technology; and λ is a negative external effect due to duplication. Our R&D equation includes a *catch-up* term $\left(\frac{A_t^*}{A_t}\right)^{\psi}$, where ψ is a technology gap parameter. The catch-up term captures the idea that the greater the technology gap between a leader and a follower, the higher the potential of the follower to catch up through imitation of existing technologies. The notion and formulation of the catch-up effect is credited to Veblen (1915), Gerschenkron (1962), Nelson and Phelps (1966), and Findlay (1978).

Third, we have the schooling equation that determines the way by which human capital is formed. Human capital technology is of particular interest in our model and deserves careful consideration. Since our aim is to take the model to the data then our specification ought to be one that maps the available data on average years of education to the stock of human capital. Using the Mincerian interpretation seems to deliver such a specification. This representation follows Bils and Klenow (1998), who suggest that the Mincerian specification of human capital is the appropriate way to incorporate years of schooling in the aggregate production function. Following their approach, human capital per capita is given by

$$h_t = e^{f(S_t)}, \tag{3}$$

where $f(S_t) = \eta S_t^{\beta}$, $\eta > 0$, $\beta > 0$; and S_t is the labor force average years of schooling at date t. The derivative $f'(S_t)$ represents the return to schooling estimated in a Mincerian wage regression: an additional year of schooling raises a worker's efficiency by $f'(S_t)$.[5]

Next, we assume that at each period agents allocate labor to human capital formation after production in the other activities has taken place. The average educational attainment can then

[5] Mincer (1974) estimates the following wage regression equation:

$$w_i = \beta_0 + \beta_1 (SCHOOL)_i + \beta_2 (EXPERIENCE)_i + \beta_3 (EXPERIENCE)_i^2 + \varepsilon_i,$$

where w_i is the log wage for individual i, $SCHOOL$ is the number of years in school, $EXPERIENCE$ is the number of years of work experience, and ε is a random disturbance term. For the original discussion on Mincerian wage regressions see Mincer (1974). For recent discussion of the advantages of the Mincerian approach in growth modeling and estimation, see Bils and Klenow (1998), Krueger and Lindahl (1998), and Topel (1998).

be written as

$$S_t = \frac{\sum_{j=0}^{t-1} L_{Hj}}{L_t}, \tag{4}$$

where L_{Ht} is the number of people enrolled in school at date t. Notice that the ratio L_{Ht} to L_t can be reinterpreted as the fraction of an individual's total time endowment devoted to schooling at time t.

An example may serve to clarify the behavior of S_t as given by equation (4). Suppose that we want to estimate the mean years of education at period 2 (S_2) in an economy with only three identical agents (x, y, z), and no population growth. Also, assume that the timing of the agents' education is as shown in table 1.

Table 1: An example using the law of motion of S

Agents	x	y	z
Education during period 0	0	0	1
Education during period 1	0	1	1
Education during period 2	1	1	1

The above table says that in period 0, z spends all of his labor endowment in education where x and y spend no time in education. In period 1, y and z spend all of their endowment in schooling where x decides once again to skip education completely. Finally, in period 3, all three agents spend all of their time endowment in education. It is therefore true that $\frac{L_{H,0}}{L_2} = \frac{1}{3}$, $\frac{L_{H,1}}{L_2} = \frac{2}{3}$, and $\frac{L_{H,2}}{L_2} = \frac{3}{3}$, and thus $S_2 = \frac{1}{3} + \frac{2}{3} + \frac{3}{3} = 2$. This means that in our economy at period 2 the mean years of schooling is 2 years.

Notice that from equation (4), we can derive the law of motion of the average educational attainment as follows:

$$\begin{aligned} S_{t+1} - S_t &= \frac{\sum_{j=0}^{t} L_{Hj}}{L_{t+1}} - \frac{\sum_{j=0}^{t-1} L_{Hj}}{L_t}, \\ &= \left(\frac{1}{1+n}\right)\left(\frac{L_{Ht}}{L_t} - n\, S_t\right). \end{aligned} \tag{5}$$

As will become clear later, equation (5) implies that average years of schooling eventually reaches an upper bound remaining constant thereafter.

2.2 Social planner's problem

Let C_t be the amount of aggregate consumption at date t. A central planner would choose the sequences $\{C_t, S_t, A_t, K_t, L_{Yt}, L_{At}, L_{Ht}\}_{t=0}^{\infty}$ so as to maximize the lifetime utility of the representative consumer subject to the feasibility constraints of the economy, and the initial values L_0, K_0, and A_0. The problem is stated as follows:

$$\max_{\{C_t,S_t,A_t,K_t,L_{Yt},L_{At},L_{Ht}\}} \sum_{t=0}^{\infty} \rho^t \left[\frac{\left(\frac{C_t}{L_t}\right)^{1-\theta} - 1}{1-\theta} \right], \tag{6}$$

subject to,

$$Y_t = A_t^{\xi} \left(e^{f(S_t)} L_{Yt} \right)^{1-\alpha} K_t^{\alpha}, \tag{7}$$

$$I_t = K_{t+1} - (1-\delta) K_t = Y_t - C_t, \tag{8}$$

$$A_{t+1} - A_t = \mu A_t^{\phi} \left(e^{f(S_t)} L_{At} \right)^{\lambda} \left(\frac{A_t^*}{A_t} \right)^{\psi}, \tag{9}$$

$$S_{t+1} - S_t = \left(\frac{1}{1+n} \right) \left(\frac{L_{Ht}}{L_t} - n\, S_t \right), \tag{10}$$

$$L_t = L_{Yt} + L_{At} + L_{Ht}, \tag{11}$$

$$\frac{L_{t+1}}{L_t} = 1 + n, \quad \text{for all } t, \tag{12}$$

$$\frac{A_{t+1}^*}{A_t^*} = 1 + g_{A^*}, \tag{13}$$

$$L_0,\ S_0,\ K_0,\ A_0 \ \text{ given,}$$

where θ is the inverse of the intertemporal elasticity of substitution; K_t is the country's stock of physical capital and denotes the sum of all producer durable units at period t; ρ is the discount factor; and δ is the depreciation rate of capital. Equation (7) is the well-known Cobb-Douglas form in which production function (1) is expressed at the aggregate level; the externality parameter ξ equals $\frac{1}{\gamma} - \alpha$. Equation (8) is the economy's budget constraint as well as the law of motion of the stock of physical capital; it says that, at the aggregate level, domestic output must equal consumption plus physical capital investment, I_t. Equation (11) is the labor constraint; the labor force – that is, the number of people employed in the output and the R&D sectors – plus the number of people going to school must be equal to the population stock.

The optimal control problem can be stated as follows:

$$V(A_t, K_t, S_t) = \max_{\{L_{Ht}, L_{At}, I_t\}} \frac{\left[\frac{A_t^{\xi}[e^{f(S_t)}(L_t - L_{Ht} - L_{At})]^{1-\alpha} K_t^{\alpha} - I_t}{L_t}\right]^{1-\theta} - 1}{1-\theta} +$$
$$+V\left[A_t + \mu A_t^{\phi}\left(e^{f(S_t)} L_{At}\right)^{\lambda}\left(\frac{A_t^*}{A_t}\right)^{\psi}; K_t(1-\delta) + I_t;\ S_t + \frac{1}{1+n}\left(\frac{L_{Ht}}{L_t} - nS_t\right)\right], \qquad (14)$$

where $V(\cdot)$ is a value function; L_{Ht}, L_{At}, I_t are the control variables; and A_t, K_t, S_t are the state variables. Solving the optimal control problem gives the Euler equations that characterize the optimal allocation of labor in human capital investment, in R&D investment, and in consumption/physical capital investment respectively as follows:

$$\left(\frac{C_t}{L_t}\right)^{-\theta} \frac{(1-\alpha)Y_t}{L_{Yt}} = \frac{\rho}{1+n}\left(\frac{C_{t+1}}{L_{t+1}}\right)^{-\theta} \frac{(1-\alpha)Y_{t+1}}{L_{Y,t+1}}\left[1 + f'(S_{t+1})\left(\frac{L_{Y,t+1}}{L_{t+1}} + \frac{L_{A,t+1}}{L_{t+1}}\right)\right], \qquad (15)$$

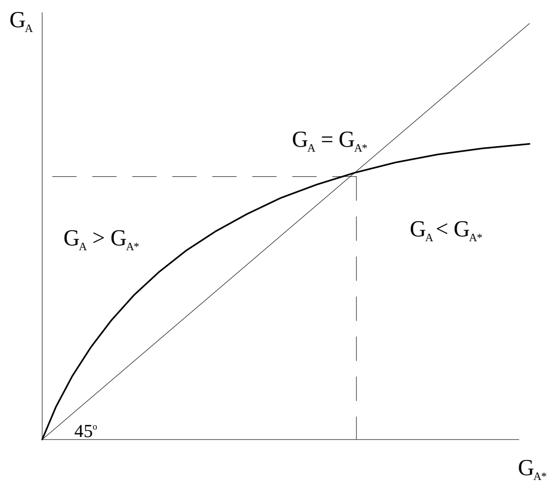
$$\left(\frac{C_t}{L_t}\right)^{-\theta} \frac{(1-\alpha)Y_t}{L_{Yt}} = \frac{\rho}{1+n}\left(\frac{C_{t+1}}{L_{t+1}}\right)^{-\theta} \frac{\lambda(A_{t+1} - A_t)}{L_{At}} *$$
$$*\left\{\frac{\xi Y_{t+1}}{A_{t+1}} + \left[1 + (\phi - \psi)\left(\frac{A_{t+2} - A_{t+1}}{A_{t+1}}\right)\right]\left[\frac{\frac{(1-\alpha)Y_{t+1}}{L_{Y,t+1}}}{\frac{\lambda(A_{t+2} - A_{t+1})}{L_{A,t+1}}}\right]\right\}, \qquad (16)$$

$$\left(\frac{C_t}{L_t}\right)^{-\theta} = \frac{\rho}{1+n}\left(\frac{C_{t+1}}{L_{t+1}}\right)^{-\theta}\left[\frac{\alpha Y_{t+1}}{K_{t+1}} + (1-\delta)\right]. \qquad (17)$$

At the optimum, the planner must be indifferent between investing one additional unit of labor in schooling, R&D, and final output production. The LHS of equations (15) and (16) represent the return from allocating one additional unit of labor to output production. The RHS of equation (15) is the discounted marginal return to schooling, taking into account population growth. The RHS term in brackets arises because human capital affects the effectiveness of labor both in output production and R&D. The RHS of equation (16) is the return to R&D investment. One additional unit of R&D labor generates $\frac{\lambda(A_{t+1} - A_t)}{L_{At}}$ new ideas for new types of producer durables. Each of these new designs will increase next period's output by $\frac{\xi Y_{t+1}}{A_{t+1}}$ and R&D production by $\frac{dA_{t+2}}{dA_{t+1}}$ *times* $\frac{(1-\alpha)Y_{t+1}}{L_{Y,t+1}}\left[\frac{\lambda(A_{t+2} - A_{t+1})}{L_{A,t+1}}\right]^{-1}$; where $\frac{(1-\alpha)Y_{t+1}}{L_{Y,t+1}}\left[\frac{\lambda(A_{t+2} - A_{t+1})}{L_{A,t+1}}\right]^{-1}$ gives the value of one additional design, which equalizes labor wages across sectors.

Euler equation (17) is standard; it says that the planner is indifferent between consuming one additional unit of output today and converting it into capital, thus consuming the proceeds tomorrow.

Figure 1: Relationship between $G_{A,ss}$ and $G_{A^*,ss}$



2.3 Steady-state growth

We now derive the steady-state conditions implied by the model. Let lower case letters denote per capita variables, and $g_x = G_x - 1$ denote the growth rate of x. The aggregate production function, given by equation (7), combined with the steady-state (ss) condition $g_{Y,ss} = g_{K,ss}$ delivers the gross growth rate of output as a function of the gross growth rate of technology as

$$G_{Y,ss} = (G_{A,ss})^{\frac{\xi}{1-\alpha}} (1+n) . \tag{18}$$

Given that at steady state $\frac{A_{t+1}-A_t}{A_t} \overset{ss}{=} \frac{A_{t+2}-A_{t+1}}{A_{t+1}}$ it follows from equation (2) that

$$G_{A,ss} = \left[(1+n)^{\lambda} (G_{A^*,ss})^{\frac{\xi}{1-\alpha}} \right]^{\frac{1}{1+\psi-\phi}} . \tag{19}$$

Equation (19) shows the relationship between the technology frontier growth rate and the technology growth rate of the model economy. Figure 1 illustrates this relationship. Notice that since the ratio $\frac{\psi}{1+\psi-\phi} < 1$ the function is concave with a unique point at which

$$G_{A,ss} = G_{A^*,ss} = (1+n)^{\frac{\lambda}{1-\phi}} . \tag{20}$$

The gross rate $G_{A,ss}$ cannot be larger than $G_{A^*,ss}$; otherwise, A_t will be eventually bigger than A_t^*, and this has been ruled out by assumption. If $G_{A,ss}$ is smaller than $G_{A^*,ss}$, on the other hand, the ratio $\frac{A_t^*}{A_t}$ will go to infinity. Equation (11) implies that along the balanced-growth path, labor devoted to different activities (L_Y, L_A, L_H) grows at the same rate as the population size. It then follows that $G_{A,ss}$ goes to infinity with $\frac{A_t^*}{A_t}$, by equation (2). The only feasible-steady state scenario is therefore one in which $G_{A,ss}$ equals $G_{A^*,ss}$, which in turn impies that

$$G_{Y,ss} = G_{C,ss} = G_{K,ss} = (1+n)^{\frac{\lambda\xi}{(1-\alpha)(1-\phi)}}. \tag{21}$$

Consistent with Jones (1995) our balanced-growth path is free of “scale effects”, and policy has no effect on long-run growth. The reason why our model's long-run growth is equivalent to that of Jones even in the presence of a schooling sector, is that at steady state the mean years of education, S_t, reaches a constant level, therefore its growth rate becomes zero.

2.4 Labor shares in output, R&D, and schooling

Next, we derive the steady-state shares of labor in the three sectors of the economy. Let $u_X = \frac{L_X}{L}$ be the fraction of labor devoted to activity X, $\forall X = H, Y, A$. Euler equation (15) combined with the balanced-growth equation (21) delivers the steady-state share of labor in schooling as

$$\begin{aligned} u_{H,ss} &= 1 - \left[\frac{G_{y,ss}^{\theta-1}\left(\frac{1+n}{\rho}\right) - 1}{f'(S_{ss})} \right], \quad \text{if } \frac{G_{y,ss}^{\theta-1}\left(\frac{1+n}{\rho}\right) - 1}{f'(S_{ss})} \leq 1, \\ &= 0 \ \text{ otherwise.} \end{aligned} \tag{22}$$

As usual, the steady-state share of labor in schooling is positively related with the return to education $f'(S_{ss})$. A more direct relationship between S and u_H at steady state is given by equation (5) as follows:

$$S_{ss} = \frac{u_{H,ss}}{n}. \tag{23}$$

Equation (23) shows that along the balanced growth path, the average number of years of education per worker remains constant; the economy invests in human capital just to provide new generations with the steady-state level of schooling. This is consistent with recent work by Jones (1996, 1997), where growth regressions are developed from steady-state predictions, and data on S_{ss} acts as a proxy for $u_{H,ss}$. The estimated coefficient on S_{ss} in part reflects the parameter $\frac{1}{n}$ in our framework.

Euler equation (16) combined with balanced-growth condition (21) deliver the steady-state labor share in R&D as

$$u_{A,ss} = \frac{1 - u_{H,ss}}{1 + \left(\frac{1-\alpha}{\lambda\xi g_{A,ss}}\right)\left[G_{y,ss}^{\theta-1}\left(\frac{G_{A,ss}}{\rho}\right) - (\phi-\psi)g_{A,ss} - 1\right]}. \tag{24}$$

Finally, the steady-state share of labor in output production is simply derived from the labor constraint and is given by

$$u_{Y,ss} = 1 - u_{H,ss} + u_{A,ss}. \tag{25}$$

Whereas equation (22) implies that human-capital investment can equal zero if the returns to schooling are not sufficiently large, R&D and final output investments will always take place because their marginal productivities go to infinity as their allocations fall to zero.

2.5 Dynamics

The aggregate production function, equation (7), suggests that we normalize variables by the term $A_t^{\frac{\xi}{1-\alpha}} L_t$. We then rewrite consumption, physical capital and output as $\hat{c}_t = \frac{C_t}{A_t^{\frac{\xi}{1-\alpha}} L_t}$, $\hat{k}_t = \frac{K_t}{A_t^{\frac{\xi}{1-\alpha}} L_t}$ and $\hat{y}_t = \frac{Y_t}{A_t^{\frac{\xi}{1-\alpha}} L_t}$, respectively. Using equation (15) gives

$$\left(\frac{\hat{c}_{t+1}}{\hat{c}_t}\right)^{\theta} \left(\frac{u_{Y,t+1}}{u_{Yt}}\right) (G_{At})^{\frac{(\theta-1)\xi}{1-\alpha}} \left(\frac{\hat{y}_t}{\hat{y}_{t+1}}\right) = \left(\frac{\rho}{1+n}\right) \left[f'(S_{t+1})(u_{Y,t+1} + u_{A,t+1}) + 1\right]. \tag{26}$$

From the R&D equation (2), we get that

$$G_{At} = \frac{A_{t+1}}{A_t} = 1 + \upsilon \left[e^{f(S_t)} u_{At}\right]^{\lambda} T^{(1+\psi-\phi)}, \tag{27}$$

where $T = \frac{A_t^*}{A_t}$; and $\upsilon = \mu \left(A_t^*\right)^{\phi-1} L_t^{\lambda}$, which is a constant.[6] From equation (16) we get that

$$\begin{aligned} \left(\frac{\hat{c}_{t+1}}{\hat{c}_t}\right)^{\theta} \left(\frac{\hat{y}_t}{\hat{y}_{t+1}}\right) \left(\frac{u_{Y,t+1}}{u_{Yt}}\right) \quad &= \quad \frac{\rho\, g_{At}}{G_{At}^{\frac{\xi}{1-\alpha}(\theta-1)+1}} \left(\frac{u_{A,t+1}}{u_{At}}\right) * \\ &* \left[\left(\frac{\lambda\xi}{1-\alpha}\right) \left(\frac{u_{Y,t+1}}{u_{A,t+1}}\right) + \left(\frac{1}{g_{A,t+1}}\right) + (\phi - \psi)\right]. \end{aligned} \tag{28}$$

Finally, from equation (17) we get

$$\frac{1+n}{\rho} \left[\left(\frac{\hat{c}_{t+1}}{\hat{c}_t}\right) (G_{At})^{\frac{\xi}{1-\alpha}}\right]^{\theta} = \alpha \frac{\hat{y}_{t+1}}{\hat{k}_{t+1}} + (1-\delta). \tag{29}$$

The system that determines the dynamic equilibrium normalized allocations are formed by the conditions associated with three control and three state variables as follows:

[6] To show that υ is constant requires some algebra. Rewriting the equality in its gross growth form, $\frac{\upsilon_{t+1}}{\upsilon_t} = G_{A^*t}^{\phi-1}(1+n)^{\lambda}$, and given that $G_{A^*t} = G_{A,ss} = (1+n)^{\frac{\lambda}{1-\phi}}$, it follows that $\frac{\upsilon_{t+1}}{\upsilon_t} = 1$.

Control Variables:

1. Euler equation for labor share in schooling, u_{Ht}: Eq. (26).
2. Euler equation for labor share in R&D, u_{At}: Eq. (28).
3. Euler equation for consumption, $\hat{c}_t$: Eq. (29).

   Subject to the constraint $u_{Yt} = 1 - u_{At} - u_{Ht}$.

State Variables:

1. Law of motion of human capital, S_t: Eq. (5).
2. Law of motion of technology, A_t: Eq. (27).
3. Law of motion of physical capital,

$$(1+n)\hat{k}_{t+1} \left(G_{At}\right)^{\frac{\xi}{1-\alpha}} = (1-\delta)\hat{k}_t + \hat{y}_t - \hat{c}_t, \tag{30}$$

where

$$T_{t+1} = T_t \left(\frac{G_{A^*t}}{G_{At}}\right), \tag{31}$$

and

$$\hat{y}_t = \hat{k}_t^{\alpha} \left[e^{f(S_t)} u_{Yt}\right]^{1-\alpha}. \tag{32}$$

3 Steady-State Level Regressions

In this section, we estimate a reduced form specification derived from steady-state conditions of the model. This is useful in two ways. First, it tells us whether inputs affect income in the direction and magnitude that the model predicts. Second, it provides a first measure of fit that will be compared to the transitional dynamics predictions in section 4.

3.1 The empirical model

We now incorporate the steady-state conditions for the different inputs into the production function. Equations (7) and (17) imply that at steady state the amount of physical capital per capita is

$$k_{ss} = A_t^{\frac{\xi}{1-\alpha}} u_{Y,ss}\, e^{f(S_{ss})} \left[\frac{i_{ss}}{G_{y,ss}\,(1+n) - 1 + \delta}\right]^{\frac{1}{1-\alpha}}, \tag{33}$$

where i_{ss} is the investment share. Using R&D technology (27), we get that

$$A_t = \left(\frac{\upsilon\,(A_t^*)^{1+\psi-\phi}}{G_{y,ss}^{\frac{1-\alpha}{\xi}} - 1}\right)^{\frac{1}{1+\psi-\phi}} \left[e^{f(S_{ss})}\, u_{A,ss}\right]^{\frac{\lambda}{1+\psi-\phi}}. \tag{34}$$

Substituting equations (23), (33) and (34) into production function (7) and taking logs, we obtain the reduced form specification: an expression for income as a function of the rate of investment in physical capital, the R&D labor share and the schooling enrollment ratio at steady state. This is given as follows:

$$\ln\left(\frac{Y_t}{L_t}\right) = \ln\left[\left(\frac{\upsilon\,(A_t^*)^{1+\psi-\phi}}{G_{y,ss}^{\frac{1-\alpha}{\xi}}-1}\right)^{\frac{\xi}{(1+\psi-\phi)(1-\alpha)}} u_{Y,ss}\right] + \frac{\lambda\,\xi\,\ln\left[e^{f\left(\frac{u_{H,ss}}{n}\right)}\,u_{A,ss}\right]}{(1+\psi-\phi)\,(1-\alpha)} + \\ +f\left(\frac{u_{H,ss}}{n}\right) + \left(\frac{\alpha}{1-\alpha}\right)\ln\left(i_{ss}\right) - \left(\frac{\alpha}{1-\alpha}\right)\ln\left[G_{y,ss}\,(1+n)-1+\delta\right]. \qquad (35)$$

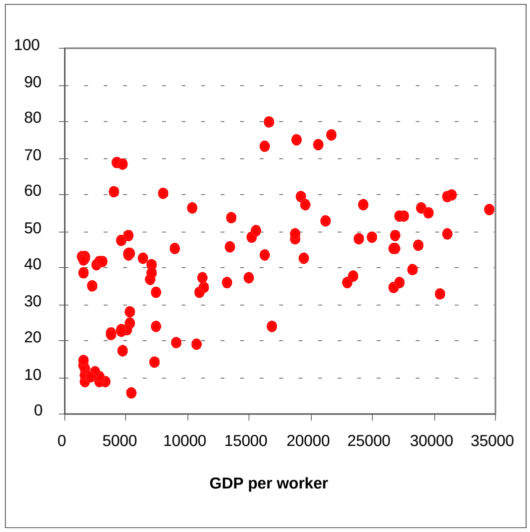
The last three summands correspond to the standard human capital-augmented Solow model predictions. For a given technological level, a country is richer along the balanced-growth path, the higher is its investment rate either in education or in physical capital, and the lower is its population growth rate. The second summand predicts that countries with higher R&D effort rates are richer. It is the result of the endogenous technological change nature of the model and, therefore, allows us to test the importance of ideas once the neoclassical growth mechanisms have been taken into account. We will assume that the first term of the RHS of equation (35) is common to all countries in the cross-section. We are then implicitly assuming that countries have access to the same pool of ideas, and allocate the same fraction of labor to output production at steady state. To the extend that this is not the case, it will be captured by the regression error term.

3.2 Data

We consider four samples of countries. The first one is the MRW's non-oil nations sample for which average years of schooling per worker are available in the STARS (World Bank) data base. After eliminating Ireland, because its schooling figures appear implausibly high, we are left with 79 countries. The second sample is a subsample of the first one and contains 56 countries for which we could construct the R&D labor measure. The third sample contains 21 OECD countries: the MRW's 22-OECD minus Ireland. Finally, the fourth sample is the second minus the third subsample; we call this the non-OECD sample.

From Penn World Tables (PWT), mark 5.6, we obtain annual data on rates of investment (i), labor force stocks (L), and real GDP per worker that we use to measure $\frac{Y}{L}$. We take n to be the implied labor force growth rate. Schooling enrollment rates (u_H) are calculated from the STARS

Figure 2: Percentage of Scientists and Engineers (S&E) in R&D personnel



educational attainment data. Following many other researchers, we compute physical capital stocks from investment rates using the perpetual inventory method. The starting point for most countries is 1960. We want to give the initial stock as many years to depreciate as possible so as to make the capital stock measure as insensitive to the initial value as possible. Since the STARS data goes to 1987, we assign to the physical capital stock its 1982-86 average. We then take the same 5-year average value for each of the above variables.[7]

To construct the R&D measure, we employ fractions of scientists and engineers (S&E) in the population. Population figures come from PWT 5.6, and S&E numbers from UNESCO. Since the latter data come primarily from censuses, they are not available in all periods. Because of that we choose a wider time interval and compute their 1980-1992 average. UNESCO statistics classifies R&D personnel into S&E, technicians, and auxiliary personnel. For the periods and countries for which the three types are available, Figure 2 shows that there is a positive relationship between the ratio of S&E to R&D labor and the level of income. Given that S&E must have similar educational attainment levels in all countries we measure $e^{f(S)}u_A$ as the fraction of S&E.

[7] The data Appendix discusses in detail data sources and construction methods. It also lists the sample of countries, and provides the mean value of relevant variables for each nation.

3.3 Findings

We first estimate the equivalent augmented-Solow model regression for the three samples. Results should not differ from other similar exercises, like MRW and Jones (1996). The empirical specification is now

$$\ln\left(\frac{Y_t}{L_t}\right) = a + f\left(\frac{u_{H,ss}}{n}\right) + \left(\frac{\alpha}{1-\alpha}\right)\ln\left(i_{ss}\right) - \left(\frac{\alpha}{1-\alpha}\right)\ln\left[G_{y,ss}\left(1+n\right) - 1 + \delta\right], \qquad (36)$$

where a equals the first RHS summand in specification (35), and represents the regression intercept. Table 2 shows the familiar MRW results. In the large sample of countries, human and physical capital investment rates and population growth rates can explain a big fraction of the output per worker variance across countries both in the unrestricted and the restricted model. The restricted regression's adjusted $R^2 = 0.697$, is a little lower than MRW's adjusted $R^2 = 0.78$ because our human capital measure varies less across countries.[8] The estimate of the elasticity of output with respect to physical capital α is 0.385, which agrees with the existing empirical evidence on income shares, e.g. Bernard and Jones (1996, page 1231). Results from the 56-country and non-OECD samples are qualitatively similar to those obtained from the large sample of countries. For the OECD sample, the fit of both models is worse. Now, the unrestricted model's adjusted $R^2 = 0.142$, and the estimate of α is 0.513 that is substiantially higher than estimates obtained in the other subsamples. Our theoretical model imposes two restrictions to its empirical specification: the coefficient associated to $f\left(\frac{u_{H,ss}}{n}\right)$ equals *one*; and the coefficients for $\ln\left(i_{ss}\right)$ and $\ln\left[G_{y,ss}\left(1+n\right) - 1 + \delta\right]$ are the same but of opposite sign. Performing Wald tests, we cannot reject these constraints at high significance levels.

We assign a value of 0.06 to the depreciation rate (δ), and a value of 1.016 percent for the steady-state gross growth rate of income ($G_{y,ss}$), the average number in the Bils and Klenow's (1998) 91-country sample. Although we recognize potential caveats, we proceed with OLS estimation.[9]

The bottom half of Table 3 (the restricted model), displays the main results of estimating specification (35). Compared with Table 2, including the R&D measure improves the fit of the

[8] Klenow and Rodríguez-Clare (1997b) find that educational attainment data given by primary, secondary, and tertiary education (as in our data) varies less than secondary enrolment rates (as in MRW's data).

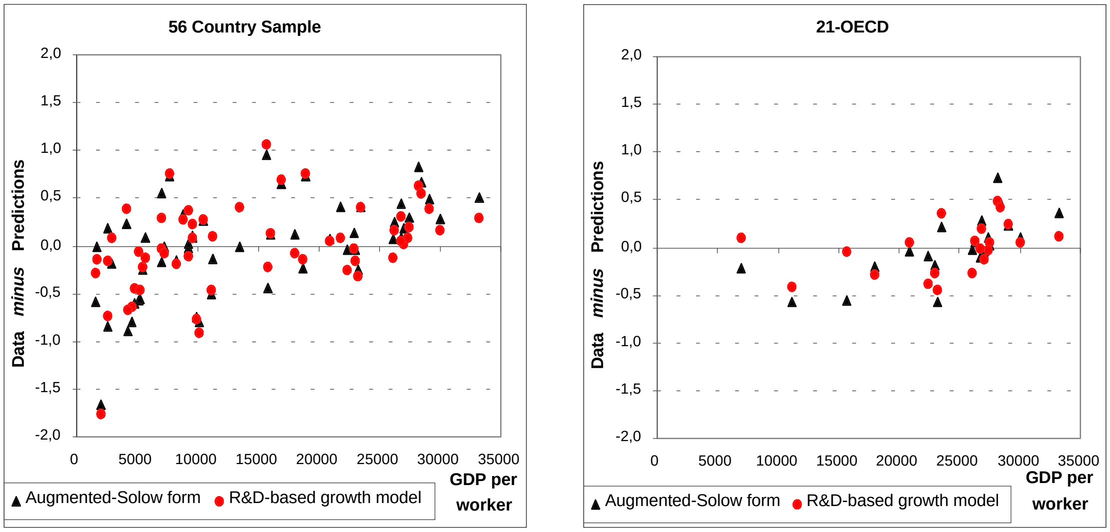
[9] As Islam (1995) and Caselli, Esquivel and Lefort (1996) pointed out, there are two important sources of inconsistency regarding the OLS estimation procedure as applied in the existing growth literature. These are, correlated country-specific effects and endogenous explanatory variables. Our R&D data set is limited to a cross-section, therefore it does not allow for fixed effects. Endogeneity problems can be corrected using Instrumental Variable (IV) estimation, however the appropriate set of instruments is not clear.

Table 2: Estimation of the augmented-Solow form under steady-state conditions

Dependent variable: Log GDP per worker, 1982-86 Averages				
Sample:	79 countries	56 countries	21-OECD	Non-OECD
Unrestricted Regression:				
Constant	6.984***	6.852***	6.983*	12.292***
	(1.430)	*(2.072)*	*(3.971)*	*(2.748)*
$f(u_H/n)$	1.108***	0.845***	0.427	1.233***
	(0.265)	*(0.305)*	*(0.379)*	*(0.368)*
$\ln(i)$	0.602***	0.632***	0.942*	0.429***
	(0.082)	*(0.091)*	*(0.495)*	*(0.110)*
$\ln[G_y(1+n)-1+\delta]$	-0.461	-0.800	-1.398	2.108
	(0.784)	*(1.036)*	*(1.742)*	*(1.443)*
$\bar{R}^2$	0.700	0.624	0.208	0.509
Restricted Regression:				
Constant	6.856***	6.951***	6.658***	6.896***
	(0.066)	*(0.073)*	*(0.477)*	*(0.087)*
$f(u_H/n)$ constraint	1	1	1	1
$\ln(i)-\ln[G_y(1+n)-1+\delta]$	0.627***	0.595***	1.057**	0.420***
	(0.063)	*(0.066)*	*(0.461)*	*(0.094)*
$\bar{R}^2$	0.697	0.636	0.142	0.450
Test of restrictions: *p-values*	0.912	0.851	0.178	0.162
Implied α	0.385	0.373	0.513	0.296
.	*(0.024)*	*(0.026)*	*(0.109)*	*(0.047)*

Note: White's heteroskedasticity-consistent standard errors are in parentheses. The p-value corresponds to the Wald test of whether the coefficient associated with f(uH,ss/n) equals one, and the coefficients for ln(iss) and ln[Gy,ss(1+n)-1+δ] are the same but of opposite sign. The implied α comes from restricted regression. *** Significantly different from 0 at the 1% level. ** Significantly different from 0 at the 5% level. * Significantly different from 0 at the 10% level.

Figure 3: Residuals in steady-state regression



regression. For the 56-country sample for, which data on R&D labor are available, the adjusted R^2 coefficient increases from 0.636 to 0.677. The increment experience in the 21-OECD case is striking; the adjusted R^2 goes from 0.142 up to 0.398. We can see this also in Figure 3. As in Jones (1996) and Dinopoulos and Thompson (forthcoming) steady-state conditions tend to overpredict the performance of poor countries and underpredict the performance of rich countries. The R&D measure helps to partially correct this, especially in the OECD group.

The results support the R&D-based growth model over the standard neoclassical growth model, especially for our large sample. In the 56-country sample the three inputs measures, that is human and physical capital accumulation and R&D labor, enter significantly at the 1 percent level. In addition, the restrictions imposed by the model cannot be rejected below the 13 percent significance level. The estimate of the elasticity of output with respect to physical capital α is now 0.268, still in agreement with other evidence on income shares.

With respect to the smaller samples, the model fits better the data for non-OECD nations, with a p-value for the test of restrictions of 0.115. In the 21-OECD case, the constraints can not be rejected only when the significance level is below 1.9 percent. But interestingly in both non-OECD and 21-OECD samples, estimated coefficients are not significantly different from theestimates obtained in the larger sample. Capital inputs do not enter significantly for OECD countries, whereas R&D

Note: White's heteroskedasticity-consistent standard errors are in parentheses. The p-value corresponds to the

Table 3: Estimation of the model under seady-state conditions

Dependent variable: Log GDP per worker, 1982-86 Averages			
Sample:	56 countries	21-OECD	Non-OECD
Unrestricted Regression:			
Constant	9.961***	11.097***	12.964***
	(2.262)	*(2.927)*	*(2.843)*
$f(u_H/n)$	0.610**	0.432	0.993**
	(0.275)	*(0.330)*	*(0.414)*
$\ln(i)$	0.434***	0.213	0.372***
	(0.0811)	*(0.356)*	*(0.107)*
$\ln[G_y(1+n)-1+\delta]$	-0.196	-0.042	1.863
	(0.991)	*(1.422)*	*(1.483)*
$\ln(S\&E)$	0.202***	0.286***	0.106
	(0.051)	*(0.066)*	*(0.077)*
$\bar{R}^2$	0.689	0.564	0.472
Restricted Regression:			
Constant	8.239***	9.027***	7.575***
	(0.338)	*(0.935)*	*(0.566)*
$f(u_H/n)$ constraint	1	1	1
$\ln(i)-\ln[G_y(1+n)-1+\delta]$	0.367***	0.366	0.346***
	(0.075)	*(0.511)*	*(0.089)*
$\ln(S\&E)$	0.150***	0.258***	0.078
	(0.039)	*(0.074)*	*(0.062)*
$\bar{R}^2$	0.677	0.398	0.434
Test of restrictions: *p-values*	0.132	0.019	0.115
Implied α	0.268	0.268	0.257
.	*(0.040)*	*(0.028)*	*(0.050)*

Wald test of whether the coefficient associated with f(uH,ss/n) equals one, and the coefficients for ln(iss) and ln[Gy,ss(1+n)-1+δ] are the same but of opposite sign. The implied α comes from restricted regression.*** Significantly different from 0 at the 1% level. ** Significantly different from 0 at the 5% level. * Significantly different from 0 at the 10% level.

labor is quite significant. The opposite is true in the non-OECD sample; only capital inputs enter significantly, and therefore adjusted R^2 decreases from 0.450 (in Table 2) to 0.434. We conclude that variations in output per worker across OECD nations are mainly explained by technological differences, whereas capital input differences seem to be the key explanatory factor among non-OECD countries.

4 Transitional Dynamics Results

Our next task is to simulate the transitional dynamics of the model, and then take their predictions to the data. To solve the dynamics equation system, stated on page 11, we follow Judd (1992), approximating the policy functions employing high-degree polynomials in the state variables.[10]

4.1 Calibration

Table 4 shows the parameter values used to carry out the simulations. As in the steady-state regression exercise, we take $\delta = 0.06$, and $g_y = 0.016$. We assign values of 0.36 to the capital-share of output (α), and 0.96 to the discount factor (ρ). We set the growth rate of the population (n) to 1.16 percent per year, which is the average growth rate of the labor force in the G-5 countries (France, West Germany, Japan, the United Kingdom, and the United States) during the period 1965-1990. Taking from Domowitz, Hubbard and Petersen (1988) a mark-up ratio charged by intermediate-goods producers of 1.35, implies a value for ξ equal to 0.126.[11]

Table 4: Parameter values used in the simulations

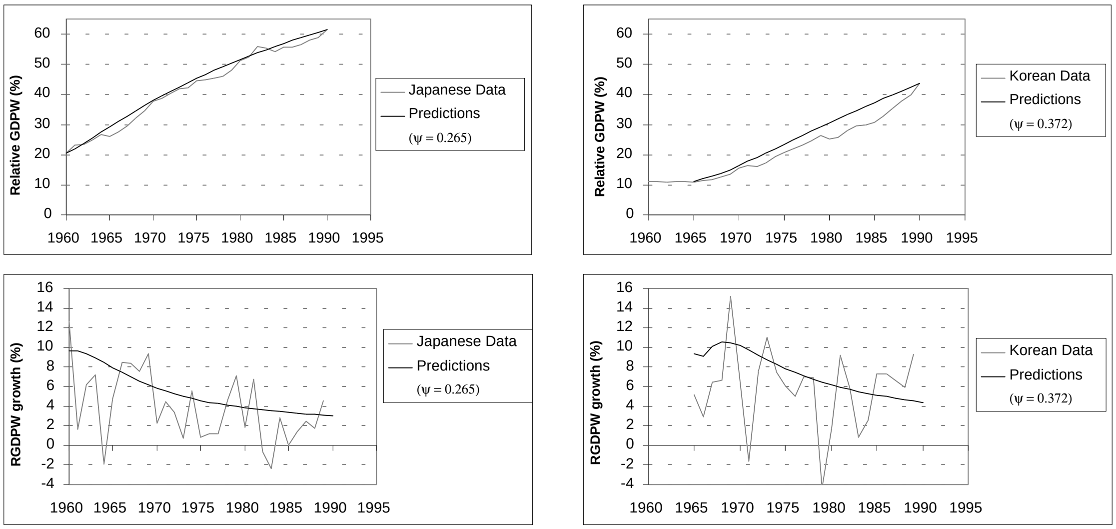
α	0.36	ξ	0.126	S_{ss}	12.5
ρ	0.96	g_y	0.016	η	0.69
δ	0.06	λ	0.5	β	0.43
n	0.0116	ϕ	0.93	θ	1.28

It is not clear what the steady-state value of the average educational attainment is given that mean years of schooling have been increasing over the last decades in most developed countries. We choose to set S_{ss} to 12.5, to match the 1993 U.S. figure. Equations (22) and (23) imply that the inverse of the intertemporal elasticity of substitution (θ) must then equal 1.28, which is well within the empirical estimates. Following Bils and Klenow (1998), we use Psacharopoulos' (1994) cross-country sample on average educational attainment and Mincerian coefficients to estimate η

[10] The parameters of the approximated decision rules are chosen to (approximately) satisfy the Euler equations over a number of points in the state space, using a nonlinear equation solver. A Chebyshev polynomial basis is used to construct the policy functions, and the zeros of the basis form the points at which the system is solved; that is, we use the method of orthogonal collocation to choose these points. Finally, tensor products of the states variables are employed in the polynomial representations. This method has proven to be highly efficient in similar contexts. For example, for the one-sector growth model, Judd (1992) finds that the approximated values of the control variables disagree with the values delivered by the true policy functions by no more than one part in 10,000.

[11] Domowitz, Hubbard and Petersen (1988) estimate a producer durable mark-up ratio using electronic and electric equipment data. Furthermore, they adjust it to separate out fixed costs, which are completely absent in our model. The parameter ξ can be recovered given that the mark-up charged by the monopoly producer holding a patent equals $\frac{1}{\alpha\gamma}$, and $\xi = \frac{1}{\gamma} - \alpha$.

Figure 4: Adjustment paths for Japan and Korea



and β. Given $f(S) = \eta S^{\beta}$, we can construct the regression

$$\ln(Mincer_i) = a + b \ln S_i + \varepsilon_i, \tag{37}$$

where $Mincer_i = f'(S_i)$ is the estimated Mincerian coefficient for country i; a and b equal $ln(\eta\beta)$ and $(\beta - 1)$, respectively; and ε_i is a disturbance. We obtain $\eta = 0.69$ and $\beta = 0.43$.

The calibration of the R&D technology parameters is more problematic. We take a value of 0.5 for λ.[12] It follows from equation (20), that we recover the value of $\phi = 0.93$. We then choose ψ so as to reproduce the output per worker evolution from 1960 to 1990 in Japan and between 1965 and 1990 in Korea. The former development experience gives a value for ψ of 0.265, whereas the latter implies that ψ equals 0.372. The initial values of the stock variables and the output data used to calibrate ψ, as well as the accuracy measures are provided in Table 5.[13]

4.2 Adjustment paths of Japan and Korea

We choose to calibrate ψ to both the Korean and the Japanese output numbers because they represent two important "miraculous" experiences. Figure 4 presents data for Korea and Japan

[12] Since the literature does not provide reliable estimates of λ, we carry out a sensitivity analysis with λ taking the values 0.25, 0.5, and 0.75. The results we obtain are almost identical, we therefore choose to concentrate on the intermediate case.

[13] Given the values assigned to the parameters, after linearizing the system of equations that determine the dynamics around the steady state, the transition is characterized by a three-dimensional stable saddle-path. The stable adjustment path is then unique, and growth rates and convergence speeds can vary across time and variables.

Table 5: Variable values used to calibrate ψ, and accuracy measures

		Initial Relative Levels			In 1990	Average Error*(%)			Max. Error*(%)		
Country	ψ	K per worker	S years	Y per worker	Y per worker	C	u_Y	u_A	C	u_Y	u_A
Japan	0.265	14.2%	10.9	20.5%	61.5%	0.01	0.02	0.01	0.04	0.08	0.05
Korea	0.372	12.0%	3.6	10.9%	43.6%	0.08	0.22	0.09	0.35	1.24	0.55
Non-oil	0.265	5.7%	3.1	10.9%	—	0.18	0.46	0.13	0.87	2.34	0.55
sample	0.372	5.7%	3.1	10.9%	—	0.16	0.41	0.15	0.74	2.01	0.69

* We assess the Euler equation error over 10,000 state-space points using the approximated rules. For each variable, the measure gives the current value decision error that agents using the approximated rules make, assuming that the (true) optimal decisions were made in the previous period.

on levels and growth rates of relative GDP per worker (RGDPW).[14] In 1960, Japan's output per worker was at 20.5 percent. In 1990, it had reached 61.5 percent. GDP per worker in Korea started its fast growing path in 1965. Between 1965 and 1990, it went up from 10.9 to 43.6 percent. During these periods, Japan and Korea exhibited, on average, a 5.2 and a 6.9 percent annual growth rate, respectively. Although showing different development experiences, both Japan and Korea deliver very close values of ψ.

The adjustment path generated by the model replicates well the relative output level paths. Convergence occurs following a quite linear motion. The model dynamics can even follow well the evolution of growth rates. For example, it predicts that Korean per capita output growth rates do not pick at the beginning of the convergence path but later on. Unlike the neoclassical growth model that needs to use a Stone-Geary utility function (see King and Rebelo (1993)), the R&D-growth model achieves this by employing standard technologies and parameter values.[15]

4.3 Can transition dynamics explain the cross-country data?

In this Section, we study how well the adjustment path induced by the model describes the international data, compared to steady-state predictions. Our first experiment assesses how well the transition dynamics fit the output per worker data. To do this, we need to estimate the policy rules that take state variables from given initial values to the steady state. The further we move away from the balanced-growth path, the lower the accuracy degree of the numerical approximation. In

[14]All along the paper, relative measures are taken with respect to U.S. levels.
[15]Lau and Wan (1994) also reproduce the growth patterns shown by Asian NIEs in a model of human capital and technological catch-up.

Table 6: Measure of fit in transition dynamics experiments

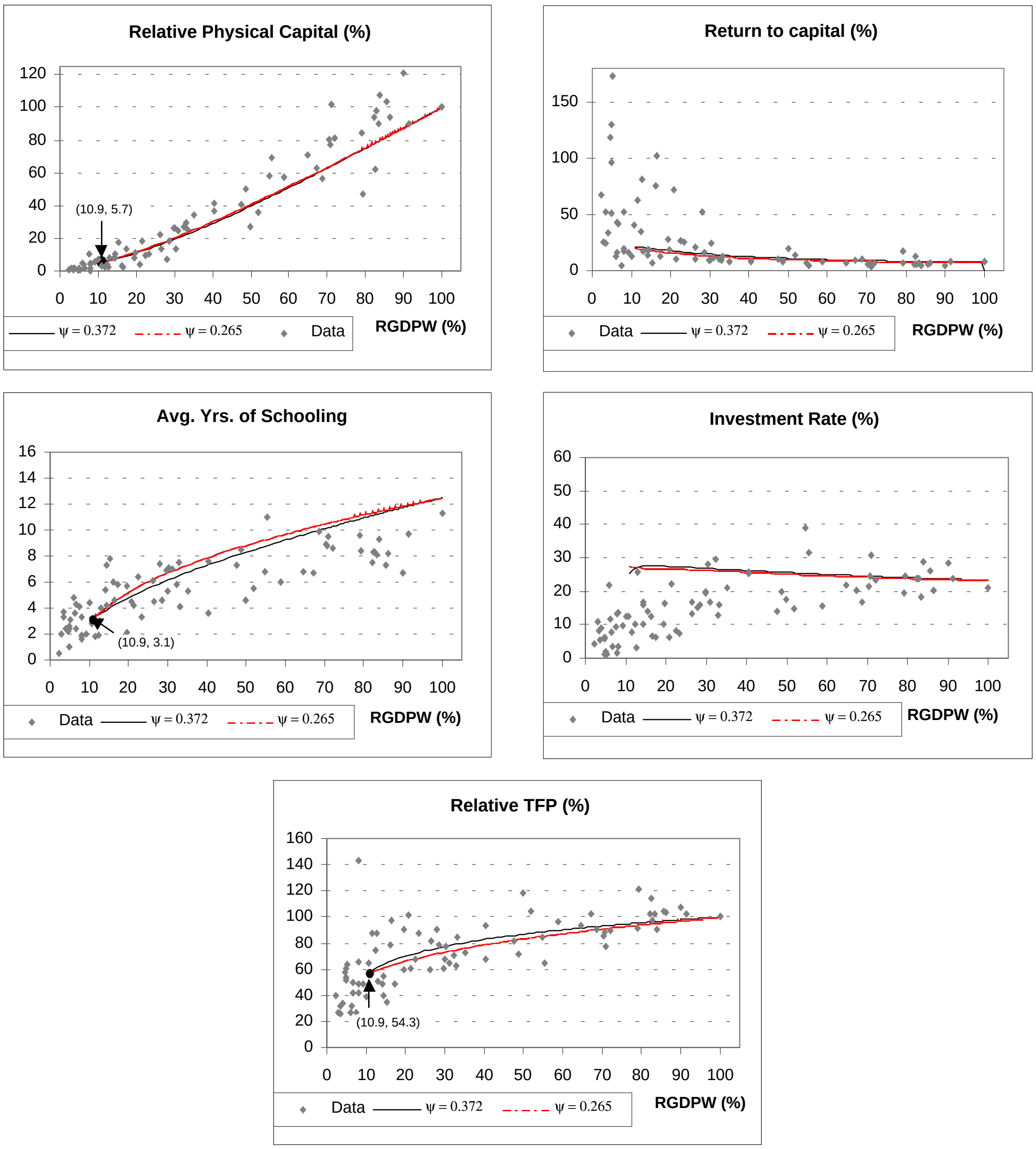
		First experiment			
Variables	Country groups	Steady state		Dynamics	
		Restric. model	Unrest. model	Value of ψ 0.265	0.372
$log - GDPW$	Whole sample	0.689	0.712	0.864	0.876
	21-OECD	0.458	0.651	0.540	0.614
	Non-OECD	0.467	0.534	0.771	0.766
		Second experiment			
u_H	Whole sample	−0.956		−1.461	−1.440
	21-OECD	−2.138		−9.290	−9.208
	Non-OECD	−2.840		−1.589	−1.563
i	Whole sample	−0.411		−2.562	−2.558
	21-OECD	+0.012		−6.830	−7.391
	Non-OECD	−0.854		−2.506	−2.375

addition, we want to start the adjustment path inside the cloud of cross-country observations. As shown in Table 5, we choose an initial value for the relative physical capital stock per worker of 5.7 percent, an initial value for the average educational attainment of 3.1 years, and an initial value for the technology stock of 54.3 percent (relative TFP) so as to generate a relative GDP per worker level of 10.9 percent. Table 5 also reports the error committed in the estimation.

Figure 5 depicts off-steady-state predictions for physical capital, average years of schooling, TFP, interest rates and investment. With fixed initial and final values of the state variables, the question is how well the transitional path follows the data cloud in between. The simulated dynamics seem to fit well across the observations. A larger degree of "backwardness advantage" (i.e., a bigger ψ) induces faster technology catch-up, and slower human capital accumulation, making the adjustment paths better fit the data. The simulated physical and human capital levels tend to diverge with respect to the rich countries' data points. This is the result of calibrating the steady state to U.S. numbers. The two variables' divergent processes, however, offset each other. As a result, the technology level series captures well the observations. Looking at Figure 5, we also see that the predicted interest and investment rates are plausible. Lower investment ratios and larger returns to capital at low levels of development would, nevertheless, better capture the data.

The simulated numbers for output and physical and human capital stocks per worker implicitly

Figure 5: Adjustment paths for the non-oil sample



define a function (Z). Under the model specification, we have that

$$\left(\frac{Y}{L_A + L_Y}\right) = Z\left[e^{f(S)(1-\alpha)}\left(\frac{K}{L_A + L_Y}\right)^{\alpha}\right]. \tag{38}$$

Feeding this function with the numbers provided by the cross-country observations, we obtain a predicted value for each nation's GDP per worker. Table 6 reports a *pseudo*-R^2 for the adjustment path predictions.[16] Compared to the (non-corrected) R^2 from the empirical specification under steady-state conditions (also reported in Table 6), the model dynamics explain a larger fraction of the output variance in all samples with exception of the OECD sample in the unrestricted model.[17] Looking at the measures of fit in the $\psi = 0.372$ case, which are higher, we see that for the whole sample the R^2 increases from 0.689 in the restricted model (0.712 in unrestricted model) to 0.876, and from 0.458 in the restricted model to 0.614 for the OECD set (it declines from 0.651 in the unrestricted model). Finally, in the case of the non-OECD sample the R^2 increases from 0.467 in the restricted and 0.534 in the unrestricted models to 0.766.

Our second experiment aims at measuring the quality of fit regarding the decision variables' predictions. The approximation accuracy considerations discussed above imply that now the set of countries must be formed by nations with relative physical capital stocks above 5.7 percent, average educational attainment more than 3.1 years, and relative GDP per worker levels over 10.9 percent. The modified non-oil sample ends up with 50 countries.[18] We focus on two decision variables: the fraction of the population enrolled in school and the physical capital investment rate. We cannot use the R&D labor measure because it does not equal the fraction of the population engaged in R&D.

For country j, steady-state predictions for enrollment rates come directly from equation (23),

$$u_{Hss,j} = S_{ss,j}\, n_j. \tag{39}$$

[16]In particular, to assess the fit, we employ the following statistic, which is equivalent to the OLS R^2:

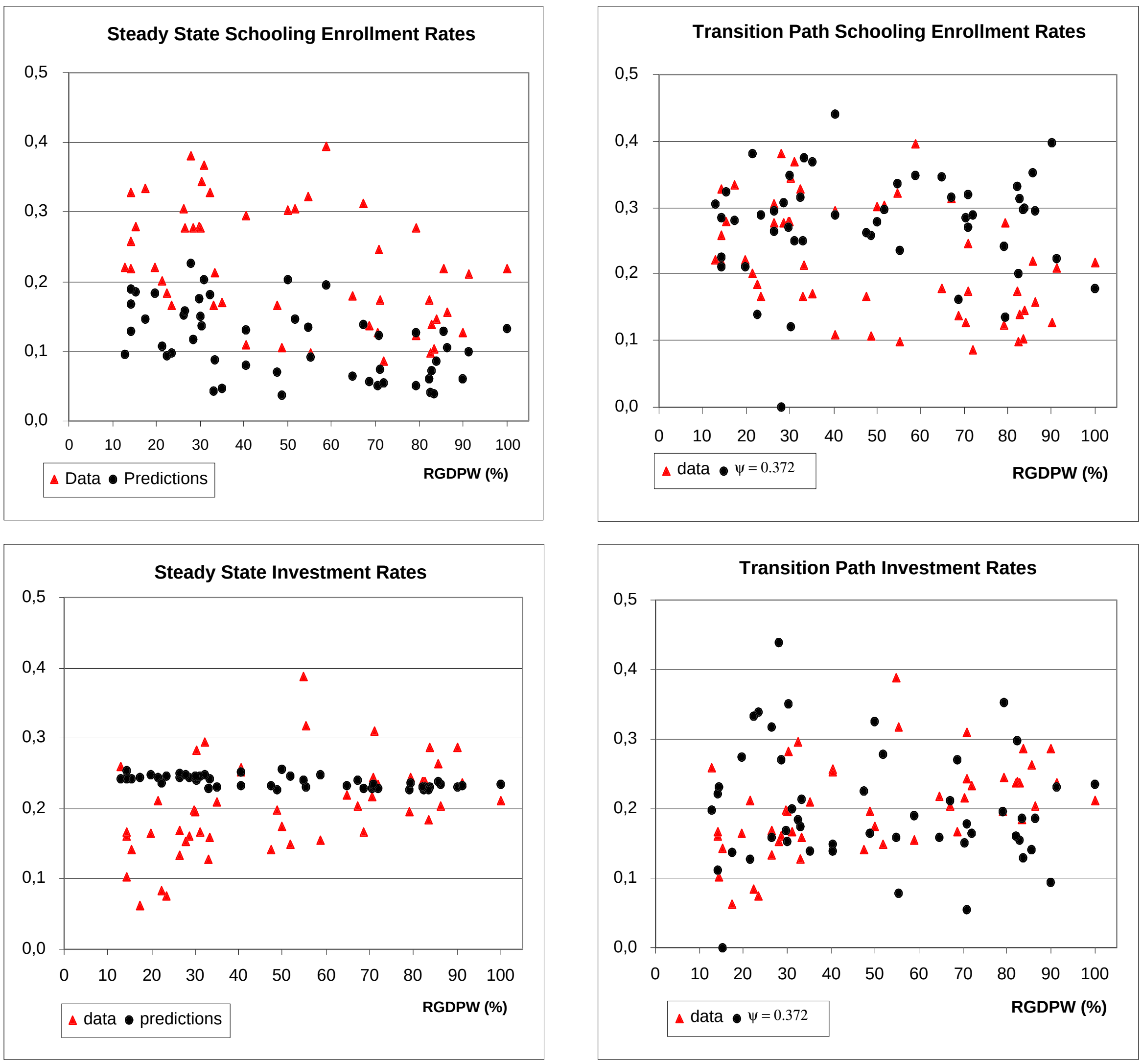
$$1 - \frac{\sum_{j=1}^{N}\left(\hat{x}_j - x_j\right)^2}{\sum_{j=1}^{N}\left(x_j - \frac{1}{N}\sum_{p=1}^{N} x_p\right)^2},$$

where $\hat{x}_j$ and x_j are the predicted and actual values of variable x for country j, respectively; and N is the number of countries included in the sample.

[17]Given the constraint imposed by the stock variables' initial values used to simulate the dynamics, we had to eliminate Madagascar, Senegal and Rwanda from the 56-country R&D sample because they show values of $e^{f(S)(1-\alpha)}\left(\frac{K}{L_A+L_Y}\right)^{\alpha}$ that are too low. For the steady-state level regressions, we report the R^2 associated with the 56-country group; eliminating the above three nations from the data set generated smaller R^2's.

[18]An asterisk identifies these 50 nations in the data table contained in the Appendix.

Figure 6: Predicted values of decision variables



From expressions (29) and (30), we obtain the balanced-growth path of physical capital investment decision,

$$i_{ss,j} = \frac{\alpha \left[G_{yss}(1+n_j) - 1 + \delta\right]}{G_{yss}^{\theta} \left(\frac{1+n_j}{\rho}\right) - 1 + \delta} \,. \tag{40}$$

The estimated policy functions provide the off-steady state values.

Figure 6 shows that steady-state predictions turn out to be very concentrated around their mean, and do not adapt to the cloud of data points, especially for investment rates. The model's transitional dynamics values, on the other hand, opperate in the opposite direction; they display a high variance, bigger than the one shown in the data. Compared to the transition dynamics, steady-state conditions show larger R^2 values, particularly in the investment rate case, and for the OECD group. Transitional dynamics better capture the schooling enrollment data for non-OECD countries. Overall, both types of predictions do not seem to comply well with the data. The negative signs in the bottom half of Table 6 say that just the sample mean is a better predictor in most cases.

5 Conclusion

This paper compared the steady-state and transitional dynamics predictions of a growth model that contained three main engines: technological progress, physical capital accumulation, and human capital formation. Our main finding is that the dynamics of the model fit the cross-country output per capita data better than steady-state regressions. Furthermore, the model achieved this using the same parameterization that reproduced the Japanese and Korean rapidly growing experiences.

Further, we found that the R&D-based growth model explains the international data better than the neoclassical growth framework. In particular, our results suggest that differences in both ideas and capital inputs are important in understanding income disparities across countries. The former are the main explanatory factor for output per worker variations across OECD nations, whereas the latter are the key factor among non-OECD countries. The normative implications of frameworks based on imperfect competition and ideas should then be taken seriously.

Clearly, our findings do not support conditional convergence. But they do not go against it either, because the convergence equation encompasses both transitional dynamics and balanced growth path conditions. Our results suggest that interpreting the lack of conditional convergence as implying that countries are close to their steady state, and using this argument to justify level regressions based on steady-state conditions (of the MRW type) is unfounded. The traditional view of a world in which nations move along their distinct balanced-growth paths is as likely as the one in which countries move along adjustment paths toward a common (very long-run) steady state. Thus the potential payoff of finding ways to integrate both types of conditions can be high, especially in level regression analysis, and future research should try to achieve this goal.

Data Appendix

Data sets and computer programs

The data and programs used in this paper are available by the authors upon request.

- *Income (GDP) and its components* [Source: PWT 5.6]

Cross-country GDP per worker and real investment shares are taken from the Penn World Tables, Version 5.6 as described by Summer and Heston (1991). This data set is available on-line at: `http://www.nber.org/pwt56.html.`

- *Labor force* [Source: PWT 5.6]

The cross-country data set on the labor force is also taken from the Penn World Table, Version 5.6. The growth rate of the labor force provides the annual n's for each country.

- *Physical capital stocks* [Source: STARS, PWT 5.6, and perpetual inventory approach]

Physical capital for S. Korea directly comes from PWT 5.6. For Japan, we take the 1960 to 1970 figures from STARS, and the 1971 to 1990 numbers from PWT 5.6. The reason is that until 1965 and after 1987 physical capital stocks are not available at PWT 5.6 and STARS, respectively. In addition, after 1970 both data sources provide very close values.

For the Non-oil cross-country sample, we follow the usual perpetual inventory approach. The capital stock is calculated by summing investment from its earlier available year (1960 or before) to 1986 with the depreciation rate set at 6 percent. The initial capital stock is determined by the initial investment rate, divided by the depreciation rate plus the growth rate of investment during the subsequent ten years.

- *Education* [Source: STARS (World Bank)]

Annual data on educational attainment are the sum of the average number of years of primary, secondary and tertiary education in labor force. These series were constructed from enrollment data using the perpetual inventory method, and they were adjusted for mortality, drop-out rates and grade repetition. For a detailed discussion on the sources and methodology used to build this data set see Nehru, Swanson, and Dubey (1995).

From the average educational attainment numbers, and the labor force growth rates, we compute annual schooling enrollment rates using equation (5).

- *R&D personnel* [Source: UNESCO]

The number of scientists and engineers (S&E), technicians, and auxiliary workers engaged in R&D is taken from the United Nations Educational, Scientific and Cultural Organization (UNESCO) Statistical Yearbook (various issues). These stock data generally come from censuses, and are not available in an annual basis. For the period from 1980 to 1992, the number of observations per country widely varies, from *one* to *six*.

For the U.K., since its annual number of S&E engaged in R&D was available only for the productive sector from 1980 to 1992, we weighted the data employing the shares of the productive and nonproductive sectors in 1993 to estimate the total number.

Countries in the comprehensive sample

Our comprehensive sample includes the 80 countries from the Mankiw, Romer and Weil (1992) non-oil sample for which annual data on income, raw labor, human capital, and investment rates were available for every year of the sample period, 1982-86. The table below provides a list of these countries along with the 1982-86 average value of relevant variables (1980-92 averages for the fraction of S&E) for each country.

An asterisk (*) denotes the nations included in the sample used to carry out the second experiment in Subsection 4.3.

Mean values of relevant variables for 80 countries

Country	GDP per worker (bill. US$)	Capital per w. (bill. US$)	Education Attain. (years)	Education Enroll. (%)	Investment over GDP (%)	Labor Force (% growth)	R&D S&E in population (%)
Algeria*	13229.2	30634.30	3.62	29.58	25.70	3.60	—
Argentina*	15516.0	33897.89	7.29	16.64	14.08	0.95	0.0348
Australia*	28000.6	87084.37	7.32	21.94	26.28	1.77	0.2090
Austria*	23542.6	68288.87	8.61	8.52	23.38	0.64	0.1016
Bangladesh	4113.0	1699.07	2.98	12.73	3.26	2.41	—-
Belgium*	27275.4	75764.03	8.14	10.27	18.48	0.47	0.1697
Bolivia*	5698.0	11236.78	5.78	33.34	6.18	2.54	0.0229
Brazil*	10862.4	21089.68	4.06	21.23	15.98	2.16	0.0296
Cameroon	3534.0	2722.23	2.78	23.69	12.54	3.92	—
Canada*	29854.6	75608.52	9.67	21.00	23.64	1.02	0.1847
Chile*	9713.8	22198.61	6.88	27.96	19.82	2.55	0.0358
China	1953.0	3764.86	4.78	26.05	21.88	2.50	0.1149
Colombia*	9326.2	15394.39	4.57	27.76	16.08	2.58	0.0039
Costa Rica*	3165.6	5681.82	7.43	38.11	15.32	3.06	0.0539
Cyprus*	13208.2	34597.46	7.57	10.95	25.20	1.05	0.0074
Denmark*	23020.0	67621.10	8.91	12.61	21.62	0.58	0.1854
Ecuador*	9790.2	22242.08	5.35	27.82	19.64	2.82	0.0164
Egypt	6825.4	3139.10	4.51	21.70	6.20	2.76	0.0451
El Salvador	1784.6	1807.23	4.61	19.05	6.62	1.38	0.0087
Ethiopia	728.6	356.18	0.45	5.85	4.34	4.27	—
Finland*	23214.6	85207.07	9.48	17.40	30.92	0.78	0.2149
France*	27058.8	82464.91	8.27	13.93	23.76	0.88	0.1893
Germany*	12259.6	52361.96	8.27	9.79	23.90	0.51	0.2736
Ghana	2166.6	1644.22	4.30	33.64	3.58	5.66	—
Greece*	15924.0	42051.60	8.51	10.61	19.70	0.45	0.0151
Guatemala*	7652.4	8596.42	3.33	16.55	7.48	2.93	0.0099
Haiti	2123.6	1565.45	2.40	10.33	7.68	1.34	—
Honduras*	4688.4	6854.14	4.19	25.88	10.18	3.99	—
Iceland*	23137.2	64949.37	8.83	24.65	24.40	1.39	0.2596
India	2626.8	3602.70	3.27	16.63	13.78	2.27	0.0132
Indonesia*	4217.0	6533.32	4.05	22.10	25.88	2.37	0.0153
Ireland	18866.0	53881.48	12.94	-2.89	25.04	0.78	—
Israel*	21956.0	52736.68	6.69	31.30	20.34	2.08	0.4833
Italy*	26873.4	78764.18	7.52	17.33	23.78	0.81	0.1150
Ivory Coast	1591.4	2005.87	1.78	16.06	7.66	2.77	—
Jamaica*	5018.4	14472.95	7.76	27.86	14.22	2.38	0.0010
Japan*	18097.0	58227.50	10.96	9.86	31.72	0.84	0.4795
Jordan*	16311.6	22616.87	4.64	30.19	17.40	4.40	0.0147
Kenya	2065.8	3404.54	3.63	37.71	11.68	4.96	—
Korea. Rep*	3990.2	11641.26	7.09	34.34	28.24	1.93	0.1208

Mean values of all variables for all 80 countries, cont.

Country	GDP per worker (bill. US$)	Capital per w. (bill. US$)	Education Attain. (years)	Education Enroll. (%)	Investment over GDP (%)	Labor Force (% growth)	R&D S&E in population (%)
Madagascar	1706.8	344.04	3.15	17.96	1.14	2.06	0.0019
Malawi	1129.2	1332.74	3.32	11.62	8.16	2.69	—
Malaysia*	10581.6	22547.62	5.77	32.89	29.54	3.16	0.0207
Mali	1609.8	1007.26	0.96	11.81	5.84	6.16	—
Mauritius*	7338.8	8191.28	6.37	18.37	8.36	1.49	0.0239
Mexico*	16929.0	29987.27	5.46	30.41	14.92	2.68	0.0227
Morocco	6379.8	6724.14	2.14	15.75	9.98	3.21	—
Mozambique	1541.0	443.78	2.20	15.22	1.36	1.04	—
Myanmar	1276.8	1145.10	2.36	12.66	8.94	2.15	—
Netherlands*	28218.4	78868.48	8.25	15.71	20.40	1.29	0.2346
New Zealand*	39480.7	39480.79	8.38	27.70	24.44	1.52	0.1553
Nigeria	3036.2	4988.88	2.00	23.53	9.88	4.54	0.0018
Norway*	27407.2	89938.15	9.29	14.59	28.68	0.92	0.2542
Pakistan	4075.2	3622.92	1.94	11.82	10.16	3.31	0.0061
Panama*	10140.8	21008.28	7.01	36.80	16.76	2.90	—
Paraguay*	6451.4	9543.62	5.70	22.12	16.40	3.23	—
Peru*	8605.0	18792.87	6.12	30.49	16.90	2.51	0.0402
Philippines*	4678.4	8643.77	7.33	32.73	16.02	2.59	0.0125
Portugal*	11464.4	28693.64	5.34	16.92	21.02	0.87	0.0426
Rwanda	1567.2	561.09	2.64	10.55	6.12	2.37	0.0011
Senegal	2638.8	1640.40	1.75	14.04	3.56	2.85	0.0342
Sierra Leone	991.6	174.71	1.92	12.57	1.38	1.67	—
Singapore*	17883.6	48914.37	6.77	32.17	38.80	1.99	0.0937
Spain*	21162.8	59324.44	6.79	17.93	21.84	0.95	0.0774
Sri Lanka	1943.2	2363.75	6.01	16.71	12.40	1.39	0.0157
Sudan	2605.6	3923.26	1.57	14.09	13.40	2.69	—
Sweden*	25875.4	70883.61	9.63	12.34	19.66	0.53	0.2631
Switzerland*	29446.0	101275.38	6.73	12.72	28.60	0.90	0.2372
Tanzania	967.4	1097.57	2.02	19.08	10.80	2.18	—
Thailand*	4657.4	6973.21	5.45	21.90	16.74	2.37	0.0171
Tunisia*	8629.6	11304.46	4.48	27.67	13.36	3.55	0.0387
Turkey*	7009.6	15438.82	4.22	20.14	22.14	2.55	0.0211
Uganda	1637.6	431.07	2.39	9.17	1.82	2.17	—
U.K.*	22472.8	47706.21	9.94	13.64	16.60	0.56	0.2318
U.S.*	32684.6	83918.58	11.35	21.78	21.14	1.17	0.3432
Uruguay*	10773.0	24664.08	7.53	16.61	12.84	0.58	0.0688
Venezuela*	19210.6	47992.71	6.02	39.49	15.48	3.24	0.0246
Zaire	1171.6	721.89	3.67	21.15	5.60	2.58	—
Zambia	2493.6	8950.54	4.06	30.49	9.52	3.53	—
Zimbabwe	3271.0	6270.08	4.36	27.81	12.34	4.97	—

References

Aghion, P. and Howitt, P., "A Model of Growth Through Creative Destruction," *Econometrica*, 60:323-51, 1992.

Barro, R. and Lee, J., "International comparisons of educational attainment," *Journal of Monetary Economics*, 32:363-394, 1993.

Barro, R. and Sala-i-Martin, M., *Economic Growth*, McGraw Hill, 1995.

Bernard, A. and Jones, C., "Comparing Apples to Oranges: Productivity, Convergence and Measurement Across Industries and Countries," *American Economic Review*, 86:1216-1238, 1996.

Bils, M. and Klenow, P., "Does Schooling Cause Growth or the Other Way Around?" *working paper*, University of Rochester, 1998.

Caballe, J. and Santos, M., "On endogenous growth with physical and human capital," *Journal of Political Economy*, 101:1042-1067, 1993.

Caselli, F., Esquivel G. and Lefort F., "Reopening the Convergence Debate: A New Look at Cross Country Growth Empirics," *Journal of Economic Growth* 1:363–389, 1996.

Chari, V.V., Kehoe P. and McGrattan E., "The Poverty of Nations: A Quantitative Exploration," *NBER working paper #5414*, 1996.

Christiano, L., "Understanding Japan's Saving Rate: The Reconstruction Hypothesis," *Federal Reserve of Minneapolis Quarterly Review*, 2:10-29, 1989.

Dinopoulos, E. and Thompson P., "Endogenous Growth in a Cross-Section of Countries," *Journal of International Economics*, forthcoming.

Domowitz, I., Hubbard, R. and Petersen, B., "Market Structure and Cyclical Fluctuations in U.S. Manufacturing," *Review of Economics and Statistics*, 70:55-66, 1988.

Easterly, W., Kremer, M., Pritchett, L. and Summers, L., "Good Policy or Good Luck? Country Growth Performance and Temporary Shocks," *Journal of Monetary Economics*, 32:459-483, 1993.

Eicher, T., "Interaction Between Endogenous Human Capital and Technological Change," *Review of Economic Studies*, 63:127-144, 1996.

Eicher, T. and Turnovsky S., "Convergence Speeds and Transitional Dynamics In Non-Scale Growth Models," *working paper*, University of Washington, 1997.

Findlay, R., "Relative Backwardness, Direct Foreign Investment, and the Transfer of Technology: A simple dynamic Model," *Quarterly Journal of Economics*, 92:1-16, 1978.

Gerschenkron, A., " Economic Backwardness in Historical Perspective," Cambridge, Harvard University Press, 1962.

Grossman, M. and Helpman, E., "Quality Ladders in the Theory of Growth," *Review of Economic Studies*, 58:43-61, 1991.

Hall, R. and Jones, C., "Why Do Some Countries Produce So Much More Output Per Worker Than Others?," *Quarterly Journal of Economics*, 114:83-116, 1999.

Islam, N., "Growth Empirics: A Panel Data Approach," *Quarterly Journal of Economics* 110:1127–1170, 1995.

Jones, C., "R&D-Based Models of Economic Growth," *Journal of Political Economy*, 103:759-784, 1995.

Jones, C., "Human Capital, Ideas, and Economic Growth," Stanford University, *mimeo*, 1996.

Jones, C., "Convergence Revisited," *Journal of Economic Growth*, 2:131-153, 1997.

Jones, C., "Sources of U.S. Economic Growth in a World of Ideas," *working paper*, Stanford, University, 1998.

Jones, L., and Manuelli R.,"A Convex Model of Equilibrium Growth: Theory and Policy Implications," *Journal of Political Economy*, 98:1008-1038, 1990.

Jovanovic, J. and Rob, R., "Solow vs. Solow," working paper, NYU, 1998.

Judd, K, "Projections Methods for Solving Aggregate Growth Models," *Journal of Economic Theory*, 58:410-452, 1992.

King, R. and Rebelo, S., "Transitional Dynamics and Economic Growth in the Neoclassical Model," *American Economic Review*, 83:908-931, 1993.

Klenow, P. and Rodríguez-Clare, A., "Economic Growth: A Review Essay," *Journal of Monetary Economics*, 40:597-617, 1997a.

Klenow, P. and Rodríguez-Clare, A., "The Neoclassical Revival in Growth Economics: Has It Gone Too Far?" *NBER Macroeconomics Annual*, MIT Press (Cambridge, MA):73-102, 1997b.

Krueger, A. and Lindahl, M., "Education for Growth in Sweden and the World," *working paper*, Princeton University, 1998.

Lau, M-L, and Wan, H., "On the Mechanism of Catching Up," *European Economic Review* 38:952-963, 1994.

Lucas, R., "On the Mechanics of Economic Development," *Journal of Monetary Economics* 22:3-42, 1988.

Mankiw, G., Romer, D. and Weil, D., "A Contribution to the Empirics of Economic Growth," *Quarterly Journal of Economics*, 107:407-437, 1992.

Mincer, J., *Schooling, Experience and Earnings*, Columbia University Press, 1974.

Mulligan, C. and Sala-i-Martin, X., "Transitional Dynamics in Two-Sector Models of Endogenous Growth," *Quarterly Journal of Economics*, 108:739-773, 1993.

Nelson, R. and Phelps, E., "Investment in Humans, Technological Diffusion, and Economic Growth," *American Economic Review*, 56:69-83, 1966.

Nehru, V., Swanson, E. and Dubey, A., "A new database on human capital stocks in developing and industrial countries: sources, methodology and results," *Journal of Development Economics*, 46:379-401, 1995.

Ortigueira, S. and Santos, M., "On the Speed of Convergence in Endogenous Growth Models," *American Economic Review*, 87:383-399, 1997.

Pack, H., and Saggi, K., "Inflows of Foreign Technology and Indigenous Technological Development," *Review of Development Economics*, 1:81-98, 1997.

Psacharopoulos, G., "Returns to Investment in Education: A Global Update," *World Development*, 22:1325-1343, 1994.

Papageorgiou, C. and Perez-Sebastian, F., "On the Specification of Human Capital," *working paper*, LSU, 1999.

Perez-Sebastian, F., "Transitional Dynamics in an R&D-Based Growth Model with Imitation: Comparing its Predictions to the Data," *Journal of Monetary Economics*, forthcoming.

Rebelo, S., "Long-Run Policy Analysis and Long-Run Growth," *Journal of Political Economy* 99:500-521, 1991.

Restuccia, D., "Technology Adoption and Schooling: Amplifier Income Effects of Policies Across Countries," *working paper*, University of Minnesota, 1997.

Romer, P., "Endogenous Technological Change," *Journal of Political Economy*, 98:S71-S96, 1990.

Sala-i-Martin, X. "The Classical Approach to Convergence Analysis," *Economic Journal*, 106:1019-1036, 1996.

Summer, R. and Heston, A., "The Penn World Table (Mark 5): An Expanded Set of International Comparisons: 1950-1988," *Quarterly Journal of Economics*, 106:327-368, 1991.

UNESCO, *Statistical Yearbook*, UNESCO Publishing, Paris, France, 1992, 1993 and 1994 issues.

UNESCO, *Statistical Yearbook*, UNESCO Publishing and Bernan Press, Lanhan, MD, 1995 and 1996 issues.

Topel, R., "Labor Markets and Economic Growth," in Ashenfelter, O. and Card, D., eds, *Handbook of Labor Economics*, North Holland, forthcoming.

Veblen, T., *Imperial Germany and the industrial revolution*, Macmillan, New York, NY, 1915.

Young, A. "Growth without Scale Effects," *Journal of Political Economy*, 106:41-63, 1998.