Human Capital and Convergence in a Non-Scale R&D Growth Model*

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Abstract

This paper extends Jones' (1995) non-scale growth framework to include endogenous human capital. The goal is to study the model's implications once the complementarity between technology and human capital commonly found by the empirical literature is taken into account. To do this, we propose a human capital accumulation technology that preserves the non-scale nature of the model. We show that focusing only on the asymptotic speed of convergence may not say much about the overall performance of a model to explain the convergence phenomenon. We find that both the predicted speeds of convergence and the adjustment path of the proposed model are consistent with the empirical evidence. Furthermore, the model suggests that cross-sector labor movements induced by the complementarity between human capital and technology can be a key factor in replicating and explaining growth miracles such as Japan and South Korea.

JEL Classification: O33, O41, O47.

Key words: Transitional dynamics, R&D, input complementarity

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1 Introduction

The importance of human capital in output production has been recognized at least since the seminal work of Becker (1964), and a close relationship between human capital and technology adoption has been emphasized at least since Nelson and Phelps (1966). The recently revived growth literature places human capital at the center of attention both in theoretical models as well as in empirical investigation. Unabugiously, human capital accumulation is one of the most accepted and most thoroughly studied determinants of economic growth.

Surprisingly, there have been few attempts in the theoretical literature to fully explore growth models of endogenous human capital *and* endogenous technical progress (another engine of growth receiving exceptional attention after the work of Romer (1990)). In light of surging evidence that these two engines are indeed complementary, it is our view that they ought to be incorporated and studied within a unified growth model.[1] In this paper we show that the value added from pursuing such a model greatly exceeds the added complexity to such an approach.

We construct a model within Jones' (1995) *hybrid* non-scale framework in which sustained long-run growth depends on both exogenous labor growth and endogenous technical change. We choose Jones' (1995) – admittedly only one of various candidates – because it has succeeded in reconciling important properties of the data such as increasing R&D intensity with constant output growth rates.[2] In particular, we present a model in which technical progress is enhanced through innovation and imitation, and human capital through formal schooling. Even though formal schooling is not the only source of human capital, we choose a schooling-based human capital technology because the model will ultimately be taken to the data (as Klenow and Rodriguez-Clare (1997) suggest), and by many accounts the best available data used to build human capital indicators across countries are the educational attainment data sets of Barro and Lee (1993) and Nehru, Swanson, and Dubey (1995) coupled with labor-wage information. Our choice of schooling technology follows the Mincerian approach (Mincer 1974) that has recently been revived by Bils and Klenow (2000).[3]

[1] For a review of empirical studies that support that human capital is complementary to technology *use*, and speeds up technology adoption, see Bils and Klenow (2000). For recent contributions, see Griliches (1988a), and Nelson and Pack (1999).

[2] Other growth models that eliminate scale effects include Sergerstrom (1998), Eicher and Turnovsky (1999), Young (1998), Dinopoulos and Thompson (1998), and Howitt (1999). The last three of these papers also permit sustained output growth in the absence of population growth.

[3] For recent discussions on the advantages of the Mincerian approach in growth modeling and estimation, see Bils and Klenow (2000), and Krueger and Lindahl (1998). Other papers that employ the Mincerian approach to model schooling include Jones (1997, 2001), Jovanovic and Rob (1998), and Hall and Jones (1999). For an interesting

The paper evaluates the model in three different dimensions. First, we study its performance at steady-state. Second, we measure the asymptotic speed of convergence of the model. Third, we explore the capacity of the model dynamics to reproduce fast output-convergence episodes such as Japan and South Korea.

The proposed human capital accumulation equation preserves the non-scale nature of the model. We find that the asymptotic speed of convergence is consistent with the evidence. However, as we show, this does not *per se* say much about the overall performance of the model at reproducing convergence episodes. In particular, we find that small variations in the asymptotic speed of convergence of different models can produce substantial changes in the initial periods of the adjustment path. This implies that a model that delivers a lower, more empirically-supported speed of convergence may perform much worse at matching the whole convergence path. Using standard technologies and parameterization, we show that our calibrated model can successfully replicate the growth experiences of Japan and S. Korea, including important changes in the growth-rate trend. The key factor contributing to this result is the complementarity between human capital and technology adoption, which induces an important reallocation of labor across sectors along the adjustment path. The model also shows that Lau and Wan (1994)'s finding that the complementarity between human capital and technology is sufficient to reproduce the growth patterns shown by East Asian miracle countries does not necessarily hold in a structural model.

The implications of Jones-type hybrid non-scale frameworks have been deeply explored by Eicher and Turnovsky (1999a, 1999b, 2001), and Perez-Sebastian (2000). Unlike us, they do not consider human capital. There is however 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) and Lloyd-Ellis and Roberts (2000) develop a model in which both human capital and technological innovation are endogenous, but they are only concerned with steady-state predictions. Restuccia (2001) presents a dynamic general equilibrium model with schooling and technology adoption. He focuses on how schooling and technology adoption may be amplifying the effects of productivity/policy differences on income disparity. Like us, Keller (1996) and Funke and Strulik (2000) study transitional dynamics in a model of human capital and blueprints. They do not however take the predictions of the model to the data.

The remainder of the paper is organized as follows. Section 2 presents the basic model. Section

alternative method to build a human capital index from the same type of data, see Mulligan and Sala-i-Martin (2000).

3 studies its steady-state properties. The transitional dynamics analysis is presented in Section 4. Section 5 concludes discussing the main findings of our work.

2 The Basic Model

This section presents an economic growth model with endogenous technological change and human capital. We focus our exposition on aggregate technologies. The main reason is that this paper's approach to incorporate human capital that is widely accepted in the literature, and which we consider most appropriate to take the model to the data, can not be easily derived from a decentralized setup, due to aggregation problems.[4] Another important reason is that previous papers (see above) that have analyzed the type of non-scale framework that we use have focus on the social planner's solution, and we want to compare our results to theirs.

Even though our analysis is fully based on the Central Planner's outcome of the model, we think that it is useful to understand the important improvement in model performance that human capital brings into the non-scale R&D-based growth framework.

2.1 Economic environment

The population in this economy consists of identical infinitely-lived agents, and grows exogenously at rate n. Agents are involved in three types of activities: consumption-goods production, R&D effort, and human capital attainment.[5] Each period, consumers are endowed with one unit of time that is allocated between working and studying. We abstract from labor/leisure decisions and assume that agents have preferences only over consumption.

Assume that at period t, output (Y_t) is produced using human capital (H_{Yt}) and physical capital (K_t) according to the following aggregate Cobb-Douglass technology:

$$Y_t = A_t^{\xi} H_{Yt}^{1-\alpha} K_t^{\alpha} \quad , \quad 0 < \alpha < 1 \, , \;\; \xi > 0; \tag{1}$$

where α is the share of capital; and ξ is the technology-output elasticity.

The R&D technology incorporates the only link between economies in our model. Ideas created anywhere in the world can be copied by local reserchers at a cost that diminishes with the country's

[4]See footnote 9 for a more detailed discussion. See footnote 3 for papers that also use the Mincerian approach to human capital.

[5]Schooling is assumed to be the only source of human capital attainment in this model. Allowing for other types of human capital attainment such as learning-by-doing, studied by Stokey (1988) and Lucas (1993), would be an interesting extension of the model and worthy of future research.

technological gap. The economy's technology level evolves as follows:

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

where δ_A represents the technology depretiation rate; H_{At} is the portion of human capital employed in the R&D sector at time t; A_t^* is the worldwide technology frontier at t, which grows exogenously at rate g_{A^*}; ϕ represents an externality due to the stock of existing technology; and λ captures the existence of decreasing returns to R&D effort.[6] The above R&D equation in the one proposed by Jones (1995, 2001) plus 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.[7]

The production function, equation (1), as well as the R&D equation, expression (2), reflect complementarity between technology and human capital. We consider that a higher human capital level allows workers to use production ideas more efficiently, and speeds up technology acquisition.

Agents increase their human capital through formal education, provided by a schooling sector. The 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 (2000), 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, aggregate human capital is given by

$$H_{jt} = e^{f(S_t)} L_{jt}\,, \quad j \in \{Y, A\}\,, \tag{3}$$

where L_{jt} is the total amount of labor allocated to sector j; and S_t is the average educational attainment of labor in period t. The derivative $f'(S)$ represents the return to schooling estimated

[6] A decentralized setup behind these aggregate equations is, for example, that of Romer (1990). We can think of technology as the mass of intermediate-goods varieties x_{it} used in an economy. Under this interpretation, the term $A_t^{\xi} K_t^{\alpha}$ in expression (1) is a reduced form for $[\int_0^{A_t} x_{it}^{\alpha\gamma}\, di]^{1/\gamma}$; where $\gamma > 0$ is a complementarity parameter. These two terms equal each other in the symmetric equilibrium in which $x_{it} = \bar{x}_t \ \forall i$, $K_t = A_t \bar{x}_t$ and $\xi = 1/\gamma - \alpha$. In Romer's, R&D effort is intended to learn new designs for new types of producer durables. There are incentives to carry out the research activity because when a new 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.

[7] Nelson and Phelps (1966) are the first to construct a formal model based on the catch-up term. Parente and Prescott (1994) notice that this formulation implies that development rates increase over time (with A_t^*), and provide empirical evidence that is consistent with this implication. Perez-Sebastian (2000) shows that the introduction of the catch-up term into Jones' (1995) model is crucial to increase its average speed of converge and reproduce the Japanese postwar output figures.

in a Mincerian wage regression: an additional year of schooling raises a worker's efficiency by $f'(S)$.[8,9]

Next, we are concerned with the behavior of S_t. Suppose that at each date agents allocate time to schooling only after supplying labor services to firms. Let L_t be the population size at date t. Define L_{Ht} as the total amount of time allocated to going to school in the economy. Assume that at the beginning of date 1 the average educational attainment equals *zero*. This implies that at the beginning of period 2, $S_2 = \frac{L_{H1}}{L_1}$. Next period, given that consumers live for ever, the average years of schooling will be $S_3 = \frac{L_{H1}+L_{H2}}{L_2}$, and so on. Hence, the average educational attainment can be written as

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

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

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

The evolution of S depends directly on the share of people in education $\frac{L_H}{L}$, whereas the growth of population induces a dilution effect.

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

$$\omega_i = \beta_0 + \beta_1 (SCH)_i + \beta_2 (EXP)_i + \beta_3 (EXP)_i^2 + \varepsilon_i,$$

where ω_i is the log wage for individual i, SCH is the number of years in school, EXP is the number of years of work experience, and ε is a random disturbance term. Based on this micro-Micer regression, Bils and Klenow (2000) present a more extensive formulation of expression (3) that includes schooling quality, and allows human capital accumulation also though work experience. We do not control for these other factors for the shake of simplicity.

[9] Because we want to take the predictions of the model to the data, we feel that we need S_t in the human capital technology. Notice however that to be fully consistent with the Mincerian interpretation, $H_{jt} = \sum_{i=1}^{L_{jt}} e^{f(s_{it})}$; where s_{it} is the educational attainment of worker i at date t. The mapping between this expression and equation (3) is not straightforward, and has not been addressed by the literature, except for Lloyd-Ellis and Roberts (2000) that perform only balanced-growth path analysis in a finitely-lived agent framework. The difficulty arises because different cohorts can possess different schooling levels. To make both expressions consistent, we could assume that the first generation of agents is the one that pins down the workers' educational attainment, and that posterior cohorts are forced to stay in school until they accumulate this educational level. In this way, all workers would have the same years of education – i.e., $s_{it} = S_t$ for all i – and then $\sum_{i=1}^{L_{jt}} e^{f(s_{it})} = L_{jt}\, e^{f(S_t)}$. Introducing this into the model however would force us to keep track across time of the different cohort's years of education, thus making the transitional dynamics analysis at least much more cumbersome, and probably impossible. We leave this important issue to future research.

2.2 Social planner's problem

As we mentioned above, we focus on a centrally planned economy.[10] A central planner internalizes the externalities and chooses 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, S_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,

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

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

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

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

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

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

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

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

where θ is the inverse of the intertemporal elasticity of substitution; and ρ is the discount factor. Equation (8) is the economy's feasibility 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 population constraint; the *labor force* – the number of people employed in the output and the R&D sectors – plus the number of individuals going to school must be equal to the *population*.

[10] It is well known that in models with externalities like ours, appropriate policies by the government can achieve the first best. We assume that these policies are imposed in our economy and focus on the social planner's problem.

The optimal control problem can be stated as follows:

$$V\left(A_t, K_t, S_t\right) = \max_{\{L_{Ht}, L_{At}, I_t\}} \frac{\left[\frac{A_t^{\xi}[e^{f(S_t)}(L_t - L_{Ht} - L_{At})]^{1-\alpha} K_t^{\alpha} - I_t}{L_t}\right]^{1-\theta} - 1}{1-\theta} +$$

$$+\rho V\left[A_t(1-\delta_A) + \mu A_t^{\phi}\left(e^{f(S_t)} L_{At}\right)^{\lambda}\left(\frac{A_t^*}{A_t}\right)^{\psi}; K_t(1-\delta_K) + I_t;\ S_t + \frac{1}{1+n}\left(\frac{L_{Ht}}{L_t} - nS_t\right)\right] \quad (14)$$

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 population in human capital investment, in R&D investment, and in consumption/physical capital investment respectively as follows:

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

$$\left(\frac{C_t}{L_t}\right)^{-\theta} \frac{(1-\alpha)Y_t}{L_{Yt}} = \frac{\rho}{1+n}\left(\frac{C_{t+1}}{L_{t+1}}\right)^{-\theta} \frac{\lambda\left[A_{t+1} - (1-\delta_A)A_t\right]}{L_{At}} *$$

$$* \left\{\frac{\xi Y_{t+1}}{A_{t+1}} + \left[1 - \delta_A + (\phi - \psi)\left(\frac{A_{t+2} - (1-\delta_A)A_{t+1}}{A_{t+1}}\right)\right]\left[\frac{\frac{(1-\alpha)Y_{t+1}}{L_{Y,t+1}}}{\frac{\lambda(A_{t+2} - (1-\delta_A)A_{t+1})}{L_{A,t+1}}}\right]\right\} (16)$$

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

At the optimum, the planner must be indifferent between investing one additional person 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 determines the effectiveness of labor employed in output production as well as in R&D. The RHS of equation (16) is the return to R&D investment. An additional unit of R&D labor generates $\frac{\lambda(A_{t+1} - A_t)}{L_{At}}$ new ideas for new types of producer durables. Every new design increases 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* $\frac{(1-\alpha)Y_{t+1}}{L_{Y,t+1}}\left[\frac{\lambda(A_{t+2}-(1-\delta_A)A_{t+1})}{L_{A,t+1}}\right]^{-1}$; where $\frac{(1-\alpha)Y_{t+1}}{L_{Y,t+1}}\left[\frac{\lambda(A_{t+2}-(1-\delta_A)A_{t+1})}{L_{A,t+1}}\right]^{-1}$ gives the value of one additional design that 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.

2.3 Steady-state growth

We now derive the model's balanced-growth path. Solving for the interior solution, equation (11) implies that in order for the labor allocations to grow at constant rates, L_{Ht}, L_{Yt} and L_{At} must all increase at the same rate as L_t. This means that the ratio $\frac{L_{Ht}}{L_t}$ is invariant along the balanced-growth path. Hence, equation (10) implies that, at steady-state (ss), S_{ss} is constant and equals

$$S_{ss} = \frac{u_{H,ss}}{n}, \tag{18}$$

where $u_{H,ss} = \left.\frac{L_H}{L}\right|_{ss}$. Equation (18) shows that along the balanced growth path, the economy invests in human capital just to provide new generations with the steady-state level of schooling. This is consistent with 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.

Let $G_{xt} = 1 + g_{xt}$. The aggregate production function, given by equation (7), combined with the steady-state 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

$$G_{Y,ss} = (G_{A,ss})^{\frac{\xi}{1-\alpha}} (1+n). \tag{19}$$

Since $G_{A,ss}$ is constant, it follows from equation (2) that

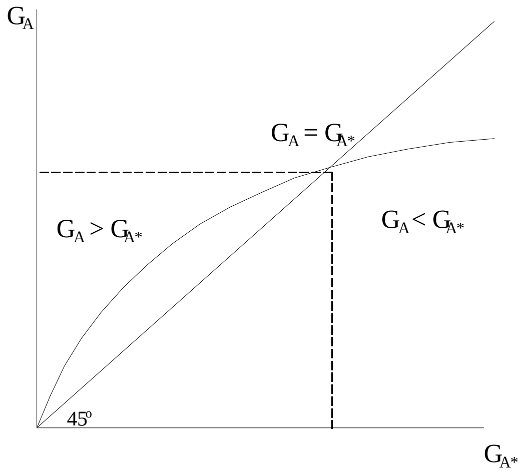
$$G_{A,ss} = \left[(1+n)^{\lambda} G^{\psi}_{A^*,ss}\right]^{\frac{1}{1+\psi-\phi}}. \tag{20}$$

Equation (20) 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 $G_{A,ss}$ equals $G_{A^*,ss}$; in particular,

$$G_{A,ss} = G_{A^*,ss} = (1+n)^{\frac{\lambda}{1-\phi}}. \tag{21}$$

The gross rate $G_{A,ss}$ cannot be larger than $G_{A^*,ss}$ otherwise A_t will eventually become bigger than A^*_t, and this has been ruled out by assumption. But $G_{A,ss}$ can be smaller than $G_{A^*,ss}$. For simplicity, we focus on the special case in which all countries grow at the same rate at steady state;

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



that is, we assume that $G_{A^*,ss}$ is given by expression (21), and therefore so is $G_{A,ss}$.[11] This in turn implies that

$$G_{Y,ss} = G_{C,ss} = G_{K,ss} = (1+n)^{\frac{\lambda\xi}{(1-\alpha)(1-\phi)}}. \tag{22}$$

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 S_{ss}.

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

Next, we derive the steady-state shares of labor in the three sectors of the economy. Euler equation (15) combined with the balanced-growth equation (22) gives

$$u_{H,ss} = 1 - \frac{1}{f'(S_{ss})}\left[\frac{G_{y,ss}^{\theta-1}(1+n)}{\rho} - 1\right], \tag{23}$$

[11] Alternatively, we could assume that a leading economy that is at steady-state is the one that moves the world technological frontier according to equation (2) which now reduces to

$$A_{t+1}^* - A_t^* = \mu A_t^{*\phi}\left(h_{At}^* L_{At}^*\right)^{\lambda};$$

where $*$ denotes the value on which variables take in the leading country. Notice that now $\frac{A_t^*}{A_t} = 1$ because imitation is not possible at the frontier. In such case $G_A^* = 1 + g_A^* = (1+n^*)^{\frac{\lambda}{1-\phi}}$ as in Jones (1995). Assuming that $n = n^*$, and substituting G_A^* into equation (20) delivers equation (21). As discuss in footnote 12, had g_A^* taken on any other value, the transitional dynamics numerical analysis would become much more tedious.

where $u_{H,ss} = \left.\frac{L_H}{L}\right|_{ss}$. As expected, the steady-state share of students is directly related to the return to education, other things constant.

Euler equation (16) combined with balanced-growth condition (22) deliver the steady-state labor share in R&D as

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

Equations (23) and (24), and the population constraint

$$u_{Y,ss} = 1 - u_{h,ss} - u_{A,ss}, \tag{25}$$

give the three steady-state equilibrium shares of labor.

3 Transitional Dynamics

This section is concerned with the transitional dynamics of the model economy. Since there is no analytical solution to our system we use numerical approximation techniques to simulate the transitional dynamics of the model, and then take their predictions to the data.

3.1 The normalized system

We start by redefining variables so that they take constant values along the balanced-growth path. The aggregate production function, equation (7), suggests that we normalize variables by the term $A_t^{\frac{\xi}{1-\alpha}} L_t$. We can 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 derive G_{At} as

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

where $T = \frac{A_t^*}{A_t}$; and $\upsilon = \mu\,(A_t^*)^{\phi-1} L_t^{\lambda}$, which is a constant.[12] From equation (16) we get

[12]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 $\frac{\upsilon_{t+1}}{\upsilon_t} = 1$. Notice that if A_t^* did not grow according to equation (21), υ could not be constant, making the simulation exercise more tedious.

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

Finally, from equation (17) we obtain

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

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

Control Variables:

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

   Subject to the population 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 normalized physical capital, $\hat{k}_t$:

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

where

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

and

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

To solve the above system of dynamic equations, we follow Judd (1992), approximating the policy functions employing high-degree polynomials in the state variables.[13]

[13]In particular, 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

Table 1: Parameter values used in the simulations

α	0.36	ξ	0.1	S_{ss}	12.5
ρ	0.96	G_y	1.016	η	0.69
δ	0.06	λ	0.5	β	0.43
n	0.0116	ϕ	0.94	θ	1.28

3.2 Calibration

Table 1 shows the parameter values used to carry out the simulations. We choose values of 0.06 for the depreciation rate of capital (δ_K) and 0 for the depretiation rate of technology (δ_A), and a value of 1.016 for the steady-state gross growth rate of income ($G_{y,ss}$), the average number in the Bils and Klenow's (forthcoming) 91-country sample. We assign values of 0.36 to the capital-share of output (α), and 0.96 to the discount factor (ρ). We set the population growth rate (n) to 0.0116 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. Regarding the value of the elasticity of output with respect to the technology, Griliches (1988b) reports estimates of ξ between 0.06 and 0.1. Following Eicher and Turnovsky (1999), we choose $\xi = 0.1$.

It is not clear what the steady-state value of the average educational attainment ought to be, 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. To estimate the human capital equations, we assume that

$$f(S) = \eta S^{\beta}, \ \ \eta > 0, \ \beta > 0. \tag{33}$$

Following Bils and Klenow (2000), we use Psacharopoulos' (1994) cross-country sample on average educational attainment and Mincerian coefficients to estimate η and β. Given equation (33), we can construct the regression equation

$$\ln (Mincer_i) = a + b \ln S_i + \varepsilon_i, \tag{34}$$

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 state 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. All programs are written in GAUSS and are available by the authors upon request.

Table 2: The Japanese and Korean experiences

Country		In 1960	In 1963	In 1990
Japan	Y per worker (%)	20.6		60.3
	K per worker (%)	16.9		104.6
	S (years)	10.2		11.0*
S. Korea	Y per worker (%)		11.0	42.2
	K per worker (%)		11.6	50.2
	S (years)		3.2	7.7*

* 1987 figures.

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 random disturbance term. We obtain estimates of $\eta = 0.69$ and $\beta = 0.43$ that are very similar to those obtained by Bils and Klenow (forthcoming).[14] Equations (18) 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.

Estimates of λ found in the literature vary from 0.2 to 0.75, so we carry out a sensitivity analysis with λ taking the values 0.25, 0.5, and 0.75. Since the results we obtain are almost identical, we choose to use the intermediate value, $\lambda = 0.5$. From equation (21), we can then recover the value of $\phi = 0.94$. We follow Parente and Prescott (1994) to calibrate te parameter ψ. In particular, we assume that countries may differ in their degrees of technology adoption barriers and, as a consequence, they may show different values of ψ. Because we focus on two nations, Japan and South Korea, the value on which the parameter ψ takes will be the one that makes transitional dynamics be able to reproduce the output per worker evolution between 1960 and 1990 in Japan, and between 1963 and 1990 in S. Korea.[15] The former development experience gives a value for ψ of 0.21, whereas the latter implies that ψ equals 0.26. The initial values of the stock variables and output data used to calibrate ψ are presented in table 2; accuracy measures are presented in table 3.

[14] Both estimates are significantly different from zero at the 1 percent level.

[15] Japan's rapid convergence toward U.S. income levels actually started right after WWII. Unfortunately, the Japanese Education Department does not possess estimates of the average educational attainment before 1960. We are grateful to Tomoya Sakagami who has attempted to obtain this data for us.

Table 3: Accuracy measures

			Average Error (%)*			Max. Error (%)*		
Country	*model***	ψ	C	u_Y	u_A	C	u_Y	u_A
Japan	Basic	0.210	0.01	0.02	0.01	0.04	0.09	0.07
Japan	Per capita	0.220	0.01	0.02	0.02	0.04	0.10	0.08
Japan	w/o H	0.135	0.00	0.00	0.01	0.01	0.00	0.03
S. Korea	Basic	0.260	0.08	0.23	0.09	0.35	1.16	0.45
S. Korea	Per capita	0.260	0.65	0.20	0.79	0.29	0.99	0.37
S. Korea	w/o H	0.103	0.01	0.00	0.02	0.03	0.00	0.08

* 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.

** "Per Capita" refers to predictions when we assume that the parameters η and β equal zero; "w/o H" refers to predictions when we suppose that per worker variables come from dividing by L, instead of by $L_Y + L_A$

3.3 Asymptotic stability and asymptotic speed of convergence

As a crucial first step, we establish the asymptotic stability of our model's long-run equilibrium. Linearizing the normalized system of equations around the steady state, we find that for any reasonable parameter values, the transition is characterized by a three-dimensional stable saddle-path. The adjustment path is then asymptotically stable and unique; furthermore, growth rates and convergence speeds can, as a consequence, vary across time and variables.

Next, we investigate the asymptotic speed of convergence – the rate by which a country's output converges to its balanced growth path once the country is sufficiently close to its long-run equilibrium. To compute the assymptotic speed of convergence (let us denote it by *asc*), we must first linearized the system of equations that governs the model dynamics around the stady state. The speed is given by the largest eigenvalue associated with the linearized system among those contained in the unit circle. The asymptotic speed of convergence of normalized varible $\hat{x}$ can be written as

$$asc(\hat{x}) = -\frac{(\hat{x}_{t+1} - \hat{x}_t) - (\hat{x}_{t+1,ss} - \hat{x}_{t,ss})}{\hat{x}_t - \hat{x}_{t,ss}} = 1 - eigen.$$

We are actually interested in the speed of convergence of output per worker. Given that $\frac{Y}{L_A+L_Y} = \hat{y}A^{\frac{\xi}{1-\alpha}}(u_A + u_Y)$, it can be shown that the speed of convergence of output per worker equals

$$asc(\hat{x}) = (1 - eigen)G_{y,ss} - g_{y,ss}$$

The one sector neoclassical growth model implies convergence speed of about 7%, which is inconsistent with most of the empirical evidence – Barro and Sala-i-Martin (1995) and Temple (1998), among others, report convergence-speed estimates for OECD nations of approximately 2%. Table 4 presents implied speeds for different values of λ and ψ.

Table 4: Asymptotic speed of convergence for different values of λ and ψ

$\lambda \backslash \psi$	0.20	0.24	0.28	0.30
0.25	1.43%	1.66%	1.93%	2.08%
0.50	1.16%	1.32%	1.46%	1.52%
0.75	1.06%	1.19%	1.31%	1.37%

Parameter values in the neighborhood of those employed in our calibration deliver speeds of convergence that vary between 1.06%−2.08%, consistent with most empirical evidence. In addition, our results are consistent with the finding of Eicher and Turnovsky (1999), that moving from one-sector to multi-sector non-scale growth models with endogenous technological change leads to severe reduction in the asymptotic speed of convergence.

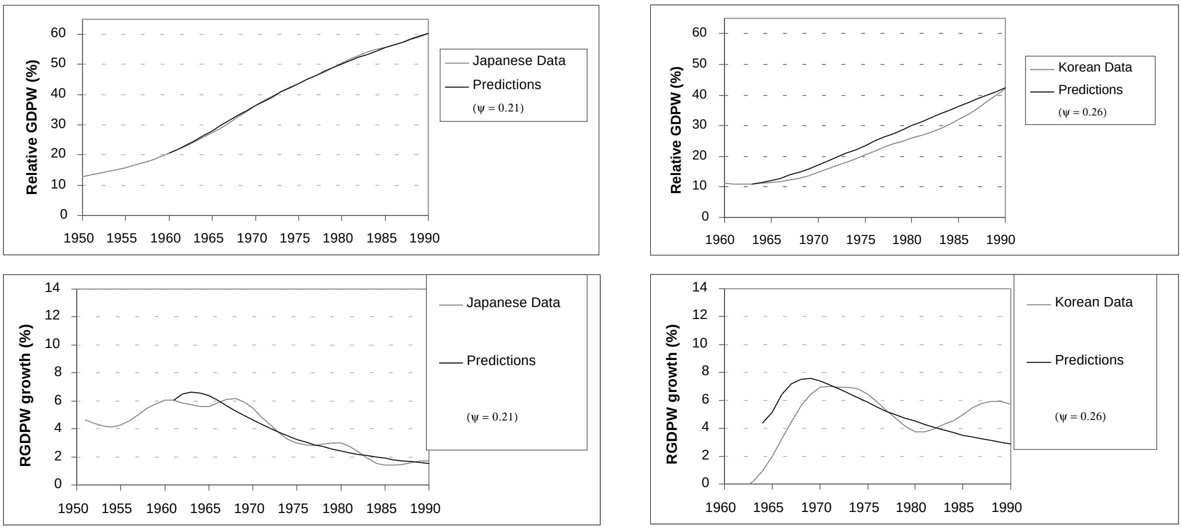
3.4 Adjustment paths of Japan and South Korea

We choose to calibrate ψ to both the S. Korean and the Japanese output paths because they represent two very different "miraculous" experiences. Table 2 presents data for S. Korea and Japan on relative levels of GDP *per worker* (RGDPW), relative physical capital *per worker*, average educational attainment, and relative TFP, which is broadly defined and includes everything not already captured by the other two stock variables (S and K).[16] Between 1960 and 1990, Japan's relative output per worker increased from 20.6 to 60.3 percent. GDP per worker in S. Korea started its fast growing path around 1963; during the period 1963-1990, its relative level increased from 11.0 to 42.2 percent. During these periods, Japan and S. Korea exhibited, on average, a 5.2 and a 6.5 percent annual growth rates, respectively.

Japan had lost a substantial portion of its physical capital during WWII, but its educational attainment in 1960 of 10.2 years compared well with those of the most developed nations – e.g., the

[16] All relative measures in the paper are with respect to U.S. levels.

Figure 2: Adjustment paths for Japan and S. Korea



U.S. educational attainment at that time was a little over 10.7.[17] What is even more interesting is that during the period 1960-1987, average years of schooling of workers increased very little, only by 0.8 years. The main engine of growth in Japan seems to have been physical capital accumulation induced in part by a very important technological catch-up process. In 1960, the Japanese physical capital stock per worker was only 16.9 percent; in 1990 reached a stunning 104.6 percent, which implies an average annual convergence rate of 6.3 percent.

The S. Korean development experience, on the other hand, is distinctly different from the Japanese experience. As shown in table 2, even though output convergence was faster in S. Korea, capital accumulated in this country at a lower rate than in Japan, growing from 11.6 to 50.2 percent during the relevant period; that is an average annual convergence rate of 5.6 percent. It is human capital accumulation that seems to have played the key role in S. Korean development process. In particular, the average educational attainment more than doubled in the period 1963-1987, increasing from 3.2 to 7.7 years.

The adjustment paths predicted by the model for the level and growth rates of relative GDP per worker are depicted in figure 2 and replicate fairly well the Japanese and the S. Korean data.

[17] Human capital levels in Japan were high before WWII. After the Meiji Restoration of 1868, one of the policy priorities of the Meiji government was to introduce a nationwide education system under which all children from 6 through 13 years of age were required to attend school (see Ozawa (1985)).

In particular, the model predicts that output per capita growth rates do not pick at the beginning of the adjustment path but later on.

3.5 Discussion of the transition results

What are the determining factors behind our results? We can write production function (7) in per worker terms as follows:

$$\left(\frac{Y_t}{L_{Yt}+L_{At}}\right) = A_t^{\xi} e^{f(S_t)(1-\alpha)} \left(\frac{L_{Yt}}{L_{Yt}+L_{At}}\right)^{1-\alpha} \left(\frac{K_t}{L_{Yt}+L_{At}}\right)^{\alpha}. \tag{35}$$

From equation (35), using a continuous time aproximation, we can decompose the output per worker growth rate (g_Y^w) as:

$$g_{Yt}^w = \xi g_{At} + (1-\alpha)\,\frac{d\,f(S_t)}{d\,t} + \alpha g_{K/L,t} + \left[(1-\alpha)\, g_{u_Y,t} - g_{1-u_H,t}\right]. \tag{36}$$

We have then splitted output growth into the effects of changes in TFP, the average educational attainment level of the population, physical capital per capita, and in a fourth factor (the one in squared brackets) that represents the net impact of labor movements across sectors.

Figures 3 and 4 present the contributions of the four different components to S. Korean and Japanese output per worker growth, in line with equation (36). We show three different sets of predictions. The first set, represented by a dashed line, is obtained by assuming that $\eta, \beta = 0$; that is, it comes from a model that neglects human capital. In this case, u_H always equals zero, and Euler equation (26) becomes then irrelevant. It should tell us whether the introduction of human capital formation is important to reproduce the main patterns shown by miracolous-country experiences. The second one, depicted by a thin black line, is the result of supposing that per worker variables come from dividing by L, instead of by $L_Y + L_A$. Notice that this means that the second summand within the squared brackets in equation (36) does not play any role; put differently, this prediction set does not consider movements in and out of the labor force. We hope that this exercise will reveal which effect of the complementarity between human capital and technology dominates, the one on TFP that occurs though the R&D equation, or the one that takes place through labor going in and out of the schooling sector. The third set, thick black line, shows predictions for the basic model described in previous sections.[18]

[18]Calibration in the two new cases considered also follows section 3.2. The values of the parameter ψ, and accuracy measures are in table 3.

Below it is true becuase otherwise ψ would not decrease. uA is larger with no H becuase with H there are two potential uses besides Y. Growth in TFP depends on ψ as well as on uA.

First, notice that if RGDPW growth rates are larger at the beginning, they must be smaller later on, and *vice versa*, because the models are calibrated to reproduce the average convergence speed of RGDPW. Having this in mind, we can focus on differences among the models that occur during the early periods of the adjustment path. The other thing that is common to the three experiments is the initial values of the state variables from which the transition dynamics start. This implies that initial incentives to invest in physical and human capital formation are very similar in the three cases, because so are, by construction, the initial capital-output ratio and average educational attainmet. As a consequence, the main forces behind the differences in RDGDPW growth rate paths seem to be located in the net contribution of labor, and in the growth rate of relative TFP charts.

Let us compare the dashed and the thin-black lines in a attempt to understand the contribution of introducing human capital into the model; but abstracting from the effect of movements into and out of the labor force. The introduction of the new sector amplifies the effect of diminishing returs, increasing the initial speed of convergence, and recucing the assymptotic speed. This is consistent with the results in section , in which we found asymptotic speeds of convergence slightly below the ones founf by Eicher and Turnovsky (2000). Except for physical capital, all variables follow the standard neoclassical declining-growth-rate result caused by diminishing returns over each one of the investment activities. There is though a difference, as we see in figure 3, the patterns depicted by the dashed line, which represents the model without human capital, are always smoother. The initial return to R&D investment when human capital is absent from the model greaterly exceeds the returns to technology acquisition when schooling is included, due to the existence of diminishing returns to imitation (this is a reason why the parameter ψ takes on a lower value). As a consequence, the final goods sector does not need to sacrify as much labor in order to reproduce Japanese and S. Korean output numbers. The initial u_Y level then does not fall as much, starting closer to its steady state value, and making the net labor contribution show initially lower and smoother agrowth rates. Physical capital also sufers a smaller initial fall and accumulates at a smoother rate for the same reason: an initially smaller movement of labor out of the consumption good sector toward other relatively more productive activities reduces final output by less, and makes consumption smoothing pull down the investment share also by less. A question that remains is why TFP does not grow faster in the Japanes case in the model without human capital if R&D is more productive. The answer must lie in the fact that investing more in R&D implies sacrifying physical capital investment and consumption, and this becomes increasingly costly. The value of u_A then increases relatively less than the absolute R&D productivity.

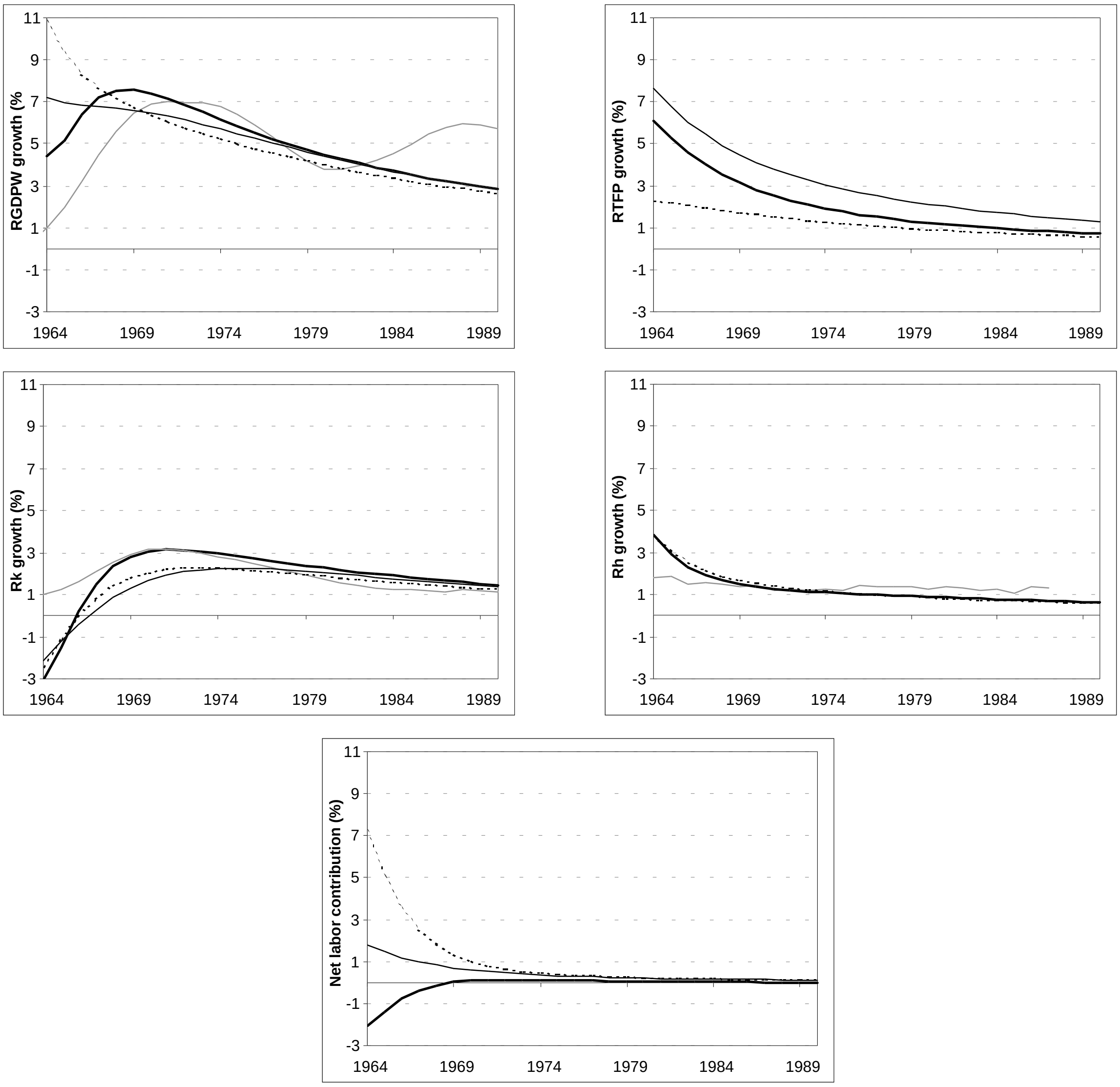
In S. Korea, The larger returns to R&D make the initial R&D labor share be bigger and, therefore, TFP grow faster thean in the basic model. For this reason, u_Y shows smaller growth rates along the adjustment path. The evolution of the output and physical capital growth rates refect mainly the u_Y behavior. With respect to the Japanese case, figure 4, the only difference is that the average educational attainment starts close to its balanced-growth value.

Looking at the dashed line it is clear that the model can not replicate the hump-shaped output growth path if we do not introduce human capital. Technology adoption fuelled by cheap imitation is the main key in Parente and Prescott (1994). The key force that generates the hump-shape is the relatively large allocation of agents in education *plus* R&D activity at the beginning of the convergence process. To see this more clearly, recall that the term in brackets in equation (36) reflects the contribution of the movement of population across sectors. More specifically, this term takes into account that output growth rises with the amount of labor devoted to final-good production, but also that additional labor force deflates output per worker. As a consequence, net labor contribution decreases with the number of students that leave school – because the amount of workers then rise – and increases as R&D effort declines – because part of the R&D labor is reallocated to the final output sector.

As shown in the bottom-right chart of figures 3 and 4, the effect of students entering the labor force is larger at the beginning, and rapidly decreasing as the economy approaches the steady state, thus generating the fast declining pattern of labor force growth. This effect combined with a decreasing R&D labor share induces the initially rising net contribution of population reallocation.

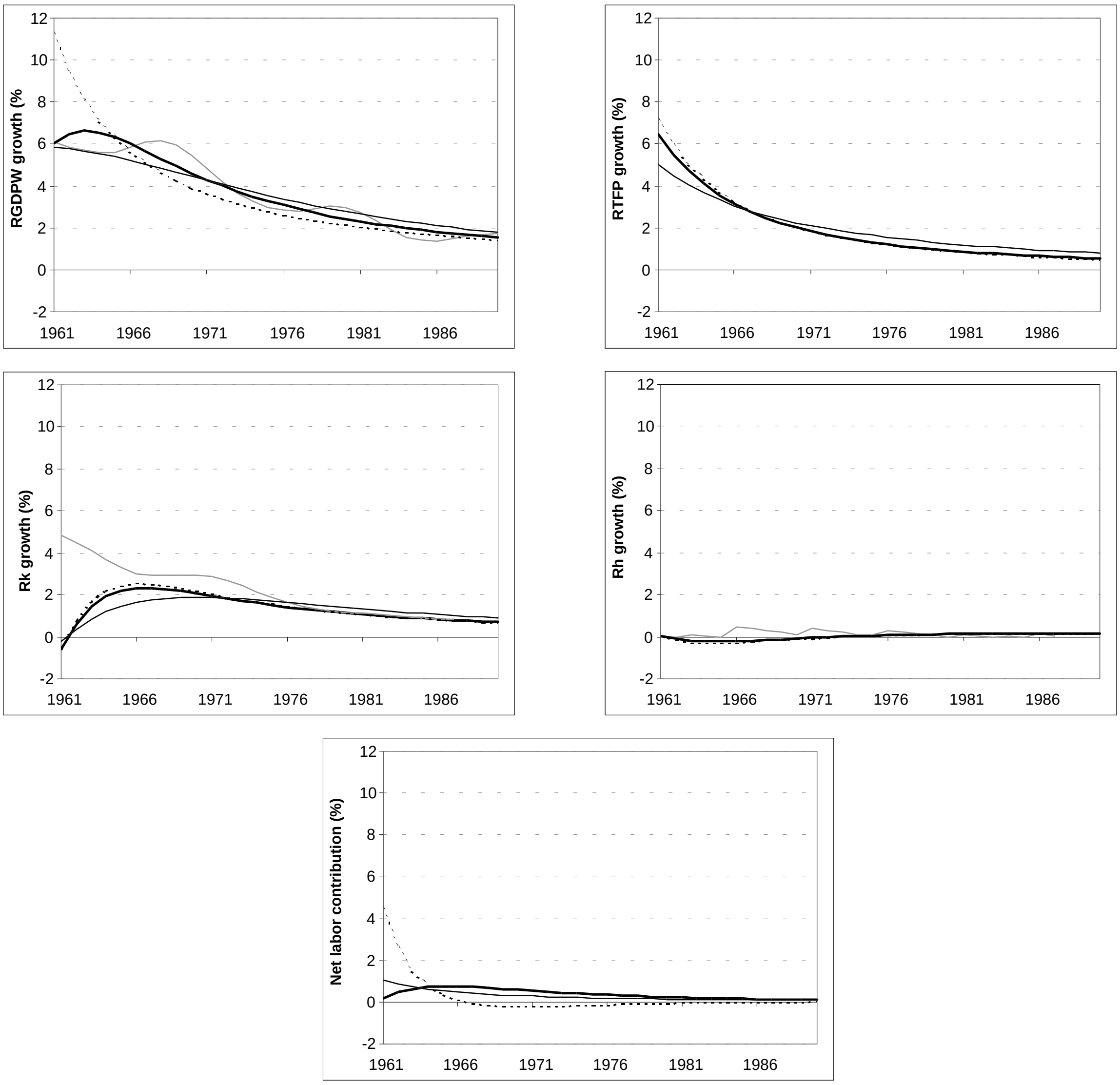
Although both Japan and S. Korea display the above pattern, the forces that cause it are different in each country. In S. Korea, schooling enrollment rates sharply increase at impact due to the low human capital level. As convergence goes on, and average educational attainment rises, a rapid decrease in enrollment rates occurs, which generates the labor force growth rate decline. Japan, on the other hand, starts with relatively high human capital levels. Economy reconstruction and technology adoption then become the priority, causing students to leave the schooling sector to joint the final-good and R&D sectors. This reallocation of population is bigger at the beginning,

Figure 3: Contribution of different components to relative output growth, S. Korea



Thick black line: Predictions in per worker terms from model with endogenous human capital formation.
Thin black line: Predictions from model without human capital.
Dashed line: Predictions dividing variables by L; model with endogenous human capital formation.
Grey line: Data.
Variables: RGDPW is relative GDP per worker; Rk is relative physical capital per capita; Rh is relative human capital per capita; Net labor contribution represents the effect of the terms in brackets in equation (36).

Figure 4: Contribution of different components to relative output growth, Japan



Thick black line: Predictions in per worker terms from model with endogenous human capital formation.
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Variables: RGDPW is relative GDP per worker; Rk is relative physical capital per capita; Rh is relative human capital per capita; Net labor contribution represents the effect of the terms in brackets in equation (36).

inducing the initial decrease in labor force growth rates. As K and A achieve a sufficiently high level, some workers return to school, generating negative labor force growth.

The predictions of the model are also consistent with the different underlying characteristics of the Japanese and S. Korean experiences. First, lower educational attainment levels in S. Korea are associated with slower physical capital accumulation. A smaller human capital stock implies a larger productivity of schooling time, thus reducing the amount of labor allocated to final output production. In turn, as the previous paragraph explains, the lower output level slows down physical capital formation. Second, output growth rates at the beginning of the convergence process increase with the average educational attainment, both because the speed at which technology is adopted rises with human capital and because physical capital accumulates faster. In per worker terms, output growth is also faster the higher the schooling level. The reason is that the number of people that leave the schooling sector is then relatively lower, reducing the discounting effect caused by the rising labor force on output per worker figures.

The main predictions of the model are, in general, consistent with the data as shown in figures 3 and 4. In the S. Korean case, physical capital growth rates start low, pick-up after seven periods, and then decline. In the Japanese case, the labor-force share growth rate is the highest during the early sixties, then becomes negative, and declines in absolute magnitude as GDP converges. In addition, both country experiences have similar education attainment growth rates as the ones predicted by the model, suffering only small changes along most of the adjustment path. The educational accumulation rate predicted by the model is, however, larger than the one shown by the data. In particular, simulated enrollment rates grow at impact above the observed rates, thus inducing too low physical capital convergence rates, and too high labor force growth rates, specially for S. Korea.

4 Conclusion

In this paper we have attempted to shed new light in the making of growth miracles. We have done that by studying the transitional dynamics of a semi-endogenous growth model with physical capital, human capital and technical change. In order to compare the model predictions to the data, we have introduced human capital following the Mincerian approach suggested in recent papers. Furthermore, we have developed a law of motion for the average educational attainment that allows for endogenous human capital formation.

We have shown that the existing R&D-based growth models (and in lesser extend the one- and two-sector endogenous growth models) are capable of delivering the average convergence speed of economic miracles, but are not able to reproduce the velocity variations observed along the output adjustment path. The argument of this paper is that our proposed model is successful in generating these velocity variations observed in the output data of growth miracles.

Our work suggests that two are the main forces necessary to replicate miracle economies: a) the complementarity between human capital and technology adoption; b) the reallocation of individuals across sectors along the adjustment path. Focusing on the well-documented Japanese and S. Korean development experiences, we have shown that labor reallocation alone is sufficient to replicate the Japanese experience, but is not sufficient to fully generate the hump-shaped output per worker growth apparent in the S. Korean case. We have argued that having different human capital technologies for final output and R&D, which increases the degree of complementarity between human capital and technology adoption effort, can be the missing part of the story. This is consistent with observation as the fraction of labor engaged in the production of new ideas is relatively small, and therefore so is its contribution to generate the observed data.

Our paper is not without limitations. In both versions, the model predicts enrollment rates that are larger than their empirical counterparts. This suggests that the model predictions could be improved if the accumulation of human capital would not necessarily imply the transfer of resources from the final-output sector. Future research could introduce leisure in the utility function, or allow for house-production. Another possibility would be to permit human capital formation though learning-by-doing or on-the-job training. In addition, we have argued that having different human capital technologies for final output and R&D labor maybe important in replicating growth experiences, yet we were constraint to use a functional form that was not based on estimation. Further research is clearly necessary in determining the appropriate weights to be assigned to the effectiveness of labor in different sectors.

The paper also has implications for other growth models. In particular, two-sector endogenous growth frameworks can also exhibit labor shifts across activities. And, as we mentioned, Mulligan and Sala-i-Martin (1993, p. 767) do generate growth rates that do not pick at the beginning of the adjustment path. To achieve it, they employ an extended measure of GDP per capita that adds a fraction of the market value of human capital labor to final output. This fraction contribution clearly depends on the amount of workers devoted to human capital formation. We then help to rationalize their result, because extending the output measure in that way raises the contribution of labor movements. In addition, two-sector growth models predict the same counterfactual (too large) share of time allocated to human capital formation along the adjustment path. The explanatory power of these models could therefore benefit from attempting some of the extensions proposed for our model in the previous paragraph.

In a general sense, we interpret our results as suggesting that a successful model of economic growth and development should include *both* technological progress and human capital accumulation as necessary engines, and the endogenous outcome of the economic system. In a more specific sense, our results suggest that labor reallocation and technology-human capital complementarity are crucial components in the making of miracles.

A Data Appendix

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

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

Cross-country real GDP per worker and real GDP per capita (chain index) are taken from the Penn World Tables (PWT), Version 5.6 as described by Summer and Heston (1991). This data set is available on-line at: http://datacentre.chass.utoronto.ca/pwt/index.html.

- *Labor force* [Source: PWT 5.6]

The cross-country data set on the labor force is calculated from the GDP per capita and GDP per worker numbers.

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

Physical capital comes from PWT 5.6. The PWT, however, only provides with physical capital data from 1965. To obtain stocks back to 1963 for S. Korea, and 1960 for Japan, we used the growth rates implied by the STARS physical capital data to deflate the 1965 PWT numbers.

- *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).

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