Dynamics in a Non-Scale R&D Growth Model with Human Capital: Explaining the Japanese and South Korean development experiences*

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Abstract

This paper constructs an R&D non-scale growth model that includes endogenous human capital. The goal is to take the model's implications to the data once the complementarity between technology and human capital, commonly found in the empirical literature, is taken into account. Our 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 development experiences such as those of Japan and South Korea. In particular it is shown that the the adjustment paths of output growth, investment rates, interest rates, and labor shares implied by the proposed model are consistent with empirical evidence.

JEL Classification: O33, O41, O47

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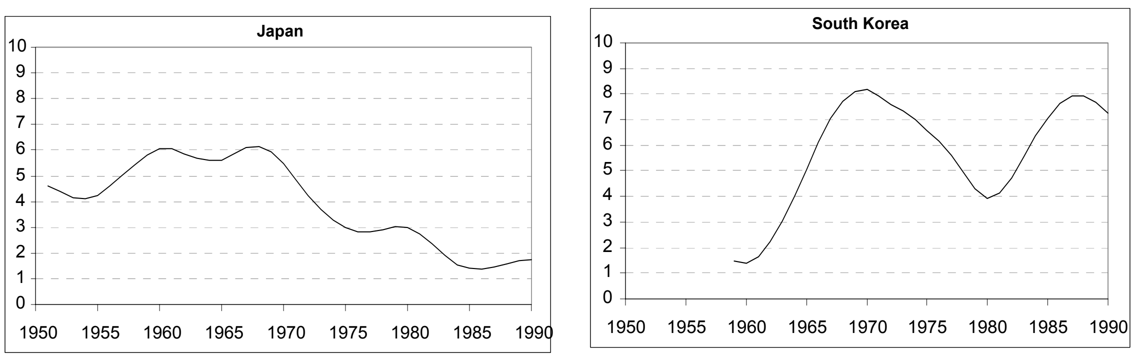
1 Introduction

One of the most intriguing phenomena in modern economic growth is "development miracles." The stylized facts concerning such fast growing economies are staggering. For example, over the period 1960-1990, Japan and South Korea averaged output growth rates over 5 percent per year. Figure 1 illustrates the growth experiences of these two miracle countries. Closer observation of Figure 1 reveals an interesting feature of miraculous experiences: the sharp increase of output per worker was characterized by growth rates that did not peak at the beginning of the convergence process but later on, thus giving way to a hump-shape growth path.

Figure 1: Output growth rates in Japan and S. Korea



What is even more interesting is that the underlying characteristics of the two East Asian miracle economies are distinctly different. Whereas Japan started its post-War convergence path with high human capital levels, S. Korea started its convergence path with very low human capital levels. In addition, although both nations began with relatively low levels of physical capital, Japan accumulated equipment, machinery, and infrastructure at a much higher rate than S. Korea. Even regarding output growth rates, miraculous experiences show important differences. In Figure 1, we see that Japanese growth rates were relatively high from the beginning of the convergence process, whereas S. Korean growth rates started low and increased rapidly.

The influential paper by Robert Lucas "Making a Miracle" (*Econometrica*, 1993) concluded that improving our understanding of the mechanics of rapid growth episodes is essential in constructing a successful theory of economic development. Since Lucas (1993), there has been surging interest in theoretical research attempting to explain economic miracles, with a number of papers being able to reproduce the average convergence speed exhibited by rapidly growing nations. However, growth models have not in general been able to predict the variable convergence speed needed to generate the observed hump-shaped adjustment path of output growth rate. Nor has the literature paid close attention to the distinct characteristics of miraculous episodes.

In this paper, we propose a model in which the complementarity between human capital and technology adoption is able to replicate and explain growth miracles. Surprisingly, there have been few attempts in the theoretical literature to explore growth models with endogenous human capital *and* technical progress, despite surging evidence that these two engines are indeed complementary.[1] We present a *hybrid* R&D-based model in which technical progress is enhanced through innovation and imitation, and human capital through formal schooling.[2] 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 following the approach suggested by Klenow and Rodriguez-Clare (1997). Our choice of schooling technology is based on the Mincerian approach (Mincer (1974)) that has recently been revived by Bils and Klenow (2000).[3]

Using standard technologies and parameterization, we show that our calibrated model is quite successful in replicating the rapid growth rates of Japan and S. Korea, including the hump-shaped output growth adjustment paths associated with these experiences. It is also found that the model can generate adjustment paths for interest rates, investment, and labor force shares that follow the patterns in the data. This is in sharp contrast to the counterfactual implications of the standard one-sector neoclassical growth framework pointed out by King and Rebelo (1993). A key factor contributing to these results is the complementarity between human capital and technology adoption, that induces reallocation of labor across sectors along the adjustment path.

The implications of the hybrid R&D-based non-scale growth model have been extensively 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 inves-

[1] For a review of empirical studies supporting that human capital is complementary to technology innovation and imitation see Nelson and Pack (1999), Bils and Klenow (2000), and Caselli and Coleman (2001), just to name a few.

[2] Our choice of this benchmark in our investigation was based on the fact that Jones (1995) has shown that the model succeeds in reconciling important regularities in the data such as the increasing R&D intensity with constant output growth rates. Admittedly, we could use other models like Lloyd-Ellis and Roberts (2002) who extend their basic model to allow for non-scale R&D as well as human capital. In addition a number of other recent non-scale R&D growth models could be extended to include a schooling sector. These include Segerstrom (1998), Young (1998), Dinopoulos and Thompson (1998), Howitt (1999), and Peretto and Smulders (2002).

[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 (2001). Other papers that employ the Mincerian approach to model schooling include Jones (1997, 2002), Jovanovic and Rob (1999), and Hall and Jones (1999).

tigates the relationship between human capital accumulation and technological progress, and their combined effect on economic growth. Eicher (1996) and Lloyd-Ellis and Roberts (2002) develop models in which both human capital and technological innovation are endogenous, but they are only concerned with steady-state predictions. Like us, Keller (1996) and Funke and Strulik (2000) study transitional dynamics in a model of human capital and blueprints. Nevertheless, they do not take the predictions of their models to the data. Perhaps closer to our main aim is Parente and Prescott (1994). Like these authors we focus on differences in barriers to technology adoption, caused by sociopolitical factors such as corruption, legal constraints and violence. However, Parente and Prescott's work reproduces postwar miraculous recoveries through exogenous changes in the size of the barriers along the adjustment path. We, instead, do not change the barrier size. In addition, Parente and Prescott do not consider human capital and, therefore, movements in and out of the labor force – which are the main driving force of our results – are not possible.

The remainder of the paper is organized as follows. Section 2 presents the basic model and examines its steady-state properties. Attention is focused on the schooling sector which is the main innovation of the model. Section 3 discusses the motivation for why our simulations target Japan and S. Korea. Section 4 explains the parameterization and calibration of our model to fit the growth processes of Japan and S. Korea, and obtains and studies the adjustment paths implied by three modifications of our theoretical model. Section 5 concludes, discussing the main findings and limitations of our work.

2 Model

This section presents an economic growth model with endogenous human capital and technical progress. We start by describing the model economy's environment. We then set up and solve the central planner's problem. Finally, we derive and discuss the steady-state implications of the model.

Our analysis is focused on aggregate technologies and is based on the central planner's solution. There are two reasons for doing that: First, the human capital technology incorporated in this paper can not easily be derived from a decentralized setup due to aggregation problems.[4] Second, most papers that have analyzed the type of non-scale framework that we incorporate in this paper

[4] See footnote 10 for a discussion on this aggregation problem.

have focused on the central planner's solution. This is important to our analysis since to distinguish our model implications we use existing models as benchmarks.

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-good 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 preference 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 A_t is the economy's technology level, ξ is the technology-output elasticity, and α is the share of capital.

The R&D technology incorporates the only link between economies in our model. Ideas created anywhere in the world can be copied by local researchers at a cost that diminishes with the country's technological gap. The economy's technology level evolves according to the following motion equation:

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

where δ_A represents the technology depreciation 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 that grows exogenously at rate g_{A^*}; μ is a technology parameter; ϕ weights the effect of the stock of existing technology on R&D productivity; and λ captures decreasing returns to R&D effort.[6] R&D equation (2) is a

[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 would be an interesting extension of the model and worthy of future research.

[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-good varieties, x_{it}, used in production. 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. The two production technologies are equal in the symmetric equilibrium case in which $x_{it} = \bar{x}_t$, $K_t = A_t \bar{x}_t$, and $\xi = 1/\gamma - \alpha$. In Romer (1990), R&D effort results in new designs for use in new types of producer durables. There are incentives to carry out R&D because when a new design is produced, an intermediate-good producer acquires a perpetual patent over the design. This allows the firm to manufacture the new variety and practice monopoly pricing.

modification of Jones (1995, 2002) R&D equation to allow for 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 given by (1) and the R&D equation given by (2) reflect the complementarity between technology and human capital. We consider that a higher human capital level allows workers to use ideas more efficiently, and speeds up technology acquisition. Agents increase their human capital through formal education provided by a schooling sector. An important qualification is in place here. One feature of our approach to modelling human capital and technological adoption is that, while education is complementary to technology, a lack of educated workers does not present a barrier to adoption (it only reduces its return). In our framework, the adoption barrier is represented by the parameter ψ. We argue that this is a reasonable characterization because it captures various possibilities for adoption barriers including institutional arrangements and policies as discussed in Parente and Prescott (2002).[8]

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 map 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 into 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 in a Mincerian wage regression: an additional year of schooling raises a worker's efficiency by

[7] Nelson and Phelps (1966) are the first to construct a formal model based on the catch-up term, although their formulation was intended to capture acquisition of human capital by individuals within a country rather than about technological catch up between countries. Parente and Prescott (1994) note that this formulation implies that development rates increase over time (with A_t^*), and provide empirical evidence that is consistent with this implication. Benhabib and Spiegel (1994), Coe and Helpman (1995), and Coe, Helpman, and Hoffmaister (1997), among others, find evidence supporting the role of foreign-technology adoption in economic growth.

[8] We thank an anonymous referee for pointing out this feature of our model.

$f'(S)$.[9,10]

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. L_t denotes the population size and L_{Ht} the total amount of time allocated to schooling in period t. Assume that at the beginning of period 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:

$$S_{t+1} = \frac{S_t\, L_t + L_{Ht}}{L_{t+1}}. \tag{5}$$

This in turn implies

$$S_{t+1} - S_t = \left(\frac{1}{1+n}\right)\left(\frac{L_{Ht}}{L_t} - n\, S_t\right). \tag{6}$$

The evolution of S across time depends on the share of people in education $\frac{L_H}{L}$ and the growth rate of population, with the latter inducing a dilution effect.

2.2 Central planner's problem

There are several external effects in the model. Variable A_t in the RHS of the R&D equation, expression (2), and the production function, equation (1), introduces externalities that run from

[9]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-Mincer regression, Bils and Klenow (2000) present a more extensive formulation of expression (3) that includes schooling quality, and work experience.

[10]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, with the exception of Lloyd-Ellis and Roberts (2002) who 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 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 $\sum_{i=1}^{L_{jt}} e^{f(s_{it})} = L_{jt}\, e^{f(S_t)}$. However, introducing these microfoundations into the model would require to keep track of the different cohorts' years of education across time, thus making the transitional dynamics analysis much more cumbersome, if not impossible. We leave this important issue to future research.

current R&D expenditure into future R&D productivity and future total factor productivity, respectively. Variable S_t in the human capital technology, expression (3), also implies a positive external effect from an individual's schooling investment into the economy's human capital level. However, as we have mentioned previously, we focus on a centrally planned economy for simplicity and for comparability to existing models.

A central planner chooses the sequence $\{C_t, S_t, A_t, K_t, L_{Yt}, L_{At}, L_{Ht}\}_{t=0}^{\infty}$ 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 characterized by the following set of equations:

$$\max_{\{C_t,S_t,A_t,K_t,L_{Yt},L_{At},L_{Ht}\}} \sum_{t=0}^{\infty} \rho^t \left[\frac{\left(\frac{C_t}{L_t}\right)^{1-\theta} - 1}{1-\theta} \right], \tag{7}$$

subject to,

$$Y_t = A_t^{\xi} \left[e^{f(S_t)} L_{Yt} \right]^{1-\alpha} K_t^{\alpha}, \tag{8}$$

$$I_t = K_{t+1} - (1-\delta_K) K_t = Y_t - C_t, \tag{9}$$

$$A_{t+1} - A_t = \mu A_t^{\phi} \left[e^{f(S_t)} L_{At} \right]^{\lambda} \left(\frac{A_t^*}{A_t} \right)^{\psi} - \delta_A A_t, \tag{10}$$

$$S_{t+1} - S_t = \left(\frac{1}{1+n} \right) \left(\frac{L_{Ht}}{L_t} - n\, S_t \right), \tag{11}$$

$$L_t = L_{Yt} + L_{At} + L_{Ht}, \tag{12}$$

$$\frac{L_{t+1}}{L_t} = 1 + n, \quad \text{for all } t, \tag{13}$$

$$\frac{A_{t+1}^*}{A_t^*} = 1 + g_{A^*}, \tag{14}$$

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

where θ is the inverse of the intertemporal elasticity of substitution; and ρ is the discount factor. Equation (9) is the economy's feasibility constraint combined with the law of motion of the stock of physical capital; it states that, at the aggregate level, domestic output must equal consumption, C_t, plus physical capital investment, I_t. Equation (12) is the population constraint; *labor force* – the number of people employed in the output and the R&D sectors – plus the number of individuals in school must equal total *population*.

The optimal control problem can be stated as follows:

$$\begin{aligned} V\left(A_t, K_t, S_t\right) &= \max_{\{L_{Ht}, L_{At}, I_t\}} \frac{\left[\frac{A_t^{\xi}[e^{f(S_t)}(L_t - L_{Ht} - L_{At})]^{1-\alpha} K_t^{\alpha} - I_t}{L_t}\right]^{1-\theta} - 1}{1-\theta} + \\ &+ \rho V\left[A_t(1-\delta_A) + \mu A_t^{\phi}\left(e^{f(S_t)} L_{At}\right)^{\lambda}\left(\frac{A_t^*}{A_t}\right)^{\psi}; K_t(1-\delta_K) + I_t;\ S_t + \frac{1}{1+n}\left(\frac{L_{Ht}}{L_t} - nS_t\right)\right], \end{aligned} \tag{15}$$

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

$$\left(\frac{C_t}{L_t}\right)^{-\theta} \frac{(1-\alpha)Y_t}{L_{Yt}} = \frac{\rho}{1+n}\left(\frac{C_{t+1}}{L_{t+1}}\right)^{-\theta} \frac{(1-\alpha)Y_{t+1}}{L_{Y,t+1}} \left[1 + f'(S_{t+1})\left(\frac{L_{Y,t+1} + L_{A,t+1}}{L_{t+1}}\right)\right], \tag{16}$$

$$\begin{aligned} \left(\frac{C_t}{L_t}\right)^{-\theta} \frac{(1-\alpha)Y_t}{L_{Yt}} &= \frac{\rho}{1+n}\left(\frac{C_{t+1}}{L_{t+1}}\right)^{-\theta} \frac{\lambda\left[A_{t+1} - (1-\delta_A)A_t\right]}{L_{At}} * \\ &* \left\{\frac{\xi Y_{t+1}}{A_{t+1}} + \left[1 - \delta_A + (\phi - \psi)\left(\frac{A_{t+2} - (1-\delta_A)A_{t+1}}{A_{t+1}}\right)\right]\left[\frac{\frac{(1-\alpha)Y_{t+1}}{L_{Y,t+1}}}{\frac{\lambda(A_{t+2} - (1-\delta_A)A_{t+1})}{L_{A,t+1}}}\right]\right\}, \end{aligned} \tag{17}$$

$$\left(\frac{C_t}{L_t}\right)^{-\theta} = \frac{\rho}{1+n}\left(\frac{C_{t+1}}{L_{t+1}}\right)^{-\theta}\left[\frac{\alpha Y_{t+1}}{K_{t+1}} + (1-\delta_K)\right]. \tag{18}$$

At the optimum, the central planner must be indifferent between investing one additional unit of labor in schooling, R&D, and final output production. The LHS of equations (16) and (17) represent the return from allocating an additional unit of labor to output production. The RHS of equation (16) is the discounted marginal return to schooling, taking into account population growth. The RHS term in brackets obtains because human capital determines the effectiveness of labor employed in output production as well as in R&D. The RHS of equation (17) is the return to R&D investment. An additional unit of R&D labor generates $\frac{\lambda[A_{t+1}-(1-\delta_A)]A_t}{L_{At}}$ 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 $\frac{(1-\alpha)Y_{t+1}}{L_{Y,t+1}}\left[\frac{\lambda(A_{t+2}-(1-\delta_A)A_{t+1})}{L_{A,t+1}}\right]^{-1}$ denotes the value of an additional design that equalizes labor wages across sectors. Euler equation (18) states that the planner is indifferent between consuming one additional unit of output today and converting it into capital, thus consuming the proceeds tomorrow.

Equations (8)-(14), and (16)-(18) constitute the system that characterizes the equilibrium dynamics of the model.

2.3 Steady-state growth

We next derive the model's balanced-growth path. Solving for the interior solution, equation (12) implies that in order for 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 (11) implies that, at steady-state (ss), S_{ss} is constant and given by

$$S_{ss} = \frac{u_{H,ss}}{n}, \tag{19}$$

where $u_{H,ss} = \left.\frac{L_H}{L}\right|_{ss}$. Equation (19) 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 Jones (1997), where growth regressions are developed from steady-state predictions; data on S_{ss} acts as a proxy for $u_{H,ss}$ and the estimated coefficient on S_{ss} partly reflects the parameter $\frac{1}{n}$ in our framework.

The aggregate production function, given by equation (8), 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

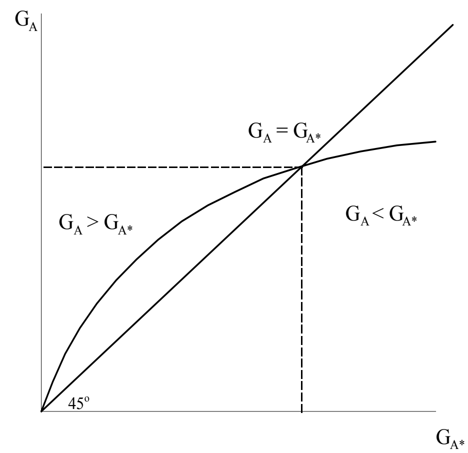
$$G_{Y,ss} = (G_{A,ss})^{\frac{\xi}{1-\alpha}}(1+n), \tag{20}$$

where $G_{xt} = 1 + g_{xt}$. Since $G_{A,ss}$ is constant, it follows from equation (2) that

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

Equation (21) presents the relationship between the technology growth rate of the model economy and the technology frontier growth rate. This relationship is illustrated in Figure 2. Notice that

Figure 2: Relationship between $G_{A,ss}$ and $G_{A^*,ss}$



since the ratio $\frac{\psi}{1+\psi-\phi} < 1$, the function is concave with a unique point at which

$$G_{A,ss} = G_{A^*,ss} = (1+n)^{\frac{\lambda}{1-\phi}}. \tag{22}$$

$G_{A,ss}$ 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; that is, we assume that $G_{A^*,ss}$ is given by expression (22) and so is $G_{A,ss}$.[11] This in turn implies that

$$G_{Y,ss} = G_{C,ss} = G_{K,ss} = (1+n)^{\frac{\lambda\xi}{(1-\alpha)(1-\phi)}}. \tag{23}$$

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}.

[11] Alternatively, we could assume that a technological leader moves the world technology frontier according to equation (2) which now reduces to

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

Notice that for the leader imitation is not possible since at the frontier $\frac{A_t^*}{A_t} = 1$. 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 (21) delivers equation (22). As discuss in footnote 22, had g_A^* taken on any other value, the transitional dynamics numerical analysis would become much more tedious.

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 (16) combined with the balanced-growth equation (23) gives

$$u_{H,ss} = 1 - \frac{1}{f'(S_{ss})}\left[\frac{G_{y,ss}^{\theta-1}(1+n)}{\rho} - 1\right], \tag{24}$$

where $u_{H,ss} = \left.\frac{L_H}{L}\right|_{ss}$. As expected, the steady-state share of students in total population ($u_{H,ss}$) is positively related to the returns to education ($f'(S_{ss})$), and the preference parameters ($\rho, 1/\theta$).

Euler equation (17) combined with balanced-growth condition (23) delivers the steady-state labor share in R&D as

$$u_{A,ss} = \frac{u_{Y,ss}}{\left(\frac{1-\alpha}{\lambda\xi(g_{A,ss}+\delta_A)}\right)\left[G_{y,ss}^{\theta-1}\left(\frac{G_{A,ss}}{\rho}\right) - (\phi-\psi)(g_{A,ss}+\delta_A) - (1-\delta_A)\right]}. \tag{25}$$

As expected, R&D effort increases with the elasticities of technological change ($\phi - \psi$) and final output (ξ) with respect to the current stock of knowledge. R&D investment also increases as the degree of diminishing returns to R&D effort decreases (i.e., as λ increases). Dividing equation (12) by L gives the labor share in the output sector as

$$u_{Y,ss} = 1 - u_{h,ss} - u_{A,ss}. \tag{26}$$

Equations (24), (25) and (26) represent the three steady-state shares of labor.

3 The Japanese and South Korean Development Experiences

As was stated in the introduction, the main goal of our paper is to take our model to the data by using our theoretical results to understand the Japanese and S. Korean development experiences. In addition, we try to distinguish between competing alternative theoretical specifications born out of our model. Given these goals, this section discusses the motivation behind the exercise and our choice of these two nations' experiences.

At least since the seminal work of Lucas (1993), it has been recognized that a desirable property of growth models is to be able to reproduce miraculous experiences. In terms of transitional dynamics analysis, this amounts to, at the minimum, being able to reproduce the average speed of convergence of miraculous economies, and country-specific changes in output growth trend. In

Table 1: Output, capital and schooling in Japan and S. Korea

Country		1960	1963	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. ** Levels relative to their U.S. counteparts.

this section, we focus on the Japanese and the S. Korean output paths. As we describe below, although these two countries have experienced unprecedented growth for the relevant period of our investigation, they also represent two distinctly different development experiences.

Table 1 presents data for Japan and S. Korea on relative GDP *per worker*, relative physical capital *per worker*, and average educational attainment.[12] 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 accelerated 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 a 5.2 and 6.5 percent average annual growth rates, respectively.

It is important to note that even though Japan had lost a substantial portion of its physical capital during WWII, its educational attainment in 1960 of 10.2 years compared well with those of most developed nations – e.g., the U.S. educational attainment at that time was a little over 10.7.[13] What is even more remarkable is that during the period 1960-1987, average years of schooling per worker increased only by 0.8 years to reach 11.0 years. The main engine of growth in Japan seems to have been physical capital accumulation complemented by a very important technological catch-up process.[14] In particular, in 1960, the Japanese physical capital stock per worker was only

[12] All relative measures in the paper are with respect to U.S. levels. Additionally, we follow Parente and Prescott (1994) and smooth all data series using the Hodrick-Prescott filter with the smoothing parameter equal to 25.

[13] 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)).

[14] For discussion on the effects of technology adoption on East Asia see Amsden (1991) and Baark (1991). For an excellent presentation of technology adoption in Japan see Minami (1994). The author explores three categories of borrowed technology which are illustrated by examples from Japanese history. He discusses in detail the introduction of the English railway technology, the machine filature technology and the silk weaving technology. According to Minami, Japan's industrialization was revolutionary in the sense that it was accomplished by the adoption of existing foreign technology.

Table 2: Parameter values

Common values to both models				Model-specific values: model w/o H		Model-specific values: model with H	
$\boldsymbol{\alpha}$	0.36	$\boldsymbol{\xi}$	0.1	$\boldsymbol{\psi}$ Japan	0.10	$\boldsymbol{\psi}$ Japan	0.131
$\boldsymbol{\delta_K}$	0.06	$\boldsymbol{\lambda}$	0.5	$\boldsymbol{\psi}$ S. Korea	0.074	$\boldsymbol{\psi}$ S. Korea	0.162
$\boldsymbol{\delta_A}$	0.1	$\boldsymbol{\rho}$	0.96			$\boldsymbol{\eta}$	0.69
$\boldsymbol{\theta}$	1	$\mathbf{T_{ss}}$	1			$\boldsymbol{\beta}$	0.43
$\boldsymbol{\phi}$	0.931	$\mathbf{g_{y,ss}}$	0.016			$\mathbf{S_{ss}}$	12.03
$\mathbf{n}$	0.015						

16.9 percent, whereas in 1990 it reached a stunning 104.6 percent, which implies an average annual convergence rate of 6.3 percent.

The S. Korean growth experience seems to be stemming from entirely different sources. Even though output convergence was faster in S. Korea, physical capital accumulation was lower than in Japan, growing from 11.6 to 50.2 percent – an average annual convergence rate of 5.6 percent. As shown in Table 1, human capital accumulation played a much larger role in the development process of S. Korea. In particular, the average educational attainment per worker more than doubled in the period 1963-1987, increasing from 3.2 to 7.7 years.

In what follows, we examine the ability of the proposed model to replicate these two countries' convergence episodes by simulating their transitional dynamics.

4 Adjustment Paths for Japan and S. Korea under Alternative Models

Next, we run simulations and assess the capacity of the model to reproduce key features of the Japanese and S. Korean development paths. In this section, we first present the parameters chosen for our analysis and discuss calibration issues. Second, we simulate transitional dynamics and obtain results for two models: our basic model with human capital, and an alternative model without human capital commonly found in the literature. Finally, we explore the forces that make our model behave better than the alternative. Details about the normalized equation systems and the numerical algorithm used for the simulations are relegated to Appendix A.

4.1 Parameterization and calibration

This subsection is concerned with parameterization and calibration of our models. First, we consider our basic framework with human capital that we call *model with H*. In addition, we also consider an alternative economy in which the schooling sector is closed. This corresponds to the type of two-sector non-scale growth model studied, for example, by Eicher and Turnovsky (1999a) and Perez-Sebastian (2000), and is similar to the neoclassical growth model with technology adoption considered by Parente and Prescott (1994). The alternative model is then characterized by two control variables (consumption and R&D-labor) and two state variables (physical capital and technology gap). There are only two sectors in this economy: a final good sector that displays constant returns in labor and capital, but increasing returns in knowledge; and an R&D sector that exhibits constant returns in knowledge and labor. We refer to this model as *model w/o H*.

Table 2 presents the calibrated parameter values used in the numerical exercises. The ones that are common to both models are very similar to those considered by Eicher and Turnovsky (1999b, 2001). In particular, we choose a value of 0.06 for the depreciation rate of capital (δ_K), 0.96 for the discount factor (ρ), 0.36 for the capital-share of output (α), and 1 for the inverse of the elasticity of consumption substitution (θ), which are standard in the literature. 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.[15] We choose an intermediate value of 0.5 for the R&D technology parameter λ, and equalize the elasticity of output with respect to the technology (ξ) and the depreciation rate of technology (δ_A) to 0.1.[16] Finally, the steady-state growth rate of income ($g_{y,ss}$) is equalized to 1.6%, consistent with the Bils and Klenow's (2000) 91-country sample. Our choice for $g_{y,ss}$ and equation (23) imply a value for the R&D externality parameter ϕ of 0.931.

In our basic model with schooling and imitation, we also need to calibrate the human capital

[15]The reason for using the average growth rate of labor in the G-5 rather than in any other group of countries is that the main role of population growth rate in the model is to move the world technology frontier in steady state, and clearly the majority of world research effort is conducted by the G5 nations. For example, Coe, Helpman and Hoffmaister (1997) report that in 1990, industrial countries accounted for 96% of the world's R&D expenditure.

[16]Estimates of λ found in the literature vary from 0.2 (Kortum 1993) to 0.75 (Jones and Williams 2000). Griliches (1988) reports estimates of the elasticity of output with respect to technology ξ between 0.06 and 0.1. If we consider that δ_A includes the creative destruction effect of new technology on old designs, a value of 0.1 would imply that new ideas possess a life-span of 10 years, very close to the lower bound found by Caballero and Jaffe (1993).

technology. Following Bils and Klenow (2000), we assume that

$$f(S) = \eta S^{\beta}, \ \ \eta > 0, \ \beta > 0. \tag{27}$$

Using Psacharopoulos' (1994) cross-country sample on average educational attainment and Mincerian coefficients we estimate η and β. Given equation (27), we can construct the loglinear regression equation

$$\ln (Mincer_i) = a + b \ln S_i + \varepsilon_i, \tag{28}$$

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 $\beta = 0.43$, both significantly different from zero at the 1 percent level, that are very similar to those obtained by Bils and Klenow (2000). Given the above numbers, equations (19) and (24) imply that the steady-state average educational attainment is 12.03 years. This calibrated parameter value is very close to the 2000 U.S. figure of 12.05 obtained by Barro and Lee (2001).

Taking the model to the data still requires assigning values to another parameter, the imitation coefficient ψ. We calibrate the parameter ψ to each country's output data. Because we focus on Japan and S. 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 – i.e., their average speed of convergence.

Notice that this approach follows Parente and Prescott (1994) who assume that countries may differ in their degrees of technology adoption barriers. We suppose that these barriers affect the value of the parameter ψ. It is important to note, however, that Parente and Prescott's (1994) technology adoption equation is different from ours. They do not include human capital, and $\phi = 0$ because they employ a neoclassical growth model. In addition, these authors assume that a parameter equivalent to $1/\mu$ in equation (2) is country-specific and captures the degree of technology adoption barriers. The value of ψ is, on the other hand, common to all countries. The parameters $1/\mu$ and ψ are calibrated using each country's average convergence speed. This formulation allows Parente and Prescott to generate very different steady-state output levels depending on the degree of the barriers. This is important for them because they propose a theory of cross-country income differences. We, on the other hand, are interested in assessing the capacity of our model to reproduce key features of miraculous economies' convergence path. For this reason, we choose $T_{ss} = 1$ that forces μ to be common to all economies, and make ψ the country-specific parameter. Whether barriers affect the exponent ψ or the coefficient μ in the technology-adoption equation is, we believe, an empirical issue that has not been addressed yet.

The model with human capital requires $\psi = 0.131$ to induce Japan's average speed of convergence, and $\psi = 0.162$ to produce the S. Korean output numbers. On the other hand, the model without human capital requires $\psi = 0.10$ for the Japanese development experience, and $\psi = 0.074$ for the S. Korean development experience. The initial values of the stock variables and output data used to calibrate ψ are presented in Table 1; accuracy measures are presented in Appendix A.

4.2 Predicted output levels and growth rates

Since we are interested in comparing the implications of our three-sector non-scale growth model with human capital (and imitation) to those of the alternative two-sector non-scale growth model without human capital (but with imitation), we generate results for both frameworks. The exercise is the same as the one that delivers the calibrated value of ψ. It consists of reproducing relative output levels of Japan and S. Korea in two different years using initial values of the state variables. In particular, the initial date for Japan is 1960, and for S. Korea is 1963 , whereas the final date for both nations is 1990. Recall that these values are presented in Table 1.

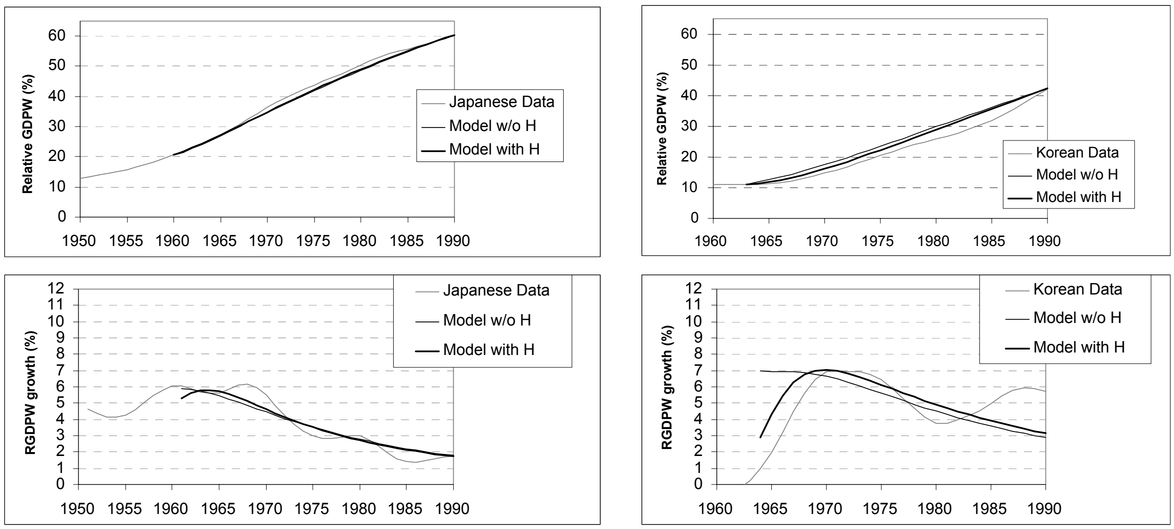
The adjustment paths predicted by the models for the level and growth rates of relative GDP per worker (RGDPW) are depicted in Figure 3. The predicted paths replicate fairly well the Japanese and the S. Korean output paths. Our model with human capital, however, does a much better job because it predicts that output per worker growth rates do not peak at the beginning of the adjustment path but later on.[17] This is an important feature that can not be reproduced by the standard one-sector neoclassical growth model (see King and Rebelo (1993)), and that characterizes the output-convergence phenomenon as Easterly and Levine (1997), among others, show.

4.3 Comparing alternative models

What are the determining factors behind our results? In this subsection we try to explain the adjustment paths by decomposing them in their relevant parts. We start by rewriting production

[17] It can be shown that both models considered in the paper can generate asymptotic speeds of convergence close to the 2 percent commonly found by the empirical literature. This result is consistent with the major finding of Eicher and Turnovsky (1999b, 2001) that going from the neoclassical one-sector growth model to a two sector non-scale growth model reduces the asymptotic speed of convergence from about 7 percent to more reasonable values.

Figure 3: Adjustment paths for Japan and S. Korea



function (8) in per worker terms as follows:

$$\left(\frac{Y_t}{L_{Yt}+L_{At}}\right) = A_t^{\xi} e^{f(S_t)(1-\alpha)} \left(\frac{L_{Yt}}{L_{Yt}+L_{At}}\right)^{1-\alpha} \left(\frac{K_t}{L_{Yt}+L_{At}}\right)^{\alpha}. \tag{29}$$

Using a continuous time approximation, equation (29) can be rewritten in its output per worker growth (g_Y^w) form

$$g_{Yt}^w = \xi g_{At} + (1-\alpha)\,\frac{d\,f(S_t)}{d\,t} + \alpha g_{(K/L),t} + \left[(1-\alpha)\,g_{u_Y,t} - g_{(1-u_H),t}\right]. \tag{30}$$

Equation (30) presents a decomposition of output growth in its four components: (a) growth of total factor productivity (TFP), (b) change in per capita educational attainment, (c) growth of per capita physical capital, (d) net impact of labor movements across sectors (term in squared brackets). Given that the population size in our model is given exogenously, this decomposition captures the impact of the different aggregates that enter the production function including the labor force size.

Figures 4 and 5 present the contributions of the four different components to the S. Korean and the Japanese output per worker growth, according to equation (30). We present the growth components for the two different R&D models with imitation. A thin-black line represents predictions of the *model w/o H*. Recall that in this model variables presented in their per capita or their per worker intensive form are identical as there is no schooling sector which would attract some of the labor force. As a result, the terms $\left[(1-\alpha)\frac{df(S_t)}{dt}\right]$ and $\left[g_{(1-u_H),t}\right]$ in equation (30) vanish. A bold-black line, represents predictions for the *model with H*; the intensive form of all relevant variables are in per worker terms (i.e. dividing by $L_Y + L_A$).

In addition, we include a third set of results in Figures 4 and 5. The dashed line represents predictions of the non-scale growth model with human capital but with the additional assumption that per worker variables come from dividing by L (the population size), instead of by $L_Y + L_A$ (the labor force) (denoted as the *model with h*). As a result, the second summand in the squared brackets in equation (30) vanishes. One of the determining features of this modified model is that it does not consider movements in and out the labor force from and to the schooling sector. This model is examined in the hope that it will reveal which effect of the complementarity between human capital and technology dominates: TFP that occurs though the R&D equation, or labor movement among sectors. Finally, a grey line depicts the data for each country.

We start our analysis with a few general points. Notice that when RGDPW growth rates obtain large values early on, they fall rapidly subsequently, and *vice versa*. This feature of the transitional path of output growth is due to the fact that all of the models considered are calibrated to reproduce the average convergence speed of RGDPW. Having this in mind, we can focus on model differences that occur during the early periods of the adjustment path. Another feature common to all three models is the initial values of the capital stocks from which the transition dynamics start. This implies that initial incentives to invest in physical and human capital formation (when the model includes a schooling sector) are very similar in the three cases, because by construction, so are the initial capital-output ratios and average educational attainments. As a consequence, the main forces behind the initial differences in RGDPW growth rates across models are the growth rate of relative TFP and the net contribution of labor (see panels B and E in figures 4 and 5).

4.3.1 Model without human capital vs. model with human capital but no labor movements

Let us continue our analysis by comparing the *model w/o H* (thin-black line) with *model with h* (dashed line) in a attempt to understand the contribution of introducing human capital into the model and abstracting from the effect of movements into and out the labor force. The introduction of the new sector amplifies the effect of diminishing returns, increasing greatly initial growth rates. The new schooling sector adds a new growth engine whose contribution to the growth rate at impact is around 4 percent for S. Korea and 0.33 percent for Japan (see Panel D), and thereafter follows the standard neoclassical declining-growth-rate pattern caused by diminishing returns.

Another important effect of introducing schooling is that the final-output labor share starts further away from its steady state level and subsequently grows faster, thus making much larger its initial contribution (see Panel E). The reason is that schooling is the only activity that enhances the productivity of the other two sectors, and consequently it is optimal for the economy to invest heavily in human capital at the beginning of the adjustment path, borrowing resources mainly from the consumption-good sector. Due to the same reason, physical capital suffers a slightly larger initial fall in the model with schooling, and accumulates at a faster rate during the first few periods following the evolution of output (see Panel C). The large initial differences between the growth rates of output and capital in both models are due to consumption smoothing, that exerts a downward pressure on the investment share as output declines, causing physical capital to grow at a much lower rate than output during the first few periods.

As shown in Panel B in figures 4 and 5, the relative TFP contribution is smaller in the *model with h* than in the *model w/o H*. This occurs because the shocks to physical capital and output are the same for both models but, in the *model with h*, there is an additional third shock to the schooling level that affects the output catch-up process. As a result, the initial technology gap required by this model becomes smaller. This decreases the productivity of R&D and the contribution of TFP, due to the existence of diminishing imitation opportunities. Note that R&D productivity declines so much that the technology-gap parameter ψ must rise to allow the model to reproduce the Japanese and S. Korean average convergence speeds.

Panel B in Figure 4 clearly illustrates that human capital speeds up technology adoption. The contribution of TFP to output growth is presented by a hump-shaped pattern in the *model with h*. This pattern, which turns out to also describe the evolution of the R&D labor share, is the consequence of two opposing effects. On the one hand, the technology imitation productivity declines as the technology gap falls toward its steady-state level. On the other hand, R&D becomes more productive as the average educational attainment grows. The latter effect dominates the former during the first few periods, whereas the reverse is true later on.[18]

[18] Lau and Wan (1994) suggest that the ability of human capital to enhance technology adoption may explain the miraculous experiences that achieve their maximum growth rates after trend acceleration. Our work shows that, at least in our structural *model with h*, human capital and TFP can not explain the output growth inverted-U path in Japan and S. Korea.

The final insight from our investigation so far is that neither the *model w/o H* nor the *model with h* can replicate the hump-shaped output growth path evident in the data.

4.3.2 Model with human capital vs. model with human capital but no labor movements

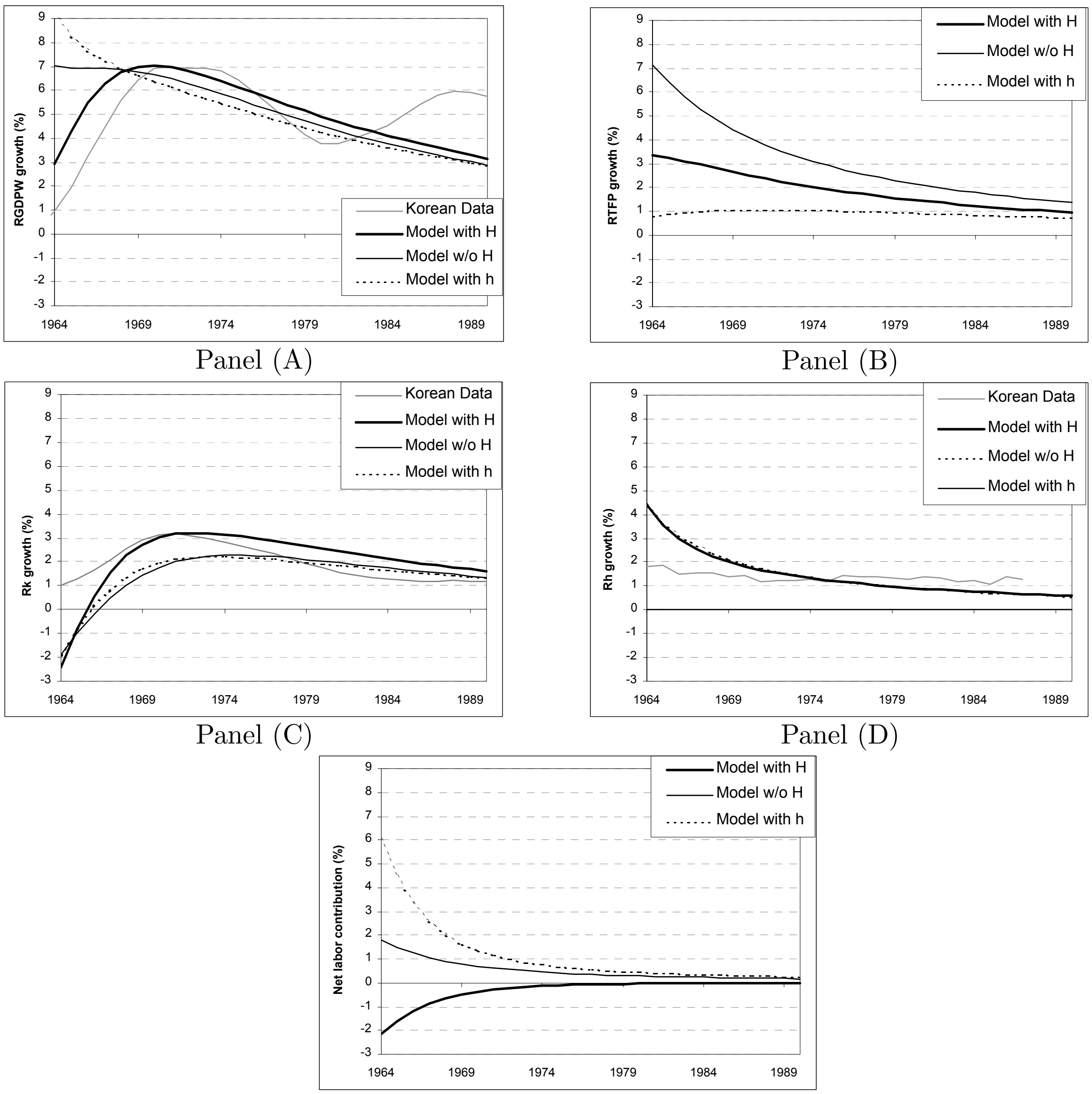
We now compare the *model with h* (dashed line) with the *model with H* (bold-black line). Recall that in the former one, per worker variables are obtained dividing by the population size, L, whereas in the latter per worker variables are obtained dividing by the labor force size, $L_Y + L_A$.

It is readily noticeable that the contribution of human capital is almost identical in both models (see Panel D). The hump-shaped physical capital contribution in the two models illustrated by the two lines is also the same, and complies well with the S. Korean data (see Panel C). A strong and declining consumption smoothing effect causes the initial increase; but after a few periods diminishing-returns dominate and physical capital growth rates start to decrease, and continue doing so as they approach their steady-state level.

The first distinct difference between the two models is that the *model with H* shows a larger decrease in physical capital investment during the first two periods, and a faster physical capital growth thereafter. This is the consequence of matching the same initial data values to per worker variables, instead of per capita. More specifically, the reason for the faster physical capital growth is that, at impact, physical capital and output must be further away from their balanced-growth path in the former case, because the initial labor force is also below its steady-state value. This lower level of physical capital produces larger returns, and raises its subsequent growth rates. On the other hand, a lower initial level of output along with the preference for consumption smoothing create the larger decrease in physical capital investment during the first two periods. Another difference between the models is that the contribution of relative TFP in the *model with H* is stronger along the whole adjustment path (see Panel B). Now, this occurs because of the slightly-larger initial technical gap required in the per-worker-term case that raises R&D productivity. The difference is larger for S. Korea because the value of the parameter ψ required is also larger.

Most importantly, the main difference between the two models is due to the net labor contribution illustrated in Panel E. Recall that net labor contribution is given by the term in brackets in equation (30), and reflects the effect of population movements across sectors. More specifically, this term takes into account that output rises with the amount of labor devoted to final-good pro-

Figure 4: Contribution of different components to relative output growth, S. Korea



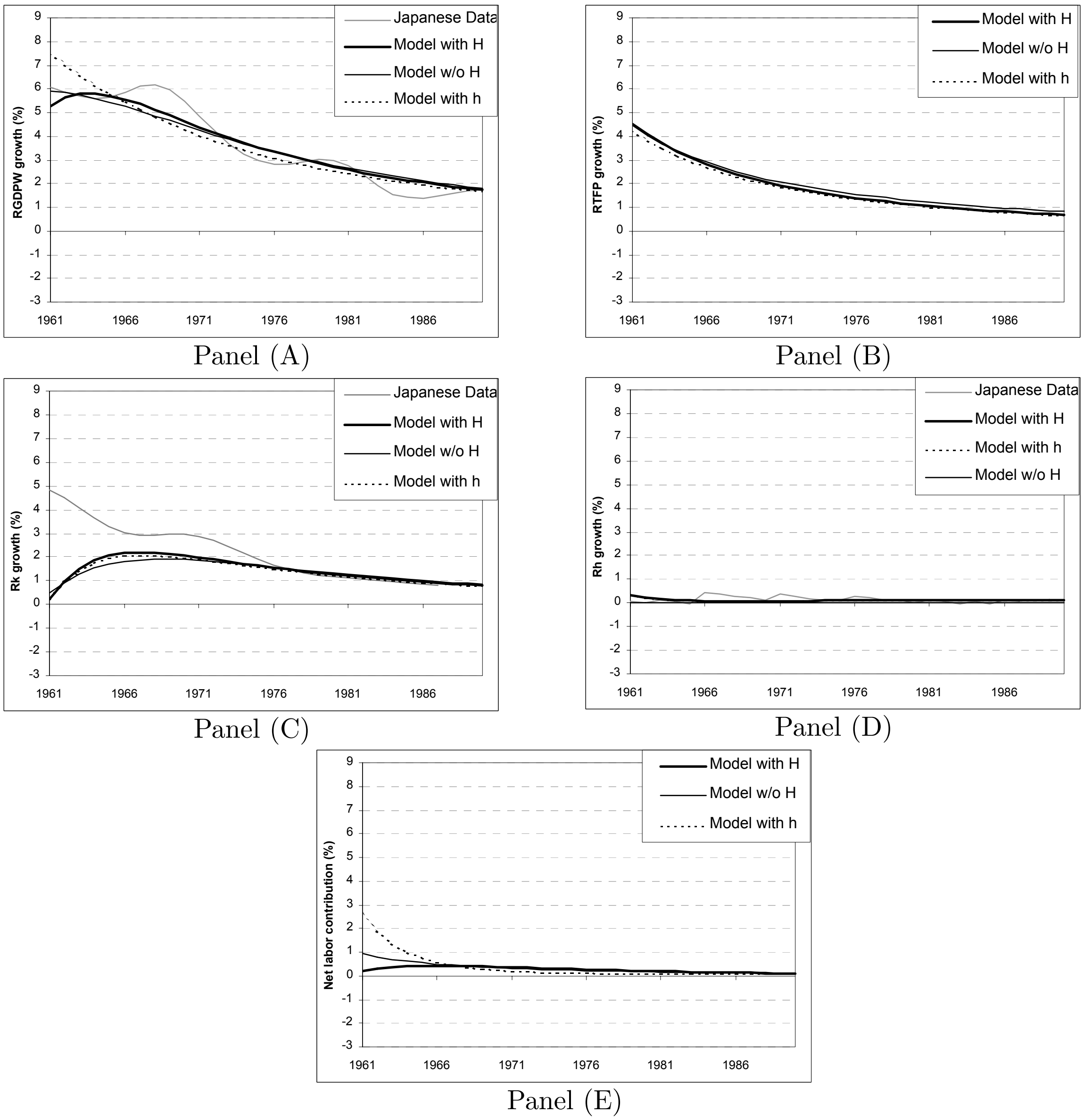
Panel (A) Panel (B)

Panel (C) Panel (D)

Panel (E)

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 (30).

Figure 5: Contribution of different components to relative output growth, Japan



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 (30).

duction, but also that additional labor deflates output per worker. As a consequence, net labor contribution decreases with the number of students that leave school and enter the labor force, and increases as R&D effort declines because part of the R&D labor is reallocated to the final output sector. Along the *model with H* transitional dynamics, the effect of students entering the labor force is larger at the beginning, and rapidly decreases as the economy approaches the steady state, which generates a fast declining pattern of labor force growth. This effect along with a decreasing R&D labor share induces the initially rising net contribution of labor illustrated by the thick-black line in Panel E.

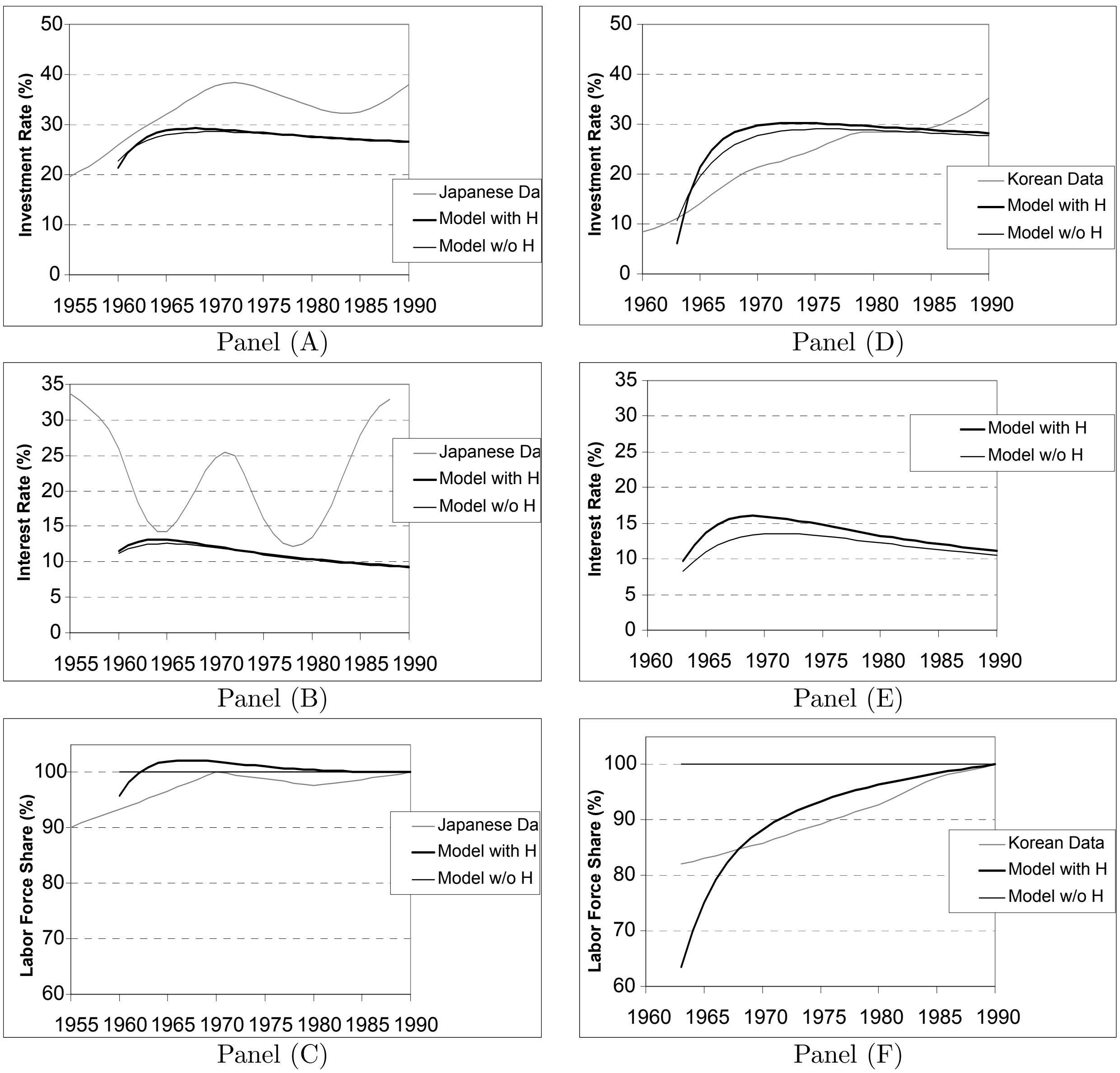
Our key finding here is that the main force that generates the hump-shaped output path is the relatively large allocation of agents in education and R&D activities at the beginning of the convergence process, which produces large movements of agents in and out of the labor force.

4.4 Interest rates, investment, and labor-force shares

In addition to the determining factors of the adjustment path described above, we also try to relate our work to important variables formerly studied in the literature. King and Rebelo (1993) note that the transitional dynamics of the neoclassical one-sector growth model of physical capital accumulation needs either implausibly high interest rates or extraordinary high investment shares in order to generate the type of rapid convergence observed in East Asia. The model's adjustment path also has troubles in generating increasing investment shares. These problems can be eliminated by substantially modifying the baseline model: Christiano (1989) introduces a subsistence level of consumption into the utility function to correct it; Gilchrist and Williams (2004), on the other hand, consider a putty-clay production technology. We show that our framework is also able to avoid these counterfactual implications of the standard neoclassical growth model.

Figure 6 provides data and predictions on investment and interest rates. We see that both non-scale growth models, the one with schooling and the one without it, generate plausible investment rates that start well below their steady-state value as the evidence suggests. When we have more than one-sector, the economy deviates resources toward the activities that are relatively more productive. This is the case for the R&D and schooling sectors during the early stages of development. As the economy closes its technical gap and accumulates human capital, the relative level of investment in physical capital grows thus raising investment rates. Regarding the interest rate, we have data on inflation-adjusted returns in the Japanese stock market, obtained from Chris-

Figure 6: Investment, interest rates, and the labor force in S. Korea and Japan



tiano (1989). These numbers show a slightly decaying trend, as predictions do.[19] Predictions are not contained within the observed values because of the calibration procedure followed that forces the steady-state interest rate to equal 7.42 percent for both Japan and S. Korea. This evidence agrees with the one supplied by King and Rebelo (1993) that suggests that interest rates do not show big variations across centuries. The difference now with the one-sector growth model is that lower levels of technology and human capital decrease the marginal productivity of capital, which mitigates the increase that interest rates suffer when physical capital declines.[20]

In addition, Figure 6 provides data on the labor force share. Here, the non-scale model with human capital (*model with H*) clearly represents an improvement, given that by construction the labor force in the two-sector non-scale growth framework is equal to the population at any point in time.[21] We see that predictions replicate fairly well the main patterns. In S. Korea the labor force share starts far below its steady state value and grows monotonically, reflecting the return of students to the labor force. In Japan the labor force share at impact is below the balanced growth path and then overshoots. The overshooting is the result of the relatively high Japanese average educational attainment in 1960 which after a few periods leads the economy to borrow labor from the schooling sector and invest heavily on the final output and R&D activities in order to accumulate capital and close the big technical gap at a faster rate. We take this last result as giving support to the important role in miraculous experiences attributed by the model to labor movements in and out the labor force.

5 Discussion and Conclusion

In this paper, we propose a new model that tries to account for development miracle experiences. Its main innovation is the introduction of a novel law of motion of human capital in an otherwise standard R&D-growth model. This allows the proposed model to determine endogenously both technology and human capital; therefore, making it possible to explicitly consider the potential

[19]The linear regression of the observed returns on a time trend gives a slope coefficient equal to -0.109.

[20]Perez-Sebastian (2000) makes the same point. He, however, finds a much larger variation in the interest rate than we do, and than the one suggested by the data.

[21]Observed labor participation rates depend on the interval of age during which people can legally provide labor services. In our model, however, people can work all along their lives. The magnitudes shown by the data and by the predictions are therefore quite different. In order to facilitate visual comparison, we measure labor shares relative to their 1990 value. Another problem is that the actual evolution of the labor force share reflects other things than just movements between the production and schooling sectors, such as the increasing relative participation of women, etc. Unfortunately, solving this problem is no easy task.

complementarity between those two engines of growth.

Our main result is that our calibrated model is quite successful in replicating the rapid growth rates of Japan and S. Korea, including the hump-shaped output growth adjustment paths associated with these experiences. In addition, the model can generate adjustment paths for interest rates, investment rates, and labor force shares that are consistent with the main trends suggested by the empirical evidence.

The key insight from our analysis and main contributing factor to our model's success in replicating the Japanese and S. Korean growth experiences is the complementarity between human capital and technology adoption. This complementarity induces reallocation of labor across sectors along the adjustment path which makes it possible to replicate the hump-shaped output growth paths of Japan and S. Korea. This is in sharp contrast to the counterfactual implications of the standard one-sector neoclassical growth framework pointed out by King and Rebelo (1993).

Our work further suggests that the hypothesis proposed in previous literature (see e.g., Griliches (1988) and Nelson and Pack (1999)) that the enhancing effect of human capital on technology adoption is sufficient to reproduce the growth patterns shown by East Asian miracle countries does not necessarily hold in a more structural model. To reiterate, our results imply that taking into account labor reallocations across sectors is crucial to replicating the Japanese and S. Korean experiences.

Like Parente and Prescott (1994), we have focused on exogenous differences in barriers to technology adoption to replicate the average speed of convergence implied by the Japanese and S. Korean experiences. However, in Parente and Prescott's setup, variable convergence speeds are possible but only through exogenous variations in the degree of barriers. Whereas, in our setup, convergence speed changes are endogenous. Our findings suggest that the main reason is that Parente and Prescott do not allow for an endogenous labor force size.

Our work is certainly not without limitations. In this paper, we have focused on the socially optimal equilibrium. Predictions with the proposed specification would differ under the decentralized problem. In particular, agents would not internalize the positive external effects and therefore choose less schooling. As we mentioned in footnote 10, a decentralized setup would make the transitional dynamics analysis much more cumbersome, if not impossible. We leave this issue to future research.

Another limitation of our work is that the proposed 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 home-production. Alternatively, we could permit human capital formation though learning-by-doing or on-the-job training. Another extension could consist of introducing different human capital technologies for final output and R&D labor, although further research is clearly necessary in determining the appropriate weights to be assigned to the effectiveness of human capital in different sectors.

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. It is shown that the value added from pursuing such model greatly exceeds the added complexity. In a more specific sense, our results suggest that the technology-human capital complementarity and the subsequent labor reallocation are crucial components in the making of growth miracles.

A Technical Appendix

A.1 Transitional dynamics

In order to generate a system of equations to study transitional dynamics in the proposed model economy, we first redefine variables so that their values remain constant at steady state.

A.1.1 The normalized system for the R&D model with human capital

The aggregate production function, equation (8), 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 (16) gives

$$\left(\frac{\hat{c}_{t+1}}{\hat{c}_t}\right)^{\theta} \left(\frac{u_{Y,t+1}}{u_{Yt}}\right) (G_{At})^{\frac{(\theta-1)\xi}{1-\alpha}} \left(\frac{\hat{y}_t}{\hat{y}_{t+1}}\right) = \left(\frac{\rho}{1+n}\right) \left[f'(S_{t+1})\ (u_{Y,t+1} + u_{A,t+1}) + 1\right]. \tag{31}$$

From the R&D equation (2), we derive G_{At} as

$$G_{At} = \frac{A_{t+1}}{A_t} = 1 - \delta_A + \upsilon \left[e^{f(S_t)} u_{At}\right]^{\lambda} T^{(1+\psi-\phi)}, \tag{32}$$

where $T = \frac{A_t^*}{A_t}$; and $\upsilon = \mu \left(A_t^*\right)^{\phi-1} L_t^{\lambda}$, which is a constant.[22] From equation (17) we obtain

$$\begin{aligned}\left(\frac{\hat{c}_{t+1}}{\hat{c}_t}\right)^{\theta} \left(\frac{\hat{y}_t}{\hat{y}_{t+1}}\right) \left(\frac{u_{Y,t+1}}{u_{Yt}}\right) \quad = \quad & \frac{\rho\left(g_{At} + \delta_A\right)}{G_{At}^{\frac{\xi}{1-\alpha}(\theta-1)+1}} \left(\frac{u_{A,t+1}}{u_{At}}\right) * \\ & * \left[\left(\frac{\lambda\xi}{1-\alpha}\right)\left(\frac{u_{Y,t+1}}{u_{A,t+1}}\right) + \left(\frac{1-\delta_A}{(g_{A,t+1}+\delta_A)}\right) + (\phi - \psi)\right]. \end{aligned} \tag{33}$$

Finally, from equation (18) we obtain

$$\frac{1+n}{\rho}\left[\left(\frac{\hat{c}_{t+1}}{\hat{c}_t}\right)(G_{At})^{\frac{\xi}{1-\alpha}}\right]^{\theta} = \alpha\frac{\hat{y}_{t+1}}{\hat{k}_{t+1}} + (1 - \delta_K). \tag{34}$$

The system that determines the dynamic equilibrium normalized allocations is 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. (31).
2. Euler equation for population share in R&D, u_{At}: Eq. (33).

[22] 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 (22), υ could not be constant, making the simulation exercise more tedious.

3. Euler equation for normalized consumption, $\hat{c}_t$: Eq. (34).

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

State Variables:

1. Law of motion of human capital, S_t: Eq. (6).
2. Law of motion of the technology gap, T_t:

$$T_{t+1} = T_t \left(\frac{G_{A^*t}}{G_{At}} \right). \tag{35}$$

3. Law of motion of normalized physical capital, $\hat{k}_t$:

$$(1+n)\hat{k}_{t+1} (G_{At})^{\frac{\xi}{1-\alpha}} = (1-\delta_K)\hat{k}_t + \hat{y}_t - \hat{c}_t, \tag{36}$$

where G_{At} is given by expression (32), $G_{A^*t} = G_{A,ss}$ for all t, and

$$\hat{y}_t = \hat{k}_t^{\alpha} \left[e^{f_Y(S_t)} u_{Yt} \right]^{1-\alpha}. \tag{37}$$

A.1.2 The normalized system for the R&D model without human capital

It is straightforward to show that the system of equations that determines the dynamics in the economy without schooling sector and without imitation technology consists of Euler conditions (33) and (34), and motion equations (35) and (36), subject to $f(S) = 0$, the population constraint $u_{Yt} = 1 - u_{At}$, $G_{A^*t} = G_{A,ss}$, and equations (32) and (37).

A.2 Methodology

What follows is a brief explanation of the methodology used in analyzing transitional dynamics. Because there is no analytical solution to our system of Euler and motion equations, we resort to numerical approximation techniques. In our analysis we follow Judd (1992) to solve the dynamic equation system, approximating the policy functions employing high-degree polynomials in the state variables.

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 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, in the one-sector growth model, Judd (1992) finds that the approximated values of the control variables disagree with

Table 3: Accuracy measures in different models

Country	*Model**	ψ	Average Error (%) C	Average Error (%) u_H	Average Error (%) u_A	Max. Error (%) C	Max. Error (%) u_H	Max. Error (%) u_A
Japan	*model w/ H*	0.131	0.01	0.02	0.01	0.04	0.07	0.04
Japan	*model w/ h*	0.132	0.01	0.02	0.01	0.04	0.07	0.04
Japan	*model w/o H*	0.10	0.00	−.−	0.00	0.01	−.−	0.02
S. Korea	*model w/ H*	0.162	0.06	0.17	0.06	0.27	0.78	0.24
S. Korea	*model w/ h*	0.14	0.06	0.17	0.06	0.27	0.73	0.23
S. Korea	*model w/o H*	0.074	0.01	−.−	0.01	0.02	−.−	0.05

**model w/ H* refers to the per worker three-sector non-scale growth model with schooling sector. *model w/o H* refers to the two-sector non-scale growth model without schooling sector. *model w/ h* refers to the three-sector growth non-scale model assuming that variables are obtained by dividing by L.

the values delivered by the true policy functions by no more than one part in 10,000. All programs were written in GAUSS and are available by the authors upon request.

For the cases considered in this paper, Table 3 gives accuracy measures. In particular, we assess the Euler equation residuals over 10,000 state-space points using the approximated rules. For each variable, the measures give the average and maximum current-value decision error that agents using the approximated rules make, assuming that the (true) optimal decisions were made in the previous period. Santos (2000) shows that the residuals are of the same order of magnitude as the policy function approximation error.

B Data Appendix

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

- *Income (GDP), and investment rates* [Source: PWT 5.6]

Cross-country real GDP per worker (chain index), real GDP per capita (chain index), and real investment shares are taken from the Penn World Tables, Version 5.6 (PWT 5.6) as described in Summer and Heston (1991). All of the series are expressed in 1985 international prices. 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 series. Worker for this variable is usually a census definition based on economically active population.

- *Physical capital stocks* [Source: STARS (World Bank), and PWT 5.6]

Physical capital comes from PWT 5.6. However, this data set reports physical capital starting in 1965. To obtain stocks from 1963 for S. Korea, and from 1960 for Japan, we used the growth rates implied by the STARS physical capital data to deflate the 1965 PWT 5.6 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).

- *Interest rates* [Source: Christiano (1989)]

Real rates of return on physical capital for Japan are approximated using inflation-adjusted returns in the Japanese stock market. More specifically, Christiano (1989) adjusts nominal returns using the price deflator for personal consumption expenditure from the last quarter of the previous year to the last quarter of the current year, from data contained in *Annual Report on National Accounts*, and *Report on National Accounts from 1955 to 1969*. Both data sets were published in 1989 by the Economic Planning Agency in Japan.

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