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New Technology, Human Capital and Growth for Developing Country

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Abstract

We consider a developing country with three sectors in economy: consumption goods, new technology, and education. Productivity of the consumption goods sector depends on new technology and skilled labor used for production of the new technology. We show that there might be three stages of economic growth. In the first stage the country concentrates on production of consumption goods; in the second stage it requires the country to import both physical capital to produce consumption goods and new technology capital to produce new technology; and finally the last stage is one where the country needs to import new technology capital and invest in the training and education of high skilled labor in the same time.

Keywords: Optimal growth model, New technology capital, Human Capital, Developing country.
JEL Classification: D51,D90, E13

1 Introduction

Technology and adoption of technology have been important subjects of research in the literature of economic growth in recent years. Sources of technical

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progress might be domestic or/and international though there always exists believes amongst economic professionals that there is an important difference between developed and developing countries, i.e. the first one innovates and exports technology while the second one imports and copies[1]. For developing countries, the adoption of technology from international market is vital since it might be the only way for them to improve their productivity growth and technical progress (Romer (1997, 1990)). But it is even more important to stress that these countries also need to care about their human capital (Lucas (1988)) which might be the key factor that determines whether a country, given their level of development, can take off or might fall into poverty trap.

This line of argument comes from the fact that the developing countries today are facing a dilemma of whether to invest in physical, technological, and human capital. As abundantly showed in literature (e.g. Barro (1997), Barro & Sala-i-Martin (2004), Eaton & Kortum (2000), Keller (2001), Kumar (2003), Kim & Lau (1994), Lau & Park (2003)) developing countries are not convergent in their growth paths and in order to move closer to the world income level, a country needs to have a certain level in capital accumulation.

Galor and Moav (2004) consider the optimisation of investment in physical capital and human capital on the view of suppliers (of capital). They assumed that technology of human capital production is not extremly good so that at initial stage of develoment when the physical capital is rare, rate of return to physical capital is higher than the return to human capital. Accordingly, at initial stage of development it is not optimal to invest in human capital but in physical capital. The accumulating physical capital progressively reduces rate of return to physical capital whereas increases rate of return to human capital. Consequently, there is some point in time investment into human capital becomes justified, then human capital accumulation gradually replaces physical

[1] See among others: Baumol (1986), Dowrick and Nguyen (1989), Gomulka (1991), Young (1995), Lall (2000), Lau & Park (2003)), Barro and Sala-i-Martin (2004).

capital accumulation as the main engine of growth.

Other than Galor and Moav (2004) we consider the optimal investments in human capital and physical capital on the demand (of capital) side. Furthermore, in Galor and Moav (2004) the source of growth is intergenerational transfer which has a threshold with respect to investment. In Bruno *et al.* (2008) and in this paper the source of growth is the ability of TFP generation which also has a threshold with respect to new technology input.

In their recent work, Bruno *et al.* (2008) point out the conditions under which a developing country can optimally decide to either concentrate their whole resources on physical capital accumulation or spend a portion of their national wealth to import technological capital. These conditions are related to the nation's stage of development which consists of level of wealth and endowment of human capital and thresholds at which the nation might switch to another stage of development. However, in their model, the role of education that contributes to accumulation of human capital and efficient use of technological capital is not fully explored[2].

In this paper we extend their model by introducing an educational sector with which the developing country would invest to train more skilled labors. We show that the country once reaches a critical value of wealth will have to consider the investment in new technology. At this point, the country can either go on with its existing production technology or improve it by investing in new technology capital in order to produce new technology. As soon as the level of wealth passes this value it is always optimal for the country to use new technology which requires high skilled workers. We show further that with possibility of investment in human capital and given "good" conditions on the qualities of the new technology, production process, and/or the number of skilled workers there exists alternatives for the country either to invest in new technology and

[2] Verspagen (1991) testifies the factors that affect an economy's ability to assimilate knowledge spill-overs in the development process and empirically shows that the education of the labor force is the most prominent one. (See also Baumol et al., 1989, on this matter)

spend money in training high skilled labor or only invest in new technology but not to spend on formation of human capital. Following this direction, we can determine the level of wealth at which the decision to invest in training and education has to be made. In this context, we can show that the critical value of wealth is inversely related to productivity of the new technology sector, number of skilled workers, and spill-over effectiveness of the new technology sector on the consumption goods sector but proportionally related to price of the new technology capital. In the whole, the paper allows us to determine the optimal share of the country's investment in physical capital, new technology capital and human capital formation in the long-run growth path. It is also noteworthy to stress that despite of different approach, our result on the replacement of physical capital accumulation by human capital accumulation in develoment process consist with those of Galor and Moav (2004).

Two main results can be pointed out: (1) the richer a country is, the more money will be invested in new technology and training and education, (2) and more interestingly, the share of investment in human capital will increase with the wealth while the one for physical and new technology capitals will decrease. In any case, the economy will grow without bound. Another point which makes our paper different from Bruno *et al.* (2008): we will test the main conclusions of our model with empirical data.

The paper is organized as follows. Section 2 is for the presentation of the one period model and its results. Section 3 deals with the dynamic properties in a model with an infinitely lived representative consumer. Section 4 will look at some empirical evidences in some developing and emerging countries, particularly China, Korea and Taiwan. The conclusion is in Section 5. Appendices are in Sections 6, 7, 8. They are for the mathematical proofs, and for the tables on Inputs and Technical Progress in Lau and Park (2003).

2 The Model

Consider an economy where exists three sectors: domestic sector which produces an aggregate good Y_d, new technology sector with output Y_e and education sector characterized by a function $h(T)$ where T is the expenditure on training and education. The output Y_e is used by domestic sector to increase its total productivity. The production functions of two sectors are Cobb-Douglas, i.e., $Y_d = \Phi(Y_e)K_d^{\alpha_d}L_d^{1-\alpha_d}$ and $Y_e = A_e K_e^{\alpha_e}L_e^{1-\alpha_e}$ where $\Phi(.)$ is a non decreasing function which satisfies $\Phi(0) = x_0 > 0$, K_d, K_e, L_d, L_e and A_e be the physical capital, the technological capital, the low-skilled labor, the high-skilled labor and the total productivity, respectively, $0 < \alpha_d < 1, 0 < \alpha_e < 1$.[3]

We assume that price of capital goods is numeraire in term of consumption goods. The price of the new technology sector is higher and equal to λ such that $\lambda \geq 1$. Assume that labor mobility between sectors is impossible and wages are exogenous.

Let S be available amount of money for spending on capital goods and human capital. We have:

$$K_d + \lambda K_e + p_T T = S.$$

For simplicity, we assume $p_T = 1$, or in other words T is measured in capital goods.

Thus, the budget constraint of the economy can be written as follows

$$K_d + \lambda K_e + T = S$$

where S be the value of wealth of the country in terms of consumption goods.

The social planner maximizes the following program

[3] This specification implies that productivity growth is largely orthogonal to the physical capital accumulation. This implication is confirmed by facts examined by Collins, Bosworth and Rodrik (1996), Lau and Park (2003)

$$\max\ Y_d = \text{Max}\ \Phi(Y_e) K_d^{\alpha_d} L_d^{1-\alpha_d}$$

subject to

$$Y_e = A_e K_e^{\alpha_e} L_e^{1-\alpha_e},$$

$$K_d + \lambda K_e + T = S,$$

$$0 \leq L_e \leq L_e^* h(T),$$

$$0 \leq L_d \leq L_d^*.$$

Where h is the human capital production technology; L_e^* is number of skilled workers in new technology sector; L_e is effective labor; L_d^* is number of non-skilled workers in domestic sector.

Assume that $h(.)$ is an increasing concave function and $h(0) = h_0 > 0$ or Y_d is a concave function of education investment[4]. Let

$$\Delta = \{(\theta, \mu) : \theta \in [0, 1], \mu \in [0, 1], \theta + \mu \leq 1\}.$$

From the budget constraint, we can define $(\theta, \mu) \in \Delta$:

$$\lambda K_e = \theta S\ , K_d = (1 - \theta - \mu) S \text{ and } \ T = \mu S.$$

Observe that since the objective function is strictly increasing, at the optimum, the constraints will be binding. Let $L_e = L_e^* h$, $L_d = L_d^*$, then we have the following problem

$$\underset{(\theta,\mu)\in\Delta}{\text{Max}}\ \Phi(r_e \theta^{\alpha_e} S^{\alpha_e} h(\mu S)^{1-\alpha_e})(1 - \theta - \mu)^{\alpha_d} S^{\alpha_d} L_d^{*1-\alpha_d}.$$

[4] This assumption captures the fact that marginal returns to education is diminishing (see Psacharopoulos, 1994)

where $r_e = \frac{A_e}{\lambda^{\alpha_e}} L_e^{*1-\alpha_e}$.

Let

$$\psi(r_e, \theta, \mu, S) = \Phi(r_e \theta^{\alpha_e} S^{\alpha_e} h(\mu S)^{1-\alpha_e})(1-\theta-\mu)^{\alpha_d} L_d^{*1-\alpha_d}.$$

The problem now is equivalent to

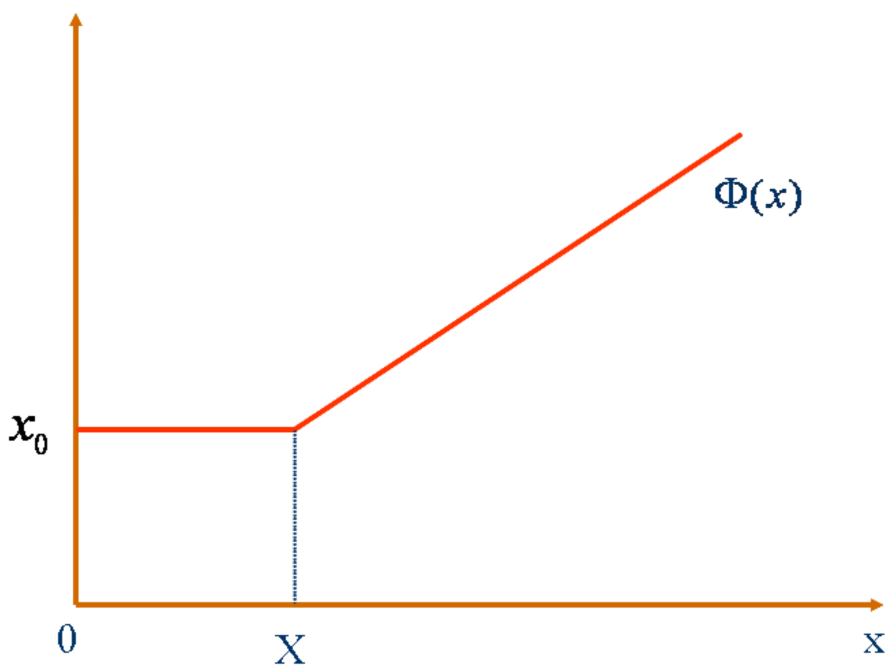
$$\underset{(\theta,\mu)\in\Delta}{\text{Max}}\, \psi(r_e, \theta, \mu, S). \tag{P}$$

Since the function ψ is continuous in θ and μ, there will exist optimal solutions. Denote

$$F(r_e, S) = \underset{(\theta,\mu)\in\Delta}{\text{Max}}\, \psi(r_e, \theta, \mu, S).$$

Suppose that function $\Phi(x)$ is a constant in an initial phase and increasing linear afterwards:

$$\Phi(x) = \begin{cases} x_0 \text{ if } x \leq X \\ x_0 + a(x - X) \text{ if } x \geq X, a > 0. \end{cases}$$



Then by Maximum Theorem, F is continuous and $F(r_e, S) \geq x_0 L_d^{*1-\alpha_d}$. The following proposition states that there exists a threshold.

Proposition 1 *There exists S^c such that, if $S < S^c$ then $\theta(S) = 0$ and $\mu(S) = 0$, and if $S > S^c$ then $\theta(S) > 0$.*

Proof: See appendix 1. ■

Remark 1 *If $S > S^c$ then $Y_e > X$ and $\Phi(Y_e) = x_0 + a(Y_e - X)$*

The following proposition shows that, when the quality of the training technology (measured by the marginal productivity at the origin $h'(0)$) is very high then for any $S > S^c$ the country will invest both in new technology and in human capital. When $h'(0)$ is finite, we are not ensured that the country will invest in human capital when $S > S^c$. But it will do if it is sufficiently rich. Moreover, if $h'(0)$ is low, then the country will not invest in human capital when S belongs to some interval $(S^c, \ S^m)$.

Proposition 2 *1. If $h'(0) = +\infty$, then for all $S > S^c$, we have $\theta(S) > 0, \mu(S) > 0$.*

2. Assume $h^{'}(0) < +\infty$. Then there exists S^M such that $\mu(S) > 0, \theta(S) > 0$ for every $S > S^M$.

3. There exists $\alpha > 0$ such that, if $h'(0) < \alpha$, then there exists $S^m > S^c$ such that $\mu(S) = 0, \theta(S) > 0$ for $S \in [S^c, S^m]$.

Proof: See Appendix 1. ■

The following proposition states there exists a threshold for both $\theta(S)$ and $\mu(S)$ to be positive.

Proposition 3 *Assume $h'(0) < +\infty$. Then there exists $\widehat{S} \geq S^c$ such that:*

(i) $S \leq \widehat{S} \Rightarrow \mu(S) = 0$,

(ii) $S > \widehat{S} \Rightarrow \mu(S) > 0, \ \theta > 0$.

Proof: See Appendix 1. ■

Let us recall $r_e = \frac{A_e L_e^{*(1-\alpha_e)}}{\lambda^{\alpha_e}} = A_e L_e^*(L_e^*\lambda)^{-\alpha_e}$ where A_e is the productivity of the new technology sector, λ is the price of the new technology capital, α_e is capital share in new technology production sector, and L_e^* is number of skilled workers.

Recall also the productivity function of the consumption goods sector $\Phi(x) = x_0 + a(x - X)$ if $x \geq X$. The parameter $a > 0$, a spill-over indicator which embodies the level of social capital and institutional capital in the economy, indicates the effectiveness of the new technology product x on the productivity. We will show in the following proposition that the critical value S^c diminishes when r_e increases, i.e. when the productivity A_e, and/or the number of skilled workers increase; and /or the price of the new technology capital λ decreases; and/or the share of capital in new technology sector α_e decreases (more human-capital intensive); and /or the spill-over indicator a increases. Put it differently, the following conditions will be favorable for initiating investment in to new technology sector: (i) potential productivity in new technology sector; (ii) number of skilled workers in the economy; (iii) price of new technology; (iv) the intensiveness of human capital in new technology sector; and (v) level of spill-over effects. Except for price of new technology, if all or one of the above-mentioned conditions are/is improved, the economy will be more quickly to initiate investment in new technology sector.

Proposition 4 *Let $\theta^c = \theta(S^c)$, $\mu^c = \mu(S^c)$. Then*

(i) $\mu^c = 0$, θ^c does not depend on r_e.

(ii) S^c decreases if a or/and r_e increases.

Proof: See Appendix 1. ■

The following proposition shows that the optimal shares θ, μ converge when S goes to infinity. Furthermore the ratios of spendings on human capital to

S and of the total of spendings on new technology capital and human capital formation to S increase when S increases.

Proposition 5 *Assume $h(z) = h_0 + bz$, with $b > 0$. Then the optimal shares $\theta(S), \mu(S)$ converge to $\theta_\infty, \mu_\infty$ when S converges to $+\infty$. Consider $\widehat{S}$ in Proposition 3. Then*

(i) Assume $x_0 < aX$. If ar_e is large enough, then $\mu(S)$ and the sum $\theta(S) + \mu(S)$ increase when S increases.

(ii) If $x_0 \geq aX$, then $\mu(S)$ and the sum $\theta(S) + \mu(S)$ increase when S increases.

Proof: For short, write θ, μ instead of $\theta(S), \mu(S)$. Consider $\widehat{S}$ in Proposition 3. When $S \leq \widehat{S}$,then $\mu = 0$ (Proposition 3).

When $S > \widehat{S}$. Then (θ, μ) satisfy equations (10) and (11) which can be written as follows:

$$\theta(\alpha_d + \alpha_e) = -\alpha_e\mu + [\alpha_e - \frac{\alpha_d(x_0 - aX){\alpha_e}^{-\alpha_e}}{ar_eS(1-\alpha_e)^{1-\alpha_e}b^{1-\alpha_e}}] \tag{1}$$

and

$$\theta(1-\alpha_e) = \alpha_e\mu + \frac{\alpha_e h_0}{bS} \tag{2}$$

We obtain

$$\theta(1+\alpha_d) = [\alpha_e - \frac{\alpha_d(x_0 - aX){\alpha_e}^{-\alpha_e}}{ar_eS(1-\alpha_e)^{1-\alpha_e}b^{1-\alpha_e}} + \frac{h_0\alpha_e}{bS}] \tag{3}$$

and

$$\mu = \theta(\frac{1}{\alpha_e} - 1) - \frac{h_0}{bS}$$

Thus

$$\theta + \mu = \frac{1}{1+\alpha_d}[1 - \frac{\alpha_d}{\alpha_e}\frac{(x_0 - aX){\alpha_e}^{-\alpha_e}}{ar_eS(1-\alpha_e)^{1-\alpha_e}b^{1-\alpha_e}}] - \frac{\alpha_d}{1+\alpha_d}\frac{h_0}{bS}.$$

Tedious computations give

$$\frac{\mu}{1-\alpha_e} = \frac{1}{1+\alpha_d}[1 - \frac{\alpha_d}{\alpha_e}\frac{(x_0 - aX)\alpha_e{}^{-\alpha_e}}{ar_e S(1-\alpha_e)^{1-\alpha_e} b^{1-\alpha_e}}] - [\frac{\alpha_d}{1+\alpha_d} + \frac{\alpha_e}{1-\alpha_e}]\frac{h_0}{bS}$$

If $x_0 \geq aX$, then $\theta + \mu$ and μ increase with S. If $x_0 < aX$, then when ar_e is large enough, then $\theta + \mu$ and μ are increasing functions in S.

When S converges to $+\infty$, then θ converges to $\theta_\infty = \frac{\alpha_e}{1+\alpha_d}$ and μ converges to $\mu_\infty = \frac{1-\alpha_e}{1+\alpha_d}$. ■

3 The Dynamic Model

In this section, we consider an economy with one infinitely lived representative consumer who has an intertemporal utility function with discount factor $\beta < 1$. At each period, her savings will be used to invest in physical capital or/and new technology capital and/or to invest in human capital. We suppose the capital depreciation rate equals 1 and growth rate of population is 0 and $L^*_{e,t} = L^*_e; L^*_{d,t} = L^*_d$.

The social planner will solve the following dynamic growth model

$$\begin{aligned}
\max \quad & \sum_{t=0}^{\infty} \beta^t u(c_t) \\
\text{s.t} \quad & c_t + S_{t+1} \leq \Phi(Y_{e,t}) K_{d,t}^{\alpha_d} L_{d,t}^{1-\alpha_d} \\
& Y_{e,t} = A_e K_{e,t}^{\alpha_e} L_{e,t}^{1-\alpha_e} \\
& K_{d,t} + \lambda K_{e,t} + T_t = S_t, \\
& 0 \leq L_{e,t} \leq L^*_e h(T_t), 0 \leq L_{d,t} \leq L^*_d. \\
& \text{ the initial resource } S_0 \text{ is given.}
\end{aligned}$$

The problem is equivalent to

$$\begin{aligned}\max \quad & \sum_{t=0}^{\infty} \beta^t u(c_t)\\ \text{s.t} \quad & c_t + S_{t+1} \leq H(r_e, S_t), \forall t,\end{aligned}$$

with

$$H(r_e, S) = F(r_e, S) S^{\alpha_d}.$$

where $r_e = \frac{A_e}{\lambda^{\alpha_e}} L_e^{*1-\alpha_e}$, β is time preference discount rate $0 \leq \beta \leq 1$ Obviously, $H(r_e, .)$ is continuous, strictly increasing and $H(r_e, 0) = 0$.

As in the previous section, we shall use S^c defined as follows:

$$S^c = \max\{S \geq 0 : F(r_e, S) = x_0 L_d^{*1-\alpha_d}\}$$

where

$$F(r_e, S_t) = \underset{0 \leq \theta_t \leq 1, 0 \leq \mu_t \leq 1}{\text{Max}} \psi(r_e, \theta_t, \mu_t, S_t).$$

We shall make standard assumptions on the function u under consideration.

H2. The utility function u is strictly concave, strictly increasing and satisfies the Inada condition: $u^{'}(0) = +\infty, u(0) = 0, u'(\infty) = 0$.

At the optimum, the constraints will be binding, the initial program is equivalent to the following problem

$$\begin{aligned}& \max \sum_{t=0}^{\infty} \beta^t u(H(r_e, S_t) - S_{t+1})\\ \text{s.t} \quad & 0 \leq S_{t+1} \leq H(r_e, S_t), \forall t.\\ & S_0 > 0 \text{ given.}\end{aligned}$$

By the same arguments as in Bruno *et al.* (2008), we have the following property

Proposition 6 *i) Every optimal path is monotonic*

ii) Every optimal trajectory (S_t^*) from S_0 can not converge to 0.

Let denote θ_t^*, μ_t^* be the optimal capital shares among technological capital stock and expenditure for human capital,

$$\lambda K_{e,t}^* = {\theta_t}^* S_t^* \text{ and } T_t^* = \mu_t^* S_t^*.$$

We then obtain the main result of this paper:

Proposition 7 *Assume $h(z) = h_0 + bz$, with $b > 0$ and $\alpha_e + \alpha_d \geq 1$. If a or/and r_e are large enough then the optimal path $\{S_t^*\}_{t=1,+\infty}$ converges to $+\infty$ when t goes to infinity. Hence:*

(i) there exists T_1 such that

$$\theta_t^* > 0 \ \forall t \geq T_1$$

(ii) there exists $T_2 \geq T_1$ such that

$$\theta_t^* > 0 \ , \mu_t^* > 0, \ \forall t \geq T_2$$

The sum $\theta_t^* + \mu_t^*$ and the share μ_t^* increase when t goes to infinity and converge to values less than 1.

Proof: See Appendix 2. ■

4 A Look At Evidence

There are numerous discusses in literature on the role of physical capital, human capital and technological progress in economic growth. King and Rebelo (1993) run simulations with neoclassical growth models and conclude that the transitional dynamics (contribution of physical capital accumulation) can only play a minor role in explaining observed growth rates. They suggest endogenous growth models such as human capital formation or endogenous technical progress. Hofman (1993) examines economic performances of Latin American countries, three Asian economies (S. Korea, Taiwan and Thailand), Portugal, Spain and six advanced economies (France, Germany, Japan, The Netherlands, UK and US) in the 20th century. The evidences show that growth in developing economies bases mainly on physical capital accumulation while growth in developed economies motivated essentially by human capital and technological progress. Young (1994), Kim and Lau (1994), Krugman (1994), Collins and Bosworth (1996) and Lau and Park (2003) all attribute the miracle growth in East Asia Economies mostly to physical capital accumulation and find no significant role of technological progress in miracle growth of East Asia Economies, which plays a crucial role in economic growth in Industrial Economies (see Table 2 in Appendix 3). Collins and Bosworth (1996) suggests "it is possible that the potential to adopt knowledge and technological from abroad depends on a country's stage of development. Growth in the early stages may be primarily associated with physical and human capital accumulation, and significant potential for growth through catchup may only emerge once a country has crossed some development thresholds". Lau and Park (2003) on the one hand, shows that the hypothesis of no technological progress in East Asia NIEs until 1986 can not rejected. On the other hand, since 1986 when these economies started investing heavily on R&D, technological progress plays significant role in growths of these economies. This evidence supports our model's prediction that there exists threshold for investing in new technology in process of economic development. Nevertheless, the question of threshold of investment in human capital is rarely raised in literature.

In this section we use pooled time-series aggregate data of educational attainment for 71 non-oil exporting, developing economies compiled by Barro and Lee (2000)[5] and real GDP per capita (y) (in PPP) of these countries in Penn World table 6.2, Heston, *et al.*, (2006) to find the correlation between human

[5]See Table 3 in appendix for list of economies

capital and level of development. In Barro and Lee (2000) we use five variables to measure human capital: percentage of labor force with completed primary school (l_1); with completed secondary school (l_2); with completed higher secondary school (l_3); and average schooling years of labor force (A). Those data are calculated for 5-year span from 1950 (if available) to 2000. Oil exporting countries are excluded from the sample because they enjoy peculiarly high level of GDP per capita regardless of production capacity of non-oil sectors. Some other developing countries whose data of human capital are available for two years also excluded.

We run two simple OLS regression equations

$$\ln y = \alpha + \beta_1 l_1 + \beta_2 l_2 + \beta_3 l_3 \tag{4}$$

and

$$\ln y = \alpha + \gamma_1 A \tag{5}$$

These equations are tested for two sub-samples: the first with GDP per capita is less than 1000 (75 observations); and the second with GDP per capita more than 1000 (533 observations). The results are presented in table 1 below and show that when GDP per capita below 1000 USD (y in PPP and constant price in 2000) all hypotheses of no contribution of human capital to economic growth can not be rejected, while when $y > 1000$ those hypotheses are decisively rejected

Table 1: **Contributions of human capital to economic growth**

	Equation 4		**Equation 5**	
	$y \leq 1000$	$y > 1000$	$y \leq 1000$	$y > 1000$
R^2	4.7%	**46.6%**	2.1%	**54.3%**
$\overline{R^2}$	0.7%	**46.3%**	0.75%	**54.2%**
β_1	−0.015 (0.08)	0.002 (**0.000**)*		
β_2	0.002 (0.88)	0.050 (**0.000**)*		
β_3	0.040 (0.63)	0.042 (**0.000**)*		
γ_1			−0.03 (0.22)	0.25 (**0.000**)*
Obs	75	533	75	533

Note: the numbers in the parentheses are p-values of corresponding coefficients;

* Indicates statistically significant at the level of significance of 0.1%

Furthermore, when $y > 1000$ coefficients of variables: percentage of labor force with completed primary school (l_1), completed secondary school, and completed higher secondary school are all in expected sign and statistically significant at level of significance of 0.1%. The results of regression on equation (5) also solidly confirms the positive contribution of human capital when it is measured by average year of schoolings.

By contrast, when $y \leq 1000$, the values of adjusted R-square in both equations are nearly zero. There is no coefficient is statistically significant at level of siginificance of 5%. These results imply that human capital, by all means, plays no role in economic growth. Put it differntly, they support our model's prediction that when income is lower than a critical level there is no demand for investing in human capital, or equivalently, there exists threshold for investing in human capital in process of development.

In the following we look closely at movement of expenditures on human capital and new technology in three economies, namely China, South Korea and Taiwan. The reasons to choose these economies are: (i) the availability of data; (ii) these economies have experienced high growth rates for long time from very low stage. The purpose of this section is to examine the our third point, that is the share of human capital and expenditure for new technology in total investment (S) in these economies shows the increasing trend in the examined periods and human capital increasingly becomes more important than two others.

Since the data for expenditure on human capital is not directly available, hence we follow Carsey and Sala-i-Martin (1995) to assume that wage paid to a worker consists of two parts: one for human capital and the other (non-skilled wage) for other things other than human capital. According to Carsey and Sala-i-Martin (1995) the latter part of wage depends on many factors such that: ratio of aggregate physical capital stock to human capital due to the complementary between physical capital and human capital; and change in relative supplies of workers. The former part depends not only on number of schooling years but also on others: on-the-job training, job experience, schooling quality, and technological level. Accordingly, this labor-income-based human capital that taking all these factors into account reflects the value of human capital more comprehensively than the conventional measurement that based on schooling years.

We assume further that minimum wage is the non-skilled wage. Consequently the expenditure for human capital can be calculated by following formula:

$$EHC_t = E_t * (AW_t - MW_t)$$

Where EHC is expenditure for human capital, E is total employed workers, AW is average wage, and MW is minimum wage. Recall that $AW - MW$ represents the part in the average wage which is rewarded for skill.

In our model, the new technological capitals are produced in R&D sector, then we use indicator of expenditure for R&D as a proxy for investment in technological capital (λK_e), and the fixed capital formation (if not available, then the gross capital formation) for expenditure on K_d.

Data

For China, the data of AW, GDP, and E are available in CEIC database from 1952 to 2006. The minimum wages in China vary from provinces and within province. Provinces and cities usually have multiple levels of minimum wage standards based upon different geographic locations and industries. The minimum wages for all provinces were only available discretely in period 2004-2006 from the Ministry of Labor and Social Security of China 2005 statistics[6]. Therefore we use average wage in sector of Farming, Forestry, Animal Husbandry & Fishery where use least human capital and physical capital as a proxy of minimum wage. All entries of this variables can be taken from CEIC database. Based on this series of indices we come up with an estimated time-series national minimum wage in China from 1980 to 2006. Since data of fixed capital formation in China are not available, we then use the data of gross capital formation, which are available in WDI database of World Bank. Finally, the statistics for R&D expenditure in period 1980-2006 are available in China statistical yearbook in various issues.

For Taiwan, the data for total compensation for employees ($E * AW$), employment (E), fixed capital formation, GDP, and average wage in manufacturing sector are available in CEIC database in period 1978-2006. The minimum wage rates are only available in period 1993-2006 and in 1984 at US Department of State[7]. For missing data in period 1983-1992 we fill in by estimated ones. For that, we assume that minimum wage (MW) is a concave function of average wage in manufacturing sector (AW_m) or more specifically, the ratio of $\frac{MW}{AW_m}$ is linearly correlated with AW_m. The result of OLS regression strongly confirms

[6] Updates are based upon news reports prior to July 2006. Minimum wages listed as monthly-based

[7] Cited at website: http://dosfan.lib.uic.edu/ERC/economics/commercial_guides/Taiwan.html and http://www.state.gov/g/drl/rls/hrrpt/2006/78770.htm

our hypothesis. Based on coefficients of this OLS regression we come up with the estimations of missing data. The data of R&D expenditure is taken from National Science Council (2007) and Lau and Park (2003).

For South Korea, CEIC database provides data of employment (E), compensations for employees ($E * AW$), fixed capital formation, GDP, and nominal wage index. The minimum wages in period 1988-2006 are taken from GPN (2001) and US State Department website. If we assume that in period 1976-1987 the minium wages proportionally change with nominal wage index, then we have the estimation of expenditure for human capital in the period 1976-1987. The data for R&D expenditure is taken from UNESCO.

Figure 1: Human capital and R&D in total available investment

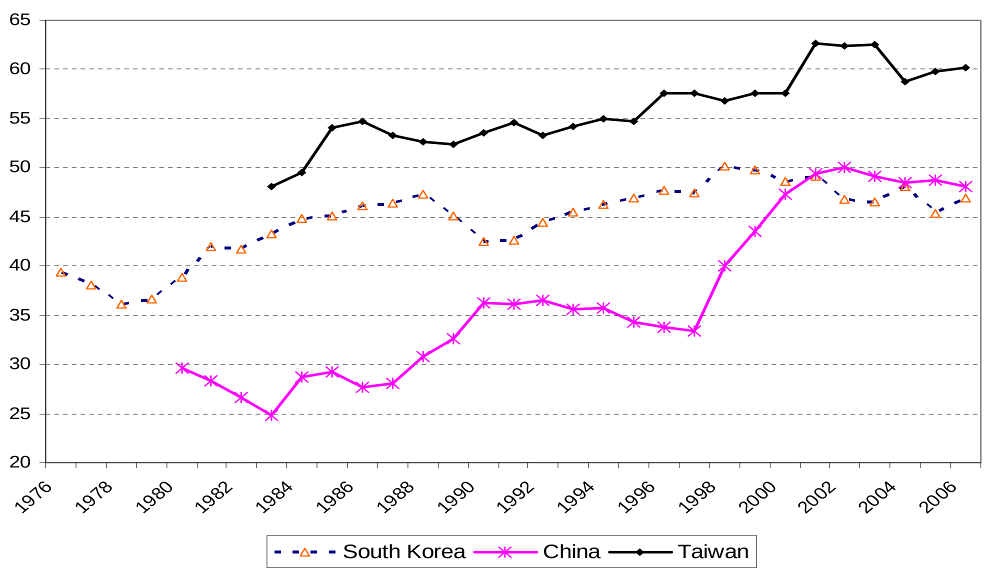


Figure 2: Share of Human Capital in Total available Investment

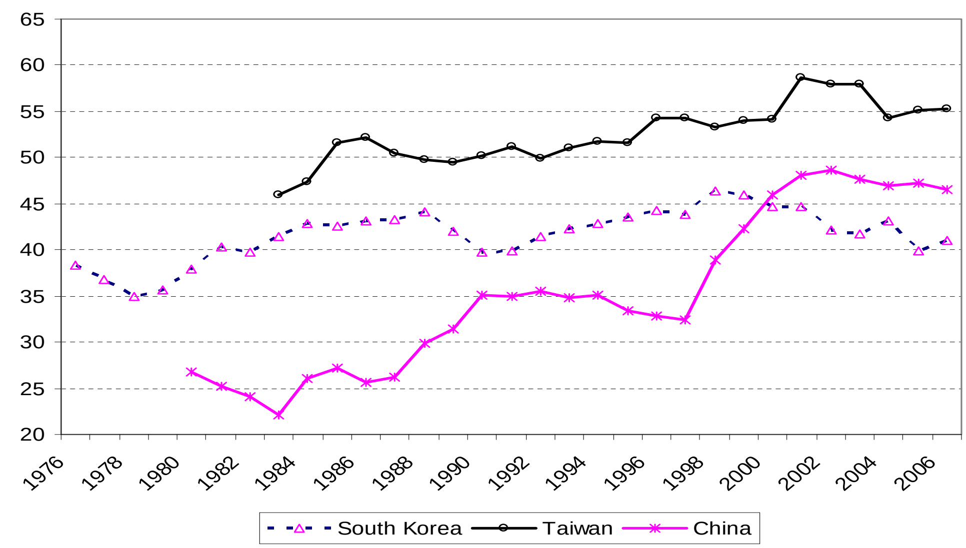
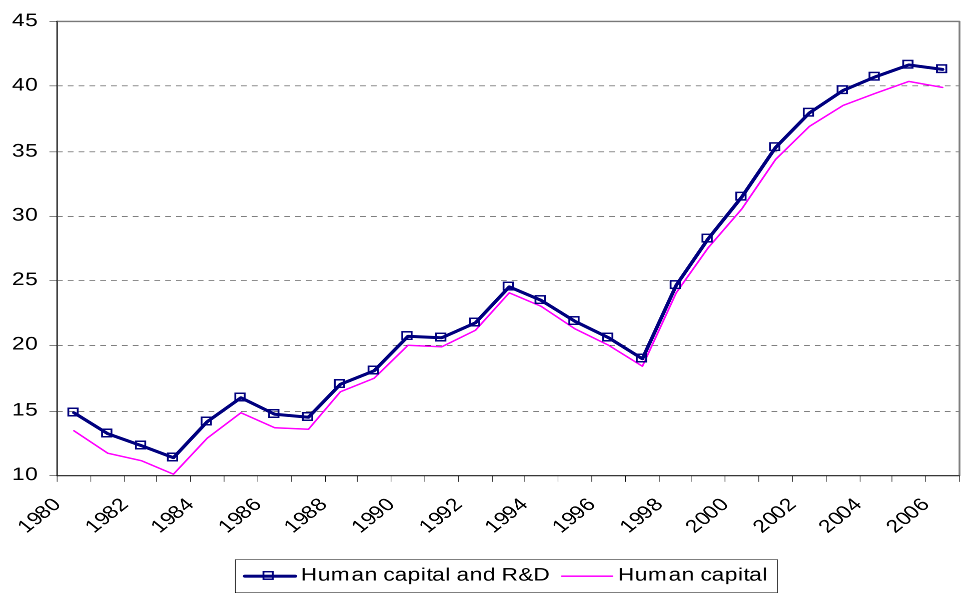


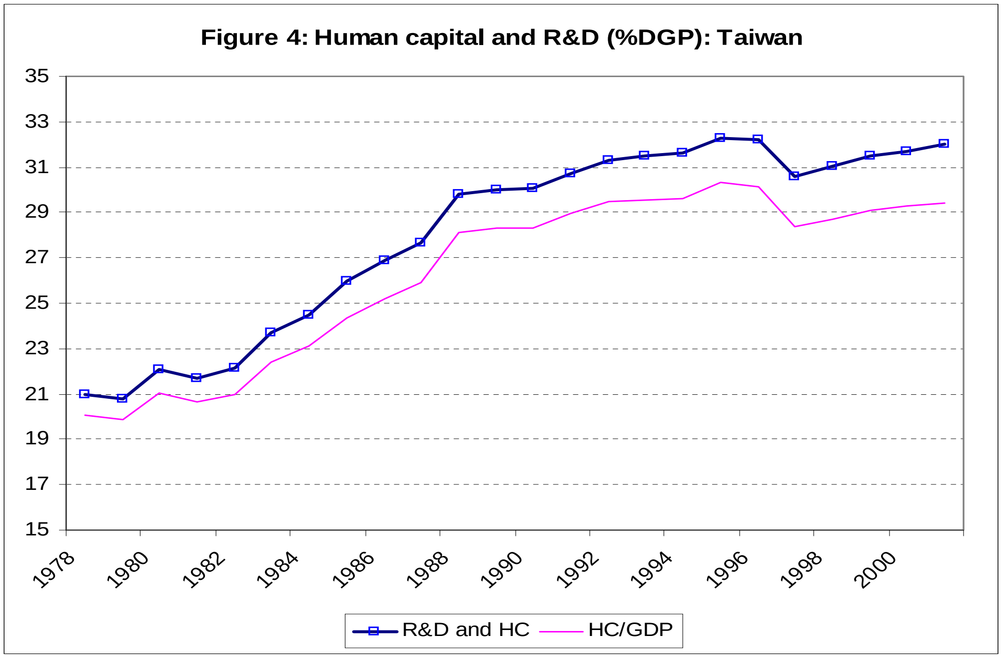
Figure 1 show the steadily increasing trend of shares of human capital and R&D in total available investment in all three economies in the examined periods. The movement of share of human capital in total available investment shown in figure 2 also show steadily increasing trend in Taiwan and China, while in South Korea the trend seems more fluctuant, nevertheless, increasing. Hence our predictions on the movements of the shares of human capital and of new technology on the one hand, and of physical capital on the other hand, cannot be rejected by evidences from these economies.

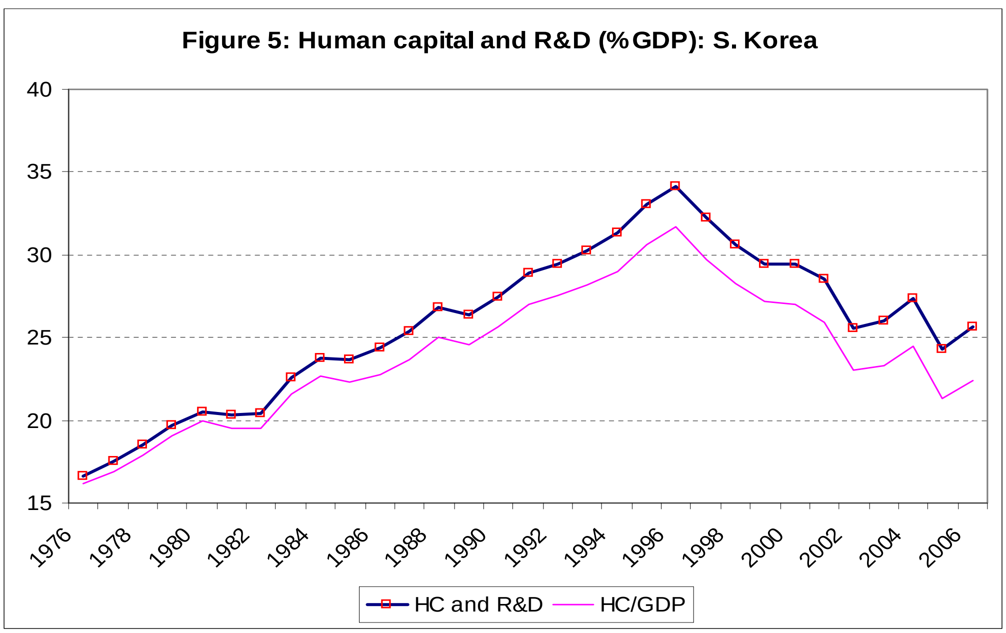
Let's consider the movements on another dimension. Assuming that the budget available (S) for total investment is positively related to GDP in the whole period. Thereby, the movement of ratios of λK_e and expenditure for human capital (T) to GDP are congruent to the movement of ratios of λK_e and T to S.

Figures below (3,4 and 5) all support our model's prediction, $\mu_t + \theta_t$, the sum of the share of human capital and R&D as well as share of human capital in GDP both increase. The figures also show the effects of Asian crisis in 1997 on investment in human capital and R&D these economies. China is the least affected and then quickly recovered the momentum investing activities. S. Korea, the most affected one and had to have recourse to IMF for help. Under pressure of IMF South Korea had to apply severely tightening expenditure policy. Even though South Korea started recovering since 1999 and GDP recovered high growth rate in following years, they remained tightening expenditure policy till early 2000s. That's why the figure 5 shows the declining trend of both variables, shares of human capital and R&D, and of human capital, since 1997.

Figure 3: Human capital and R&D (%GDP): China







5 Conclusion

We first summarize the main conclusions from our model.

1. At low level of economic growth this country would only invest in physical capital but when the economy grows this country would need to invest not only

in physical capital but also in first, new technology and then, formation of high skilled labor.

2. Under some mild conditions on the quality of the new technology production process and on the supply of skilled workers, the shares of the investments, respectively in human capital, and in new technology and human capital, will increase when the country becomes rich.

3. Thanks to New Technology and Human Capital, the TFP will increase and induces a growth process, i.e. the optimal path (S_t^*) converges to $+\infty$. In other words, the country grows without bound. In this case, the share of investment in new technology and human capital $(\theta_t^* + \mu_t^*)$ will increase while the one in physical capital will decrease. More interestingly, and in accordance with the results in Barro and Sala-i-Martin (2004), the share μ_t^* will become more important than the one for physical and new technology capitals when t goes to infinity. But they will converge to strictly positive values when time goes to infinity.

Second, the empirical tests seem confirm the results mentioned above.

1. They support our model's prediction that when income is lower than a critical level there is no demand for investing in human capital, or equivalently, there exists threshold for investing in human capital in process of development.

2. Our predictions on the movements of the shares of human capital and of new technology on the one hand, and of physical capital on the other hand, cannot be rejected by evidences from the economies of China, Korea and Taiwan.

6 Appendix 1

Proof of Proposition 1 The proof will be done in three steps.

Step 1 Define

$$B = \{S \geq 0 : F(r_e, S) = x_0 L_d^{*1-\alpha_d}\},$$

Lemma 1 *B is a nonempty compact set.*

Proof: It is easy, see e.g. Bruno *et al* (2008). ■

Remark 2 *Observe that $F(r_e, S) \geq x_0 L_d^{*1-\alpha_d}$. If the optimal value for θ equals 0 then the one for μ is also 0 and $F(r_e, S) = x_0 L_d^{*1-\alpha_d}$.*

Step 2 The following lemma shows that if S is small, then the country will not invest in new technology and human capital. When S is large, then it will invest in new technology.

Lemma 2 *i) There exists $\underline{S} > 0$ such that if $S \leq \underline{S}$ then $\theta = 0$ and $\mu = 0$.*

ii) There exists $\overline{S}$ such that if $S > \overline{S}$ then $\theta > 0$.

Proof: For any S, denote by $\theta(S)$, $\mu(S)$ the corresponding optimal values for θ and μ.

(i) Let $\underline{S}$ satisfies

$$r_e \underline{S}^{\alpha_e} h(\underline{S})^{1-\alpha_e} = X,$$

Then for any $(\theta, \mu) \in \Delta$, for any $S \leq \underline{S}$,

$$r_e \theta^{\alpha_e} S^{\alpha_e} h(\mu S)^{1-\alpha_e} \leq X$$

and $(\theta(S), \mu(S)) = (0, 0)$.

(ii) Fix $\mu = 0$ and $\theta \in (0,1)$. Then $\psi(r_e, \theta, 0, S) \to +\infty$ when $S \to +\infty$. Let $\overline{S}$ satisfy $\psi(r_e, \theta, 0, \overline{S}) > x_0 L_d^{*1-\alpha_d}$. Obviously, $F(r_e, \overline{S}) \geq \psi(r_e, \theta, 0, \overline{S}) > x_0 L_d^{*1-\alpha_d}$, and $\theta(\overline{S}) > 0$. If not, then $\mu(\overline{S}) = 0$ and $F(r_e, \overline{S}) = x_0 L_d^{*1-\alpha_d}$ (see Remark 2). ■

Step 3 : Proof of Proposition 1

Now, let us define

$$S^c = \max\{S \geq 0 : S \in B\}.$$

It is obvious that $0 < S^c < +\infty$, since $S^c \geq \underline{S} > 0$ and B is compact.

Note that for any $S \geq 0$ we have

$$F(r_e, S) \geq x_0 L_d^{*1-\alpha_d}.$$

If $S < S^c$ then for any $(\theta, \mu) \in \Delta$,

$$\psi(r_e, \theta, \mu, S) \leq \psi(r_e, \theta, \mu, S^c)$$

which implies

$$F(r_e, S) \leq F(r_e, S^c) = x_0 L_d^{*1-\alpha_d}.$$

Thus,

$$F(r_e, S) = x_0 L_d^{*1-\alpha_d}.$$

Let $S_0 < S^c$. Assume there exists two optimal values for (θ, μ) which are $(0, 0)$ and (θ_0, μ_0) with $\theta_0 > 0$. We have $F(r_e, S_0) = x_0 L_d^{*1-\alpha_d} = \psi(r_e, \theta_0, \mu_0, S_0)$. We must have $r_e \theta_0^{\alpha_e} S_0^{\alpha_e} h(\mu_0 S_0)^{1-\alpha_e} > X$ (if not, $\Phi(r_e, \theta_0, \mu_0, S_0) = x_0$ and $\theta_0 = 0, \mu_0 = 0$.)

Since $\theta_0 > 0$, we have $r_e \theta_0^{\alpha_e} (S^c)^{\alpha_e} h(\mu_0 S_0)^{1-\alpha_e} > r_e \theta_0^{\alpha_e} S_0^{\alpha_e} h(\mu_0 S_0)^{1-\alpha_e} > X$. Hence

$$\begin{aligned} x_0 L_d^{*1-\alpha_d} = F(r_e, S^c) &\geq \psi(r_e, \theta_0, \mu_0, S^c) \\ &> \psi(r_e, \theta_0, \mu_0, S_0) = x_0 L_d^{*1-\alpha_d} \end{aligned}$$

which is a contradiction.

Therefore, if $S > S^c$ then

$$F(r_e, S) > x_0 L_d^{*1-\alpha_d}$$

which implies $\theta(S) > 0$.

Proof of Proposition 2

1. Take $S > S^c$. From the previous proposition, $\theta(S) > 0$. Assume $\mu(S) = 0$. For short, denote $\theta^* = \theta(S)$. Define

$$F^0(r_e, S, \theta^*, 0) = \underset{0\leq\theta\leq 1}{\text{Max}}\, \psi(r_e, \theta, 0, S) = \Phi(r_e \theta^{*\alpha_e} S^{\alpha_e} h(0)^{1-\alpha_e})(1-\theta^*)^{\alpha_d} L_d^{*1-\alpha_d}.$$

and consider a feasible couple (θ, μ) in Δ which satisfies $\theta^* = \theta + \mu$. Denote

$$F^1(r_e, S, \theta, \mu) = \Phi(r_e \theta^{\alpha_e} S^{\alpha_e} h(\mu S)^{1-\alpha_e})(1-\theta^*)^{\alpha_d} L_d^{*1-\alpha_d}.$$

We then have

$$\begin{aligned} &\frac{F^1(r_e, S, \theta, \mu) - F^0(r_e, S, \theta^*, 0)}{(1-\theta^*)^{\alpha_d} L_d^{*1-\alpha_d}} = \\ &\Phi(r_e \theta^{\alpha_e} S^{\alpha_e} h(\mu S)^{1-\alpha_e}) - \Phi(r_e \theta^{*\alpha_e} S^{\alpha_e} h(0)^{1-\alpha_e}) \\ = \ & r_e S^{\alpha_e} [\theta^{\alpha_e} h(\mu S)^{1-\alpha_e} - \theta^{*\alpha_e} h(\mu S)^{1-\alpha_e} + \theta^{*\alpha_e} h(\mu S)^{1-\alpha_e} - \theta^{*\alpha_e} h(0)^{1-\alpha_e}]. \end{aligned}$$

By the concavity of $h(x)$ and $f(x) = x^{\alpha_e}$, we obtain

$$\begin{aligned} &F^1(r_e, S, \theta, \mu) - F^0(r_e, S, \theta^*, 0) \geq \\ &r_e S^{\alpha_e} \mu h(\mu S)^{-\alpha_e} [-\alpha_e h(\mu S)(\theta^* - \mu)^{\alpha_e - 1} + S(1-\alpha_e)\theta^{*\alpha_e} h'(\mu S)]. \end{aligned}$$

Let $\mu \to 0$. We have $h'(\mu S) \to +\infty$. The expression in the brackets will converge to $+\infty$, and we get a contradiction with the optimality of θ^*.

2. Assume that $\mu(S) = 0$ for any $S \in \{S^1, S^2, ..., S^n, ...\}$ where the infinite sequence $\{S^n\}_n$ is increasing, converges to $+\infty$ and satisfies $S^1 > S^c$. For short, denote $\theta = \theta(S)$. Then we have the following F.O.C.:

$$\frac{a r_e \theta^{\alpha_e - 1} S^{\alpha_e} h(0)^{1-\alpha_e} \alpha_e}{x_0 + a[r_e \theta^{\alpha_e} S^{\alpha_e} h(0)^{1-\alpha_e} - X]} = \frac{\alpha_d}{1-\theta}, \tag{6}$$

and

$$\frac{ar_e\theta^{\alpha_e}S^{\alpha_e+1}h'(0)h(0)^{-\alpha_e}(1-\alpha_e)}{x_0+a[r_e\theta^{\alpha_e}S^{\alpha_e}h(0)^{1-\alpha_e}-X]} \leq \frac{\alpha_d}{1-\theta}. \tag{7}$$

Equation (6) implies

$$\frac{ar_e\theta^{\alpha_e-1}h(0)^{1-\alpha_e}\alpha_e}{\frac{x_0}{S^{\alpha_e}}+a[r_e\theta^{\alpha_e}h(0)^{1-\alpha_e}]} \leq \frac{\alpha_d}{1-\theta}. \tag{8}$$

If $\theta \to 0$ when $S \to +\infty$, then the LHS of inequality (8) converges to infinity while the RHS converges to α_d: a contradiction. Thus θ will be bounded away from 0 when S goes to infinity.

Combining equality (6) and inequality (7) we get

$$h'(0)(1-\alpha_e)S \leq h_0\alpha_e\theta^{-1}. \tag{9}$$

When $S \to +\infty$, we have a contradiction since the LHS of (9) will go to infinity while the RHS will be bounded from above. That means there exists S_M such that for any $S \geq S_M$, we have $\mu(S) > 0$.

3. Let $S > S^c$. For short, we denote μ and θ instead of $\mu(S)$ and $\theta(S)$. If $\mu > 0$ then we have the F.O.C:

$$\frac{ar_e\theta^{\alpha_e-1}S^{\alpha_e}h(\mu S)^{1-\alpha_e}\alpha_e}{x_0+a[r_e\theta^{\alpha_e}S^{\alpha_e}h(\mu S)^{1-\alpha_e}-X]} = \frac{\alpha_d}{1-\theta-\mu}, \tag{10}$$

and

$$\frac{ar_e\theta^{\alpha_e}S^{\alpha_e+1}h'(\mu S)h(\mu S)^{-\alpha_e}(1-\alpha_e)}{x_0+a[r_e\theta^{\alpha_e}S^{\alpha_e}h(\mu S)^{1-\alpha_e}-X]} = \frac{\alpha_d}{1-\theta-\mu}. \tag{11}$$

Let θ^c and S^c satisfy the following equations

$$\frac{ar_e(\theta^c)^{\alpha_e-1}(S^c)^{\alpha_e}h(0)^{1-\alpha_e}\alpha_e}{x_0+a[r_e(\theta^c)^{\alpha_e}(S^c)^{\alpha_e}h(0)^{1-\alpha_e}-X]} = \frac{\alpha_d}{1-\theta^c}, \tag{12}$$

and

$$(x_0+a[r_e(\theta^c)^{\alpha_e}(S^c)^{\alpha_e}h(0)^{1-\alpha_e}-X])(1-\theta^c)^{\alpha_d} = x_0. \tag{13}$$

Equality (12) is the F.O.C. with respect to θ, while equality (13) states that $\psi(r_e, \theta^c, 0, S^c) = x_0 L_d^{*1-\alpha_d}$. If $h'(0) < \alpha = h(0)\frac{1}{\theta^c S^c}\frac{\alpha_e}{1-\alpha_e}$, $\theta^c > 0$ as defined in Bruno *et al.* (2008), then we get

$$\frac{ar_e(\theta^c)^{\alpha_e}(S^c)^{\alpha_e+1}h'(0)h(0)^{-\alpha_e}(1-\alpha_e)}{x_0 + a[r_e(\theta^c)^{\alpha_e}(S^c)^{\alpha_e}h(0)^{1-\alpha_e} - X]} < \frac{\alpha_d}{1-\theta^c}. \tag{14}$$

Relations (12), (13) and (14) give the the values of S^c and $\theta(S^c) = \theta^c$ and $\mu(S^c) = \mu^c = 0$. When $S > S^c$ and close to S^c, equality (12) and inequality (14) still hold. That means $\mu(S) = 0$ for any S close to S^c.

Proof of Proposition 3 The proof will be done in two steps.

Step 1

Lemma 3 *Assume $h'(0) < +\infty$. Let $S^1 > S^c$. If $\mu(S^1) = 0$, then for $S^2 < S^1$, we also have $\mu(S^2) = 0$.*

Proof: If $S^2 \leq S^c$ then $\mu(S^2) = 0$ since $\theta(S^2) = 0$ (see Proposition 1). For short, we write $\theta_1 = \theta(S^1),\ \theta_2 = \theta(S^2),\ \mu_1 = \mu(S^1),\ \mu_2 = \mu(S^2)$.

Observe that (θ_1, S^1) satisfy (6) and (7), or equivalently (6) and (9). Equality (6) can be written as

$$h_0^{1-\alpha_e} ar_e[\alpha_e\theta_1^{\alpha_e - 1} - (\alpha_e + \alpha_d)\theta_1^{\alpha_e}] = \frac{\alpha_d(x_0 - aX)}{S^{1\alpha_e}}. \tag{15}$$

If $x_0 - aX = 0$, then $\theta_1 = \frac{\alpha_e}{\alpha_e+\alpha_d}$. Take $\theta_2 = \theta_1$. If $S^2 < S^1$ then (θ_2, S^2) satisfy (6) and (9). That means they satisfy the F.O.C. with $\mu_2 = 0$.

Observe that the LHS of equation (15) is a decreasing function in θ_1. Hence θ_1 is uniquely determined.

When $x_0 > aX$, if (θ_2, S^2) satisfy (15), with $S^2 < S^1$, then $\theta_2 < \theta_1$. In this case, (θ_2, S^2) also satisfy (9), and we have $\mu_2 = 0$.

When $x_0 < aX$, write equation (15) as:

$$h_0^{1-\alpha_e} a r_e[\alpha_e \theta_1^{-1} - (\alpha_e + \alpha_d)] = \frac{\alpha_d(x_0 - aX)}{(\theta_1 S^1)^{\alpha_e}}. \tag{16}$$

If (θ_2, S^2) satisfy (15), with $S^2 < S^1$, then $\theta_2 > \theta_1$. Since $x_0 < aX$, from (16), we have $\theta_2 S^2 < \theta_1 S^1$. Again (θ_2, S^2) satisfy (15) and (9). That implies $\mu_2 = 0$.

■

Step 2 Proof of the proposition.

Let

$$\widetilde{S} = \max\{S_m : S_m \geq S^c, \text{ and } S \leq S_m \Rightarrow \mu(S) = 0\},$$

and

$$\widetilde{\widetilde{S}} = \inf\{S_M : S_M > S^c, \text{ and } S > S_M \Rightarrow \mu(S) > 0\}.$$

From Proposition 2, the sets $\{S_m : S_m > S^c, \text{ and } S \leq S_m \Rightarrow \mu(S) = 0\}$ and $\{S_M : S_M > S^c, \text{ and } S > S_M \Rightarrow \mu(S) > 0\}$ are not empty. From Step 1, we have $\widetilde{\widetilde{S}} \geq \widetilde{S}$. If $\widetilde{\widetilde{S}} > \widetilde{S}$, then take $S \in (\widetilde{S}, \widetilde{\widetilde{S}})$. From the definitions of $\widetilde{S}$ and $\widetilde{\widetilde{S}}$, there exist $S_1 < S$, $S_2 > S$ such that $\mu(S_1) > 0$ and $\mu(S_2) = 0$. But that contradicts Step 1. Hence $\widetilde{\widetilde{S}} = \widetilde{S}$. Put $\widehat{S} = \widetilde{\widetilde{S}} = \widetilde{S}$ and conclude.

Proof of Proposition 4

From Proposition 3, we have $\mu^c = 0$. In this case, θ^c and S^c satisfy equation (10) and, since $S^c \in B$, we also have $F(r_e, S^c) = \psi(r_e, \theta^c, 0, S^c) = x_0 L_d^{*1-\alpha_d}$.

Explicitly, we have

$$\frac{a r_e (\theta^c)^{\alpha_e - 1}(S^c)^{\alpha_e} h_0^{1-\alpha_e} \alpha_e}{x_0 + a[r_e(\theta^c)^{\alpha_e}(S^c)^{\alpha_e} h_0^{1-\alpha_e} - X]} = \frac{\alpha_d}{1 - \theta^c}$$

and

$$(x_0 + a[r_e(\theta^c)^{\alpha_e}(S^c)^{\alpha_e} h_0^{1-\alpha_e} - X])(1 - \theta^c)^{\alpha_d} = x_0 \tag{17}$$

Tedious computations show that θ^c satisfies the equation

$$\alpha_e[1 - \frac{x_0 - aX}{x_0}(1-\theta)^{\alpha_d+1}] = \theta(\alpha_d + \alpha_e)$$

If $x_0 > aX$, then the LHS is a strictly concave function which increases from $\frac{\alpha_e aX}{x_0}$ when $\theta = 0$ to α_e when $\theta = 1$. The RHS is linear increasing, equal to 0 at the origin and to $\alpha_d + \alpha_e$ when $\theta = 1$. Therefore, there exists a unique solution $\theta^c \in (0,1)$.

If $x_0 < aX$, then the LHS is a strictly convex function which decreases from $\frac{\alpha_e aX}{x_0}$ when $\theta = 0$ to α_e when $\theta = 1$. The RHS is linear increasing, equal to 0 at the origin and to $\alpha_d + \alpha_e$ when $\theta = 1$. Therefore, there exists a unique solution $\theta^c \in (0,1)$.

If $x_0 = aX$, then $\theta^c = \frac{\alpha_e}{\alpha_e+\alpha_d}$.

In any case, θ^c does not depend on r_e. It is easy to show that θ^c is positively related with a if $x_0 \neq aX$. With higher value of spill-over indicator, a (*e.g.* better social capital and institutional capital), the economy in question not only invest in new technology earlier but also invest more initially.

Equation (17) gives:

$$ar_e(S^c)^{\alpha_e} = [x_0(\frac{1}{(1-\theta^c)^{\alpha_d}} - 1) + aX]\frac{1}{(\theta^c)^{\alpha_e} h_0^{1-\alpha_e}} \quad (18)$$

We see immediately that S^c is a decreasing function in a and r_e.

7 Appendix 2

Proof of Proposition 7 Let S^s be defined by

$$\alpha_d (S^s)^{\alpha_d - 1} x_0 L_d^{*1-\alpha_d} = \frac{1}{\beta}.$$

If $S_0 > \widehat{S}$ ($\widehat{S}$ is defined in Proposition 3) then $\theta_t^* > 0,\ \mu_t^* > 0$ for every t.

If $S_0 > S^c$ then $\theta^*_t > 0$ for every t. If S^*_t converges to infinity, then there exists T_2 where $S^*_{T_2} > \widehat{S}$ and $\theta^*_t > 0,\ \mu^*_t > 0$ for every $t \geq T_2$.

Now consider the case where $0 < S_0 < S^c$. Obviously, $\theta^*_0 = 0$. It is easy to see that if a or/and r_e are large then $S^c < S^s$. If for any t, we have $\theta^*_t = 0$, we also have $K^*_{e,t} = 0\ \forall t$, and the optimal path (S^*_t) will converge to S^s (see Le Van and Dana (2003)). But, we have $S^c < S^s$. Hence the optimal path $\{S^*_t\}$ will be non decreasing and will pass over S^c after some date T_1 and hence $\theta^*_t > 0$ when $t \geq T_1$.

If the optimal path $\{S^*_t\}$ converges to infinity, then after some date T_2, $S^*_t > \widehat{S}$ for any $t > T_2$ and $\theta^*_t > 0, \mu^*_t > 0$.

It remains to prove that the optimal path converges to infinity if a or/and r_e are large enough.

Since the utility function u satisfies the Inada condition $u'(0) = +\infty$, we have Euler equation:

$$u^{'}(c^*_t) = \beta u^{'}(c^*_{t+1}) H^{'}_s(r_e, S^*_{t+1}).$$

If $S^*_t \to \overline{S} < \infty$, then $c^*_t \to \overline{c} > 0$. From Euler equation, we get

$$H^{'}_s(r_e, \overline{S}) = \frac{1}{\beta}.$$

We will show that $H^{'}_s(r_e, S) > \frac{1}{\beta}$ for any $S > S^c$. We have

$$\begin{aligned} H^{'}_s(r_e, S) &= F^{'}_s(r_e, S) S^{\alpha_d} + \alpha_d F(r_e, S) S^{\alpha_d - 1} \\ &\geq F^{'}_s(r_e, S) S^{\alpha_d}. \end{aligned}$$

From the envelope theorem we get:

$F_s^{'}(r_e, S)S^{\alpha_d} =$

$$[ar_e\theta^{*\alpha_e}(h(\mu^*S))^{-\alpha_e}(\alpha_e h(\mu^*S) + (1-\alpha_e)\mu^* S h'(\mu^*S))S^{\alpha_d+\alpha_e-1}]$$
$$\times L_d^{*1-\alpha_d}(1-\theta^*-\mu^*)^{\alpha_d}$$

When ar_e is large, from Proposition 5, we have $\theta^* \geq \underline{\theta} = \min\{\theta^c, \theta_\infty\}$ and $\theta^* + \mu^* \leq \overline{\zeta} = \max\{\theta^c, \theta_\infty + \mu_\infty\}$. We then obtain

$$\begin{aligned} H_s^{'}(r_e, S) &\geq L_d^{*1-\alpha_d}(1-\theta^*-\mu^*)^{\alpha_d}[ar_e\theta^{*\alpha_e}(h^*(\mu S))^{1-\alpha_e}\alpha_e S^{\alpha_d+\alpha_e-1}] \\ &\geq L_d^{*1-\alpha_d}(1-\overline{\zeta})^{\alpha_d}[ar_e\underline{\theta}^{\alpha_e}(h^*(0))^{1-\alpha_e}\alpha_e(S^c)^{\alpha_d+\alpha_e-1}] \end{aligned}$$

since $h(x) \geq h(0)$ and $\alpha_d + \alpha_e - 1 \geq 0$.

If $\alpha_d + \alpha_e = 1$, then

$$H_s^{'}(r_e, S) \geq L_d^{*1-\alpha_d}(1-\overline{\zeta})^{\alpha_d}[ar_e\underline{\theta}^{\alpha_e}(h^*(0))^{1-\alpha_e}\alpha_e], \tag{19}$$

and when ar_e becomes very large, the RHS of inequality (19) will be larger than $\frac{1}{\beta}$.

Now assume $\alpha_d+\alpha_e > 1$. From equation (18), the quantity $ar_e(S^c)^{\alpha_e}$ equals

$$\gamma = [x_0(\frac{1}{(1-\theta^c)^{\alpha_d}} - 1) + aX]\frac{1}{(\theta^c)^{\alpha_e}h_0^{1-\alpha_e}}$$

and

$$S^c = (\frac{\gamma}{ar_e})^{\frac{1}{\alpha_e}}.$$

We now have

$$H_s^{'}(r_e, S) \geq L_d^{*1-\alpha_d}(1-\overline{\zeta})^{\alpha_d}\underline{\theta}^{\alpha_e}(h^*(0))^{1-\alpha_e}\alpha_e\gamma(\frac{\gamma}{ar_e})^{\frac{\alpha_d-1}{\alpha_e}}$$

It is obvious that, since $\alpha_d - 1 < 0$, when ar_e is large, we have $H_s^{'}(r_e, S) > \frac{1}{\beta}$.

8 Appendix 3

Table 2: Inputs and Technical Progress: Breaks in 1973 and 1985

Contributions (%) of the Sources of Growth

	Sample period	Physical capital	Labor	Human capital	Technical progress
(1) Pre-1973					
Hong Kong	66-73	68.37 (9.67)	28.50 (3.10)	3.13 (5.57)	0.00
S. Korea	60-73	72.60 (11.58)	21.87 (4.14)	5.53 (7.70)	0.00
Singapore	64-73	55.59 (12.73)	40.18 (7.56)	4.22 (9.17)	0.00
Taiwan	53-73	80.63 (13.21)	15.45 (2.63)	3.91 (6.73)	0.00
Indonesia	70-73	73.09 (11.09)	9.37 (2.15)	17.54 (19.50)	0.00
Malaysia	70-73	59.97 (9.56)	29.99 (4.32)	10.05 (12.64)	0.00
Philippines	70-73	39.79 (5.12)	49.97 (7.36)	10.24 (11.51)	0.00
Thailand	70-73	82.11 (10.96)	7.67 (0.57)	10.22 (11.44)	0.00
China	65-73	85.29 (13.51)	10.36 (3.19)	4.35 (7.01)	0.00
Japan	57-73	55.01 (11.43)	4.85 (0.82)	1.06 (2.87)	39.09
G-5	57-73	41.50 (4.62)	6.00 (4.24)	1.43 (1.70)	51.07
(2) 1974-85					
Hong Kong	74-85	64.31 (9.58)	32.73 (3.40)	2.96 (5.67)	0.00
S. Korea	74-85	78.08 (13.28)	18.10 (2.83)	3.81 (6.41)	0.00
Singapore	74-85	64.68 (9.94)	31.72 (3.42)	3.60 (5.48)	0.00
Taiwan	74-85	78.91 (11.89)	18.12 (2.23)	2.97 (4.98)	0.00
Indonesia	74-85	77.69 (12.22)	13.55 (2.65)	8.76 (10.20)	0.00
Malaysia	74-85	61.39 (10.76)	33.61 (4.94)	5.00 (8.15)	0.00
Philippines	74-85	62.59 (7.29)	29.28 (3.53)	8.13 (8.07)	0.00
Thailand	74-85	67.53 (8.69)	25.02 (3.55)	7.46 (8.96)	0.00
China	74-85	80.46 (9.44)	14.64 (2.53)	4.09 (6.37)	0.00
Japan	74-85	40.65 (6.73)	10.22 (0.93)	0.96 (1.69)	48.17
G-5	74-85	36.29 (2.65)	-14.55 (-0.42)	2.53 (1.90)	75.73

Note: The numbers in the parentheses are the average annual rates of growth of each of inputs.

G-5: France, W. Germany, Japan, UK and US

Table 2 (*cont.*): Inputs and Technical Progress: Breaks in 1973 and 1985

Contributions (%) of the Sources of Growth

	Sample period	Physical capital	Labor	Human capital	Technical progress
(3) Post-1986					
Hong Kong	86-95	41.81 (7.56)	6.46 (0.53)	1.58 (3.10)	50.14
S. Korea	86-95	44.54 (11.90)	14.98 (2.76)	1.75 (4.15)	38.73
Singapore	86-95	37.01 (8.50)	31.30 (4.32)	1.52 (3.38)	30.17
Taiwan	86-95	43.00 (9.01)	10.46 (1.34)	1.38 (3.13)	45.16
Indonesia	86-94	62.79 (8.88)	15.91 (2.31)	5.69 (6.94)	15.61
Malaysia	86-95	42.87 (8.53)	33.41 (4.83)	3.25 (6.15)	20.47
Philippines	86-95	52.18 (3.77)	41.63 (2.96)	6.23 (5.09)	-0.03
Thailand	86-94	51.01 (11.27)	13.32 (2.72)	2.36 (5.25)	33.31
China	86-95	86.39 (12.54)	10.34 (1.92)	3.27 (4.54)	0.00
Japan	86-94	38.21 (4.86)	2.47 (0.11)	1.17 (1.44)	58.14
G-5	86-94	27.14 (2.70)	13.83 (5.37)	1.58 (1.36)	57.45

Note: The numbers in the parentheses are the average annual rates of growth of each of inputs.

G-5: France, W. Germany, Japan, UK and US

Source: Reproduced from Lau and Park (2003)

Table 3: List of Economies in the Sample of Human Capital

Economies	***Range***	**Economies**	***Range***
Algeria	1950-2000	Malaysia	1960-2000
Argentina	1950,1960-2000	Mali	1960-2000
Bangladesh	1960-2000	Malta	1950,1960-2000
Barbados	1960-2000	Mauritius	1950,1960-2000
Benin	1960-2000	Mexico	1950,1960-2000
Bolivia	1960-2000	Mozambique	1960-2000
Botswana	1960-2000	Nepal	1960-2000
Brazil	1960-2000	Nicaragua	1950,1960-2000
Cameroon	1960-2000	Niger	1960-2000
Central African Republic	1960-2000	Pakistan	1960-2000
Chile	1950,1960-2000	Panama	1950,1960-2000
China	1960-2000	Paraguay	1950,1960-2000
Colombia	1950,1960-2000	Peru	1960-2000
Congo, Dem. Rep.	1955-2000	Philippines	1950-2000
Congo, Republic of	1960-2000	Poland	1960-2000
Costa Rica	1950,1960-2000	Romania	1950,1960-2000
Cuba	1955-2000	Rwanda	1960-2000
Cyprus	1960-2000	Senegal	1960-2000
Dominican Republic	1960-2000	Sierra Leone	1960-2000
Ecuador	1950,1960-2000	Singapore	1960-2000
Egypt	1960-2000	South Africa	1960-2000
El Salvador	1950,1960-2000	Sri Lanka	1960-2000
Gambia, The	1960-2000	Sudan	1955-2000
Ghana	1960-2000	Swaziland	1960-2000
Guatemala	1950,1960-2000	Syria	1960-2000
Haiti	1950,1960-2000	Taiwan	1960-2000
Honduras	1960-2000	Thailand	1960-2000
Hungary	1960-2000	Togo	1960-2000
India	1960-2000	Trinidad &Tobago	1960-2000
Indonesia	1960-2000	Tunisia	1960-2000
Jamaica	1960-2000	Uganda	1960-2000
Jordan	1960-2000	Uruguay	1960-2000
Kenya	1960-2000	Venezuela	1950,1960-2000
Korea, Republic of	1955-2000	Zambia	1960-2000
Lesotho	1960-2000	Zimbabwe	1960-2000
Malawi	1960-2000		

Source: Extracted from Barro and Lee (2000)

Data is calculated at 5-years span and some economies data for 1955 are missing

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