

# New Technology, Human Capital and Growth for a Developing Country

Cuong Le Van<sup>1</sup>, Tu Anh Nguyen<sup>1</sup>, Manh-Hung Nguyen<sup>2</sup>, Thai Bao Luong<sup>3</sup>

<sup>1</sup>Université Paris-1, Pantheon-Sorbonne, CNRS

<sup>2</sup>LERNA-INRA, Toulouse School of Economics

<sup>3</sup>National University of Hanoi

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## Abstract

In a developing country with three sectorsconsumption goods, new technology, and educationthe productivity of the consumption goods depends on new technology and skilled labor used to produce this new technology. In the first stage of economic growth, the country concentrates on the production of consumption goods; in the second, the country must import both physical capital and new technology capital to produce consumption goods and new technology; in the third, the country must import capital and invest in the training and education of highly skilled labor.

**Keywords:** Optimal growth model, New technology capital, Human Capital, Developing country.

**JEL Classification:** D51, E13

## 1 INTRODUCTION

Sources of technical progress can be domestic or international, although some economists believe that developed countries innovate and export technology

while developing countries import and copy ( Baumol 1986, Dowrick and Nguyen 1989, Gomulka 1991, Young 1995, Lall 2000, Lau & Park 2003, Barro and Sala-i-Martin 2004). Developing countries need to adopt technology from the international market in order to improve their productivity (Romer 1997, 1990). These countries also need to care for their human capital (Lucas 1988).

Developing countries must choose between investing in technological and human capital. Barro (1997), Barro and Sala-i-Martin (2004), Eaton and Kortum (2000), Keller (2001), Kumar (2003), Kim and Lau (1994), Lau and Park (2003) showed that developing countries are not convergent and that a certain level in capital accumulation is necessary to hope for economic growth.

Galor and Moav (2004) consider the optimization of investment in physical and human capital from the point of view of capital suppliers. They assumed that the technology for producing human capital is not that good so that, when physical capital is rare, the rate of return to physical capital is higher than the one to human capital. It is, then better to invest in physical than human capital. Accumulation gradually reduces the rate of return to physical capital where the rate of return to human capital increases. There is some time, when investment in human capital supercedes physical capital as the main engine of growth.

In contrast to Galor and Moav (2004), we consider the optimal investments in human and physical capital on the demand of capital. In Galor and Moav (2004) the source of growth is inter-generational transfer, in Bruno et al. (2009) and here the source of growth is the ability of Total Factor Productivity (TFP) generation.

Bruno et al. (2009) specify the conditions under which a developing country can decide optimally either to concentrate whole resources on the accumulation of physical capital, or to devote a portion of its national wealth to import technological capital. These conditions are related to the level of wealth and endowment in human capital and thresholds at which the country switches to another stage of development. However, they do not fully explore the role of

education which contributes to the accumulation of human capital.

We extend their model by introducing education. We show that after a critical value of wealth the country ought to invest in new technology. The country can either keep its existing technology or invest in new technology capital in order to produce new technology. It is always optimal for the country to use new technology. We show further that under certain conditions the country can either invest in new technology and high education or only invest in new technology. We shall determine the level of wealth at which the decision to invest in training and education has to be made. We shall show that the critical value of wealth is inversely related to productivity in the new technology sector, to the total number of skilled workers, and to the spill-over effectiveness of the new technology sector on the sector of consumption goods but proportionally related to the price of the new capital of the technology. We shall determine the optimal share of the investment in physical capital, new technology capital, and human capital formation on the long-run growth path. Our result on the replacement of physical by human capital accumulation in the course of development is consistent with those of Galor and Moav (2004).

Our two main results are: (1) the richer a country, the more money is invested in new technology, training, and education, (2) the share of investment in human capital increases with wealth while the share for physical and new technology capitals decrease. In any case, the economy grows unabated. In contrast with Bruno et al. (2009), we shall confront our model with empirical data.

## 2 Model

Consider a three-sector economy constituted of a domestic sector which produces an aggregate good  $Y_d$ , a new technology sector with output  $Y_e$ , and an education sector characterized by a function  $h(T)$  where  $T$  is the total spend-

ing in education. The domestic sector uses  $Y_e$  to increase its total productivity. The production functions are Cobb-Douglas:  $Y_d = \Phi(Y_e)K_d^{\alpha_d}L_d^{1-\alpha_d}$  and  $Y_e = A_eK_e^{\alpha_e}L_e^{1-\alpha_e}$  where  $\Phi(\cdot)$  is a non-decreasing function satisfying  $\Phi(0) = x_0 > 0$ ,  $K_d, K_e, L_d, L_e$ , and  $A_e$  stand for physical capital, technological capital, low-skilled labor, high-skilled labor and total productivity,  $0 < \alpha_d < 1, 0 < \alpha_e < 1$ . This specification implies that productivity growth is orthogonal to physical capital accumulation (Collins et al. 1996, Lau and Park 2003).

The price of capital goods is the numéraire in terms of consumption goods. The price of the new technology sector is higher and equal to  $\lambda \geq 1$ . Labor mobility between the sectors is impossible and wages are exogenous.

$S$  being the available spending in capital goods and human capital,

$$K_d + \lambda K_e + p_T T = S. \quad (1)$$

For simplicity,  $p_T = 1$ ,  $T$  is measured in capital goods. The budget constraint of the economy is

$$K_d + \lambda K_e + T = S \quad (2)$$

where  $S$  is the wealth of the country in terms of consumption goods.

The social planner maximizes

$$\max_{(K_d, K_e, T, L_d, L_e)} Y_d = \max_{(K_d, K_e, T, L_d, L_e)} \Phi(Y_e)K_d^{\alpha_d}L_d^{1-\alpha_d} \quad (3)$$

subject to

$$\begin{cases} Y_e = A_e K_e^{\alpha_e} L_e^{1-\alpha_e} \\ K_d + \lambda K_e + T = S, \\ 0 \leq L_e \leq L_e^* h(T), \\ 0 \leq L_d \leq L_d^*. \end{cases} \quad (4)$$

where  $h$  represents the technology to produce human capital;  $L_e^*$  is the total

number of skilled workers in the new technology sector;  $L_e$  is effective labor;  $L_d^*$  is the total number of non-skilled workers in the domestic sector.

$h(\cdot)$  is an increasing concave function with  $h(0) = h_0 > 0$ ,  $Y_d$  is a concave function of investment in education (marginal returns to education are diminishing, Psacharopoulos, 1994). Let

$$\Delta = \{(\theta, \mu) : \theta \in [0, 1], \mu \in [0, 1], \theta + \mu \leq 1\}. \quad (5)$$

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

$$\lambda K_e = \theta S, K_d = (1 - \theta - \mu)S \text{ and } T = \mu S. \quad (6)$$

The objective function being strictly increasing, at the optimum, the constraints are binding. Let  $L_e = L_e^* h$ ,  $L_d = L_d^*$ , then the problem is:

$$\text{Max}_{(\theta, \mu) \in \Delta} \Phi(r_e \theta^{\alpha_e} S^{\alpha_e} h(\mu S)^{1-\alpha_e}) (1 - \theta - \mu)^{\alpha_d} S^{\alpha_d} L_d^{*1-\alpha_d} \quad (7)$$

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

Let

$$\psi(r_e, \theta, \mu, S) = \Phi(r_e \theta^{\alpha_e} S^{\alpha_e} h(\mu S)^{1-\alpha_e}) (1 - \theta - \mu)^{\alpha_d} L_d^{*1-\alpha_d}. \quad (8)$$

The problem is equivalent to

$$\text{Max}_{(\theta, \mu) \in \Delta} \psi(r_e, \theta, \mu, S). \quad (9)$$

$\psi$  is continuous in  $\theta$  and  $\mu$ , there exist optimal solutions. Denote

$$F(r_e, S) = \text{Max}_{(\theta, \mu) \in \Delta} \psi(r_e, \theta, \mu, S). \quad (10)$$

If  $\Phi(x)$  is constant in an initial phase and increasing linearly afterwards:

$$\Phi(x) = \begin{cases} x_0 & \text{if } x \leq X \\ x_0 + a(x - X) & \text{if } x \geq X, a > 0. \end{cases} \quad (11)$$

The threshold in function  $\Phi$  may be interpreted either as a setup cost as in Azariadis and Drazen (1990), or a minimum level of adoption of new technology which is necessary in order for them to impact the economy. Alternatively a productive innovation cannot be realized without necessary non-productive knowledge, the critical level  $X$  can be understood as cumulative level of non-productive knowledge that is necessary for the first productive innovation comes out. The surveys by Lau and Park (2003) and Young (1995) show that between mid of 1960s and 1986 East Asian economies enjoyed high growth rate but technological progress plays no role at all. Our assumption on  $\Phi$  can be justified by these surveys.

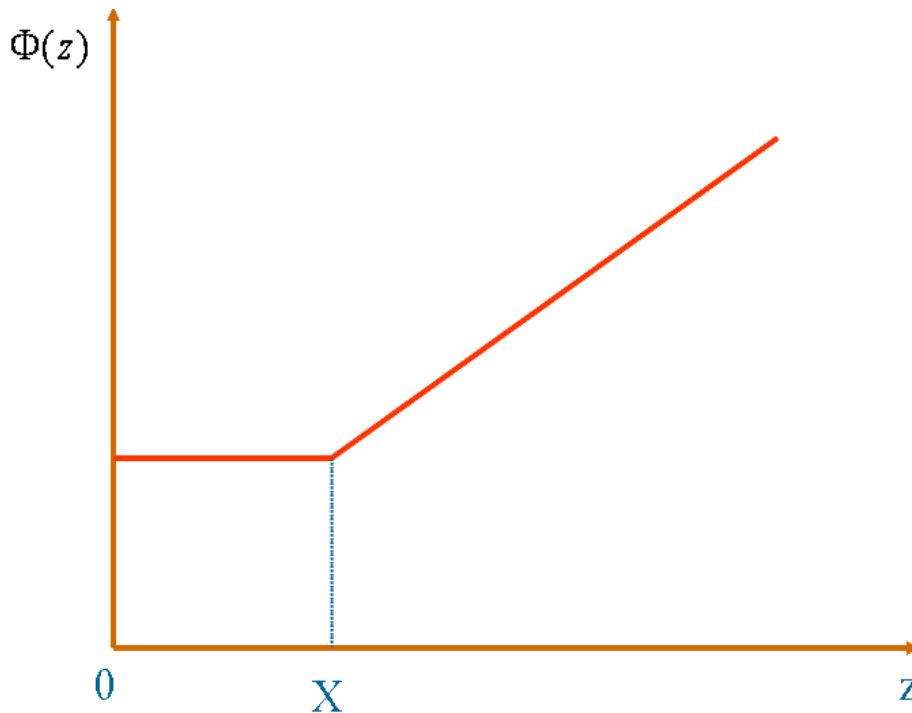


Figure 1: Technological progress in the production of consumption good

By the Theorem of Maximum,  $F$  is continuous and  $F(r_e, S) \geq x_0 L_d^{*1-\alpha_d}$ .

Proposition 1 establishes the existence of 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:* In appendix 1.

**Remark 1** *If  $S > S^c$  then*

$$Y_e > X \text{ and } \Phi(Y_e) = x_0 + a(Y_e - X) \quad (12)$$

Proposition 2 shows that, when the quality of the training technology (measured by the marginal productivity  $h'(0)$  at the origin) is very high, then for any  $S > S^c$  the country invests both in the new technology and in human capital. When  $h'(0)$  is finite, the country no longer has to invest in human capital when  $S > S^c$ , but does it if it is sufficiently rich. If  $h'(0)$  is low, the country does 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  $S > S^c$ ,  $\theta(S) > 0$ ,  $\mu(S) > 0$ .*

*2. If  $h'(0) < +\infty$ , 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  $h'(0) < \alpha$ , there exists  $S^m > S^c$  such that  $\mu(S) = 0$ ,  $\theta(S) > 0$  for  $S \in [S^c, S^m]$ .*

*Proof:* in Appendix 1.

Proposition 3 states that there exists a threshold above which  $\theta(S)$  and  $\mu(S)$  are positive.

**Proposition 3** *If  $h'(0) < +\infty$ , 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:* in Appendix 1.

Let us recall that  $r_e = \frac{A_e L_e^{*(1-\alpha_e)}}{\lambda^{\alpha_e}} = A_e L_e^* (L_e^* \lambda)^{-\alpha_e}$  where  $A_e$  is the productivity of the new technology sector,  $\lambda$  the price of the new technology capital,  $\alpha_e$  the capital share in the new technology production sector, and  $L_e^*$  the total number of skilled workers. The productivity function of the consumption goods sector is  $\Phi(x) = x_0 + a(x - X)$  if  $x \geq X$ . The spill-over indicator  $a > 0$  represents the level of social and institutional capital. It indicates the effectiveness of the new technology product on the productivity. We will show in Proposition 4 that the critical value  $S^c$  decreases when  $r_e$  increases, when the productivity  $A_e$  or the total number of skilled workers increase, when the price of the new technology capital  $\lambda$  decreases, when the share of capital in the new technology sector  $\alpha_e$  decreases (more human-capital intensive), or when the spill-over indicator  $a$  increases. Initiating investment into the new technology sector is favoured by: (i) the potential productivity in the new technology sector; (ii) the total number of skilled workers; (iii) the price of the new technology; (iv) and the intensity of human capital in the new technology sector and of spill-over effects.

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

- (i)  $\mu^c = 0$ ,  $\theta^c$  does not depend on  $r_e$ .
- (ii)  $S^c$  decreases if  $a$  or  $r_e$  increases.

*Proof:* in Appendix 1.

Proposition 5 shows that the optimal shares  $\theta$  and  $\mu$  converge when  $S$  goes to infinity. The ratio of spendings on human capital to  $S$  and the ratio of spendings on new technology and education to  $S$  increase when  $S$  increases.

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



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

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

*Proof:* Write  $\theta, \mu$  instead of  $\theta(S)$  and  $\mu(S)$ . Consider  $\widehat{S}$  in Proposition 3. When  $S \leq \widehat{S}$ , then  $\mu = 0$  (Proposition 3). When  $S > \widehat{S}$ ,  $(\theta, \mu)$  satisfy Eq. (48) and (49) which can be written as:

$$\theta(\alpha_d + \alpha_e) = -\alpha_e \mu + \alpha_e - \frac{\alpha_d(x_0 - aX)\alpha_e^{-\alpha_e}}{ar_e S(1 - \alpha_e)^{1-\alpha_e} b^{1-\alpha_e}} \quad (13)$$

and

$$\theta(1 - \alpha_e) = \alpha_e \mu + \frac{\alpha_e h_0}{bS} \quad (14)$$

We obtain

$$\theta(1 + \alpha_d) = \alpha_e - \frac{\alpha_d(x_0 - aX)\alpha_e^{-\alpha_e}}{ar_e S(1 - \alpha_e)^{1-\alpha_e} b^{1-\alpha_e}} + \frac{h_0 \alpha_e}{bS} \quad (15)$$

and

$$\mu = \theta\left(\frac{1}{\alpha_e} - 1\right) - \frac{h_0}{bS} \quad (16)$$

Thus

$$\theta + \mu = \frac{1}{1 + \alpha_d} \left(1 - \frac{\alpha_d}{\alpha_e} \frac{(x_0 - aX)\alpha_e^{-\alpha_e}}{ar_e S(1 - \alpha_e)^{1-\alpha_e} b^{1-\alpha_e}}\right) - \frac{\alpha_d}{1 + \alpha_d} \frac{h_0}{bS}. \quad (17)$$

and:

$$\frac{\mu}{1 - \alpha_e} = \frac{1}{1 + \alpha_d} \left(1 - \frac{\alpha_d}{\alpha_e} \frac{(x_0 - aX)\alpha_e^{-\alpha_e}}{ar_e S(1 - \alpha_e)^{1-\alpha_e} b^{1-\alpha_e}}\right) - \left(\frac{\alpha_d}{1 + \alpha_d} + \frac{\alpha_e}{1 - \alpha_e}\right) \frac{h_0}{bS} \quad (18)$$

If  $x_0 \geq aX$ ,  $\theta + \mu$  and  $\mu$  increase with  $S$ . If  $x_0 < aX$ , when  $ar_e$  is large enough,  $\theta + \mu$  and  $\mu$  increase with  $S$ . When  $S$  goes to  $+\infty$ ,  $\theta$  converges to  $\theta_\infty = \frac{\alpha_e}{1 + \alpha_d}$  and  $\mu$  converges to  $\mu_\infty = \frac{1 - \alpha_e}{1 + \alpha_d}$ .

### 3 Dynamic Model

The representative consumer lives infinitely and has an intertemporal utility function with discount factor  $\beta < 1$ . At each period, she uses her savings to invest in physical capital, in new technology capital or in human capital. The depreciation rate of capital equals 1 and the population growth rate is 0,  $L_{e,t}^* = L_e^*$  and  $L_{d,t}^* = L_d^*$ .

The social planner solves the dynamic growth model:

$$\max_{(c_t)_t} \sum_{t=0}^{\infty} \beta^t u(c_t)$$

subject to:

$$\begin{cases} c_t + S_{t+1} \leq \Phi(Y_{e,t}) K_{d,t}^{\alpha_d} L_{d,t}^{1-\alpha_d} \\ Y_{e,t} = A_e K_{e,t}^{\alpha_e} L_{e,t}^{1-\alpha_e} \\ K_{d,t} + \lambda K_{e,t} + T_t = S_t, \\ 0 \leq L_{e,t} \leq L_e^* h(T_t), \quad 0 \leq L_{d,t} \leq L_d^*. \end{cases} \quad (19)$$

the initial resource  $S_0$  is given

The problem is equivalent to

$$\begin{aligned} \max_{(c_t)_t} \quad & \sum_{t=0}^{\infty} \beta^t u(c_t) \\ \text{s.t} \quad & \forall t, \quad c_t + S_{t+1} \leq H(r_e, S_t), \end{aligned} \quad (20)$$

with

$$H(r_e, S) = F(r_e, S) S^{\alpha_d}. \quad (21)$$

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

We again use  $S^c$  defined as:

$$S^c = \max\{S \geq 0 : F(r_e, S) = x_0 L_d^{*1-\alpha_d}\} \quad (22)$$

where

$$F(r_e, S_t) = \text{Max}_{0 \leq \theta_t \leq 1, 0 \leq \mu_t \leq 1} \psi(r_e, \theta_t, \mu_t, S_t). \quad (23)$$

**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 are binding, the initial program is equivalent to:

$$\begin{aligned} & \max_{(S_t)_t} \sum_{t=0}^{\infty} \beta^t u(H(r_e, S_t) - S_{t+1}) \\ \text{s.t.} \quad & \forall t, 0 \leq S_{t+1} \leq H(r_e, S_t). \\ & S_0 > 0 \text{ is given.} \end{aligned} \quad (24)$$

As in Bruno et al. (2009), we have:

**Proposition 6** *i) Every optimal path is monotonic.*

*ii) No optimal trajectory  $(S_t^*)$  from  $S_0$  can converge to 0.*

Denote  $\theta_t^*$  the optimal capital shares among the technological capital stock and  $\mu_t^*$  the total spendings for human capital:

$$\lambda K_{e,t}^* = \theta_t^* S_t^* \text{ and } T_t^* = \mu_t^* S_t^*. \quad (25)$$

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

*(i) there exists  $T_1$  such that*

$$\theta_t^* > 0 \quad \forall t \geq T_1 \quad (26)$$

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

$$\theta_t^* > 0, \mu_t^* > 0, \forall t \geq T_2 \quad (27)$$

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

*Proof:* in Appendix 1.

In the course of economic growth, initially a country invests only in physical capital. When the country reaches a critical level, it must invest not only in physical capital but also in new technology and in high education. Under some mild conditions on the quality of the production of the new technology and on the supply of skilled workers, the share of the investment, in human capital, and in new technology and human capital, increases when the country becomes rich.

Thanks to new technology and human capital, the TFP increases and induces growth, the economy grows unabated.

## 4 Results

King and Rebelo (1993) simulate neoclassical growth models to conclude that contribution of physical capital accumulation plays only 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 the economic performances of South Korea, Taiwan and Thailand, Portugal, Spain, France, Germany, Japan, The Netherlands, the UK and US in the twentieth century. He concludes that growth is driven by physical capital accumulation in developing economies, by human capital and technological progress in developed economies. Young (1994), Kim and Lau (1994), Krugman (1994), Collins and Bosworth (1996, p.186) and Lau and Park (2003) claim that

the economic miracle in East Asia was mostly due to physical capital accumulation and not at all to technological progress. Collins and Bosworth (1996) suggests that “it is possible that the potential to adopt knowledge and technology 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”. On the one hand, Lau and Park (2003) show that the hypothesis of no technological progress in East Asia Newly Industrialized Economies (NIEs) until 1986 cannot be rejected. On the other hand, since 1986 when these economies started investing heavily on R& D, technological progress has generated significant growth. This fact supports our prediction that there exists a threshold for investing in new technology.

In this section we use pooled time-series of educational attainment for 71 non-oil exporting, developing economies compiled by Barro and Lee (2000) and real Gross Domestic Product per head ( $y$ ) (in purchasing power parity, PPP) of these countries in Penn World Table 6.2 (Heston, et al., 2006) to compute a correlation between human 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 ( $A$ ). These data are calculated for every five-year period from 1950 at least, to 2000. Oil exporting countries are excluded from the sample because they have enjoyed a high level of GDP per head.

The two OLS regressions:

$$\ln y = \alpha + \beta_1 l_1 + \beta_2 l_2 + \beta_3 l_3 + \varepsilon \quad (28)$$

and

$$\ln y = \alpha + \gamma_1 A + \varepsilon \quad (29)$$

are first tested on a whole sample for checking the stability. Employing rolling regression procedure we detect that estimated coefficients of Eq. (29) and one estimated coefficient in Eq. (28) are negative for all regressions on sub-sample with GDP per head under 1267 USD. Second, Chow break point and forecast tests reject the null hypothesis of equality of regression coefficients in the 2 sub-samples: one with GDP per head under 1267 USD (149 observations), and another with GDP per head over 1267 USD (459 observations).

The results presented in Table 1 show that when the GDP per head is under 1267 USD ( $y$  in PPP and constant price in 2000) the hypothesis of no contribution of human capital to economic growth cannot be rejected, while when  $y > 1267$  this hypothesis is rejected with a risk of five percentage to be wrong.

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

	Equation 28		Equation 29	
	$y \leq 1267$	$y > 1267$	$y \leq 1267$	$y > 1267$
$R^2$	0.021	<b>0.371</b>	0.0002	<b>0.464</b>
$\overline{R^2}$	0.001	<b>0.366</b>	- 0.007	<b>0.462</b>
$\beta_1$	$\sim 0.000$ (0.005)	0.017 ( <b>0.003</b> )*		
$\beta_2$	- 0.009 (0.012)	0.043 ( <b>0.007</b> )*		
$\beta_3$	0.092 (0.053)	0.028 ( <b>0.009</b> )*		
$\gamma_1$			-0.003 (0.018)	0.21 ( <b>0.01</b> )*
Obs	149	459	149	459

Note: the numbers in the parentheses are standard deviations;

\* statistically significant at the level of significance of 5%

When  $y > 1267$  the coefficients: of the percentage of labor force with com-

pleted primary school ( $l_1$ ), of completed secondary school, and of completed higher secondary school are all of expected sign and statistically significant. The results of Eq. (29) confirm the positive contribution of human capital when it is measured by the average total number of schooling years.

By contrast, when  $y \leq 1267$ , the adjusted  $R^2$  in Eq. (28) and Eq. (29) are nearly zero, no coefficient is statistically significant. These results imply that human capital plays no role in economic growth, that there is no demand for investing in human capital when income is lower than a critical level.

We examine the total spendings on human capital and new technology in China, South Korea and Taiwan. Does share of human capital and spendings for new technology in total investment ( $S$ ) in these economies increase?

The data of total spendings in human capital is not directly available. We follow Carsey and Sala-i-Martin (1995) to assume that wages contain a part devoted to finance human capital. This part depends not only on the total number of schooling years but also on-the-job training, job experience, schooling quality, and technological level.

The minimum wage is assumed to be the non-skilled one. The spendings in human capital  $EHC_t$  at time  $t$  are:

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

where  $E$  is total number of employed workers,  $AW$  the mean wage, and  $MW$  the minimum wage. The part  $AW - MW$  is rewarded for skill.

The new technological capitals are produced in the R&D sector, then the total spendings in R&D is a proxy for investment in technological capital ( $\lambda K_e$ ), and the fixed capital formation (if not available, then the formation of gross capital) is a proxy for spendings on  $K_d$ .

For China, the data of  $AW$ ,  $GDP$ , and  $E$  are available in the Census and Economic Information Center (CEIC) database from 1952 to 2006. The minimum

wage in China varies between provinces and within province. The minimum wage for all provinces is available between 2004-2006 from the Ministry of Labor and Social Security of China. Therefore we use the average wage in the sector of farming, forestry, animal husbandry and fishery which use the least human capital and physical capital as a proxy of the minimum wage. From the CEIC database, we come up with a time-series of national minimum wages in China from 1980 to 2006. As data of fixed capital formation in China are not available, we use the data of gross capital formation, which are available in the World Development Indicator (WDI) database of the World Bank. Finally, the statistics for R&D expenditure in period 1980-2006 are available in statistical yearbooks.

For Taiwan, the data for the total compensation of employees ( $E_t \times AW_t$ ), employment ( $E_t$ ), fixed capital formation, GDP, and average wage in the manufacturing sector are available in the CEIC database between 1978 and 2006. The minimum wage rates are only available between 1993 and 2006 and in 1984 at the US Department of State<sup>1</sup>. We fill in the missing data between 1983 and 1992 by estimated ones. For that, we assume that the minimum wage (MW) is a concave function of average wage in the manufacturing sector ( $AW_m$ ) or more specifically, the ratio of  $\frac{MW}{AW_m}$  is linearly correlated with  $AW_m$ . The OLS regression yields estimations for missing data. The data of R&D expenditure is taken from the National Science Council (2007) and Lau and Park (2003).

For South Korea, the CEIC database provides data of employment ( $E$ ), compensations for employees ( $E \times AW$ ), fixed capital formation, GDP, and nominal wage index. The minimum wages between 1988 and 2006 are taken from Global Production Network (GPN) (2001) and from the US State Department website. If we assume that between 1976 and 1987, the minimal wage changes with the nominal wage index, then we can estimate the total spendings for human capital between 1976 and 1987. The data for the total spendings in R&D is

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<sup>1</sup>Cited at the website: [http://dosfan.lib.uic.edu/ERC/economics/commercial\\_guides/Taiwan.html](http://dosfan.lib.uic.edu/ERC/economics/commercial_guides/Taiwan.html) and <http://www.state.gov/g/drl/rls/hrrpt/2006/78770.htm>



taken from UNESCO.

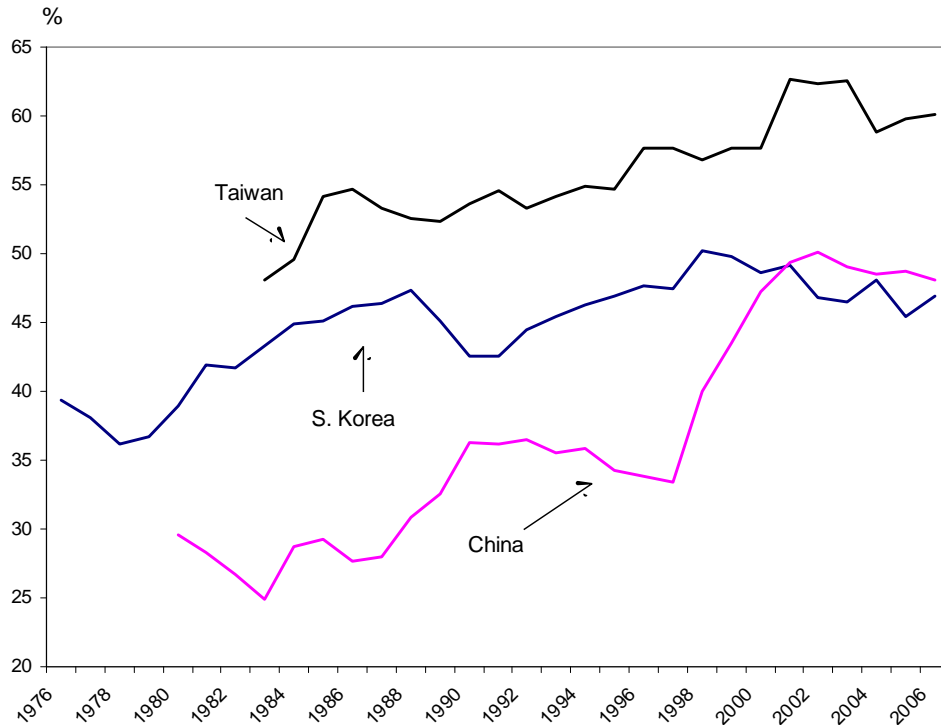


Figure 2: Human capital and R&D in total available investment

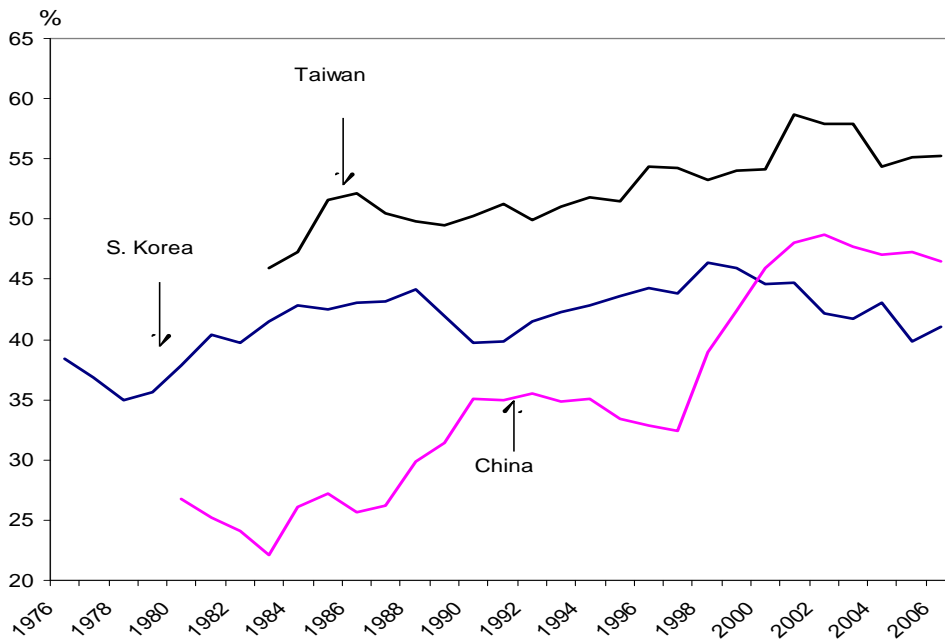


Figure 3: Share of Human Capital in Total available Investment

Figure 2 shows the increasing share of human capital and R&D in total

available investment in the three economies. Figure 3 shows the increasing share of human capital in total available investment in Taiwan and China, as well as, although with fluctuation, in South Korea. Our predictions of the shares of human capital and new technology, and of physical capital are consistent with Figures 2 and 3.

If the available budget  $S$  for total investment is positively related to GDP, the movement of ratios of  $\lambda K_e$  and spendings for human capital  $T$  to GDP follow the ratios of  $\lambda K_e$  and  $T$  to  $S$ .

Figures 4, 5 and 6 are consistent with our prediction that both the sum  $\mu_t + \theta$  of the share of human capital and R&D and the share of human capital in GDP increase. The Asian crisis of 1997 on investment in human capital and R&D is visible on Figures 4, 5 and 6. China was the least affected, South Korea the most, it had to resort to International Monetary Fund (IMF). South Korea recovered after 1999 keeping a drastic spending policy till the early 2000s. That is why the figure 6 shows a declining trend for both the share of human capital and R&D, and the share of human capital, after 1997.

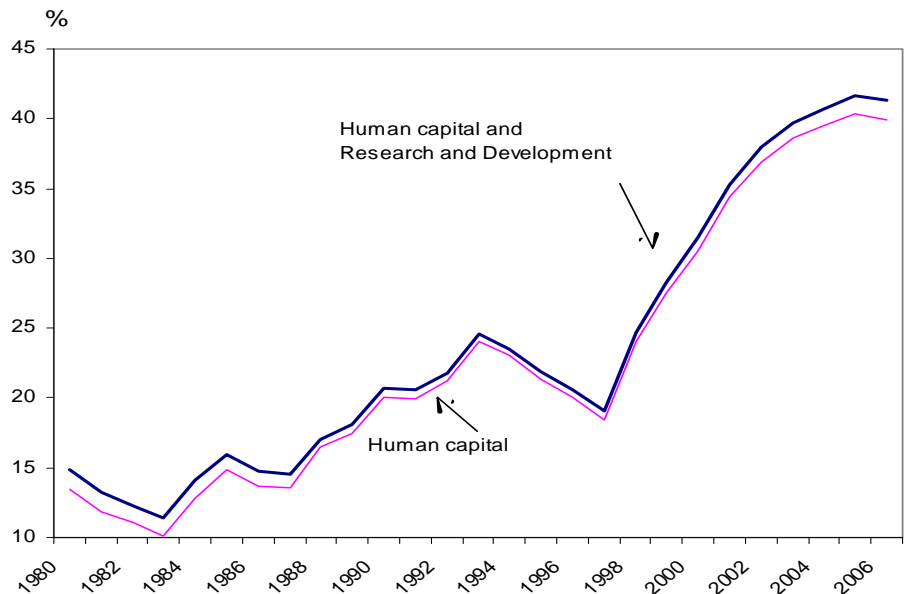


Figure 4: Human capital and R&D (%GDP): China

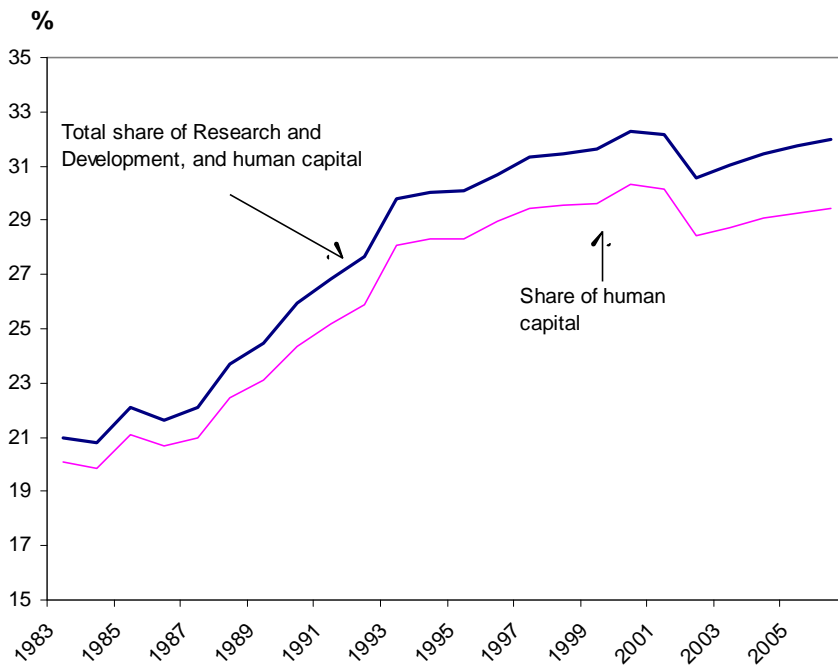


Figure 5: Human capital and R&D (%GDP): Taiwan

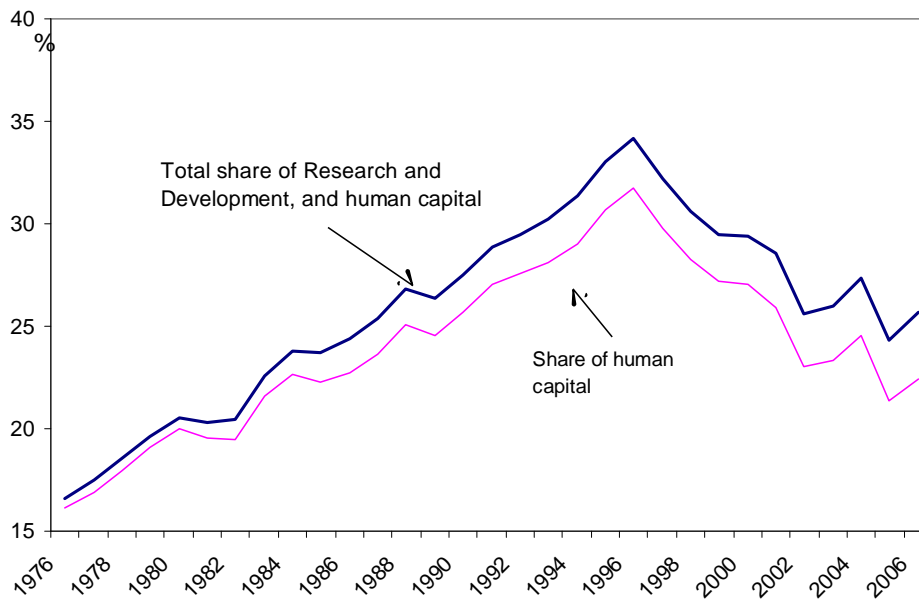


Figure 6: Human capital and R&D (%GDP): South Korea

## 5 Conclusion

At low economic level, a country would invest only in physical capital but at higher stage it would need to invest not only in physical capital but also in new technology and in high education.

Under some mild conditions on the quality of the production of new technology and on the supply of skilled workers, the share of the investment, in human capital, and in new technology and human capital, increases when the country becomes rich.

Thanks to new technology and human capital, the Total Factor Productivity increases and induces growth, the optimal path ( $S_t^*$ ) goes to  $+\infty$ . The economy grows unabated. The share  $\theta_t^* + \mu_t^*$  of investment in new technology and human capital ( $\theta_t^* + \mu_t^*$ ) increases while the share in physical capital decreases. In concordance with Barro and Sala-i-Martin (2004), the share  $\mu_t^*$  exceeds the share for physical and new technology capitals when  $t$  goes to infinity. They converge to strictly positive values when time goes to infinity.

The empirical tests confirm the theoretical results. They support our prediction that when income is under a critical level there is no demand for investing in human capital. There exists a threshold for investing in human capital in the course of development.

Our predictions of the shares of human capital and of new technology, and of physical capital, are coherent with empirical data from the economies of China, Korea, and Taiwan.

## 6 Appendix 1

### Proof of Proposition 1 .

*Step 1* Define

$$B = \{S \geq 0 : F(r_e, S) = x_0 L_d^{*1-\alpha_d}\} \quad (30)$$

**Lemma 1** *B is a nonempty compact set.*

*Proof:* Bruno *et al* (2008).

As  $F(r_e, S) \geq x_0 L_d^{*1-\alpha_d}$ , if the optimal value for  $\theta$  equals 0 then the one for  $\mu$  is also 0 and  $F(r_e, S) = x_0 L_d^{*1-\alpha_d}$ .

*Step 2* Lemma 2 shows that if  $S$  is small, then the country does 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  $\bar{S}$  such that if  $S > \bar{S}$  then  $\theta > 0$ .*

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

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

$$r_e \underline{S}^{\alpha_e} h(\underline{S})^{1-\alpha_e} = X \quad (31)$$

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

$$r_e \theta^{\alpha_e} S^{\alpha_e} h(\mu S)^{1-\alpha_e} \leq X \quad (32)$$

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

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

*Step 3 : Proof of Proposition 1*

Define

$$S^c = \max\{S \geq 0 : S \in B\} \quad (33)$$

As  $S^c \geq \underline{S} > 0$  and  $B$  is compact,  $0 < S^c < +\infty$

For any  $S \geq 0$  we have:

$$F(r_e, S) \geq x_0 L_d^{*1-\alpha_d} \quad (34)$$

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

$$\psi(r_e, \theta, \mu, S) \leq \psi(r_e, \theta, \mu, S^c) \quad (35)$$

which implies

$$F(r_e, S) \leq F(r_e, S^c) = x_0 L_d^{*1-\alpha_d} \quad (36)$$

Thus,

$$F(r_e, S) = x_0 L_d^{*1-\alpha_d} \quad (37)$$

Let  $S_0 < S^c$ . Assume that there exists two optimal values for  $(\theta, \mu)$  which are  $(0, 0)$  and  $(\theta_0, \mu_0)$  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  $\theta_0 = 0, \mu_0 = 0$ .)

As  $\theta_0 > 0$ , 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

$$\begin{aligned} x_0 L_d^{*1-\alpha_d} = F(r_e, S^c) &\geq \psi(r_e, \theta_0, \mu_0, S^c) \\ &> \psi(r_e, \theta_0, \mu_0, S_0) = x_0 L_d^{*1-\alpha_d} \end{aligned} \quad (38)$$

which is a contradiction.

Therefore, if  $S > S^c$  then

$$F(r_e, S) > x_0 L_d^{*1-\alpha_d} \quad (39)$$

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

### **Proof of Proposition 2**

1. Take  $S > S^c$ . From the Proposition 1,  $\theta(S) > 0$ . Assume  $\mu(S) = 0$ . For

short, denote  $\theta^* = \theta(S)$ . Define

$$F^0(r_e, S, \theta^*, 0) = \underset{0 \leq \theta \leq 1}{\text{Max}} \psi(r_e, \theta, 0, S) = \Phi(r_e \theta^{*\alpha_e} S^{\alpha_e} h(0)^{1-\alpha_e}) (1 - \theta^*)^{\alpha_d} L_d^{*1-\alpha_d} \quad (40)$$

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

$$F^1(r_e, S, \theta, \mu) = \Phi(r_e \theta^{\alpha_e} S^{\alpha_e} h(\mu S)^{1-\alpha_e}) (1 - \theta^*)^{\alpha_d} L_d^{*1-\alpha_d} \quad (41)$$

We then have:

$$\begin{aligned} & \frac{F^1(r_e, S, \theta, \mu) - F^0(r_e, S, \theta^*, 0)}{(1 - \theta^*)^{\alpha_d} L_d^{*1-\alpha_d}} \\ &= \Phi(r_e \theta^{\alpha_e} S^{\alpha_e} h(\mu S)^{1-\alpha_e}) - \Phi(r_e \theta^{*\alpha_e} S^{\alpha_e} h(0)^{1-\alpha_e}) \\ &= r_e S^{\alpha_e} \left( \theta^{\alpha_e} h(\mu S)^{1-\alpha_e} - \theta^{*\alpha_e} h(\mu S)^{1-\alpha_e} + \theta^{*\alpha_e} h(\mu S)^{1-\alpha_e} - \theta^{*\alpha_e} h(0)^{1-\alpha_e} \right) \end{aligned} \quad (42)$$

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

$$\begin{aligned} & F^1(r_e, S, \theta, \mu) - F^0(r_e, S, \theta^*, 0) \geq \\ & r_e S^{\alpha_e} \mu h(\mu S)^{-\alpha_e} \left( -\alpha_e h(\mu S) (\theta^* - \mu)^{\alpha_e - 1} + S(1 - \alpha_e) \theta^{*\alpha_e} h'(\mu S) \right) \end{aligned} \quad (43)$$

When  $\mu \rightarrow 0$ ,  $h'(\mu S) \rightarrow +\infty$ . The expression in the big parentheses converges to  $+\infty$ , which is contradicting with the optimality of  $\theta^*$ .

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

$$\frac{ar_e \theta^{\alpha_e - 1} S^{\alpha_e} h(0)^{1-\alpha_e} \alpha_e}{x_0 + a \left( r_e \theta^{\alpha_e} S^{\alpha_e} h(0)^{1-\alpha_e} - X \right)} = \frac{\alpha_d}{1 - \theta} \quad (44)$$

and

$$\frac{ar_e \theta^{\alpha_e} S^{\alpha_e + 1} h'(0) h(0)^{-\alpha_e} (1 - \alpha_e)}{x_0 + a \left( r_e \theta^{\alpha_e} S^{\alpha_e} h(0)^{1-\alpha_e} - X \right)} \leq \frac{\alpha_d}{1 - \theta}. \quad (45)$$

Eq. (44) implies

$$\frac{ar_e\theta^{\alpha_e-1}h(0)^{1-\alpha_e}\alpha_e}{\frac{x_0}{S^{\alpha_e}} + a(r_e\theta^{\alpha_e}h(0)^{1-\alpha_e})} \leq \frac{\alpha_d}{1-\theta}. \quad (46)$$

If  $\theta \rightarrow 0$  when  $S \rightarrow +\infty$ , then the LHS of inequality (46) converges to infinity while the RHS converges to  $\alpha_d$ : this is a contradiction. Thus  $\theta$  will be bounded away from 0 when  $S$  goes to infinity.

Combining Eq. (44) and inequality (45) we get:

$$h'(0)(1-\alpha_e)S \leq h_0\alpha_e\theta^{-1}. \quad (47)$$

When  $S \rightarrow +\infty$ , we have a contradiction because the LHS of Eq.(47) goes to infinity while the RHS is upper bounded. There exists  $S_M$  such that for any  $S \geq S_M$ ,  $\mu(S) > 0$ .

3. Let  $S > S^c$ . For short, we denote  $\mu$  and  $\theta$  instead of  $\mu(S)$  and  $\theta(S)$ . If  $\mu > 0$  then we have the first order condition:

$$\frac{ar_e\theta^{\alpha_e-1}S^{\alpha_e}h(\mu S)^{1-\alpha_e}\alpha_e}{x_0 + a(r_e\theta^{\alpha_e}S^{\alpha_e}h(\mu S)^{1-\alpha_e} - X)} = \frac{\alpha_d}{1-\theta-\mu}, \quad (48)$$

and

$$\frac{ar_e\theta^{\alpha_e}S^{\alpha_e+1}h'(\mu S)h(\mu S)^{-\alpha_e}(1-\alpha_e)}{x_0 + a(r_e\theta^{\alpha_e}S^{\alpha_e}h(\mu S)^{1-\alpha_e} - X)} = \frac{\alpha_d}{1-\theta-\mu}. \quad (49)$$

Let  $\theta^c$  and  $S^c$  satisfy:

$$\frac{ar_e(\theta^c)^{\alpha_e-1}(S^c)^{\alpha_e}h(0)^{1-\alpha_e}\alpha_e}{x_0 + a(r_e(\theta^c)^{\alpha_e}(S^c)^{\alpha_e}h(0)^{1-\alpha_e} - X)} = \frac{\alpha_d}{1-\theta^c}, \quad (50)$$

and

$$\left(x_0 + a(r_e(\theta^c)^{\alpha_e}(S^c)^{\alpha_e}h(0)^{1-\alpha_e} - X)\right)(1-\theta^c)^{\alpha_d} = x_0. \quad (51)$$

Eq.(50) is the first order condition with respect to  $\theta$ , while Eq. (51) states that  $\psi(r_e, \theta^c, 0, S^c) = x_0L_d^{*1-\alpha_d}$ . 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:

$$\frac{ar_e(\theta^c)^{\alpha_e}(S^c)^{\alpha_e+1}h'(0)h(0)^{-\alpha_e}(1-\alpha_e)}{x_0+a\left(r_e(\theta^c)^{\alpha_e}(S^c)^{\alpha_e}h(0)^{1-\alpha_e}-X\right)} < \frac{\alpha_d}{1-\theta^c}. \quad (52)$$

Eq. (50), (51), and (52) give 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  $S^c$ , Eq. (50) and inequality (52) still hold true. That means  $\mu(S) = 0$  for any  $S$  close to  $S^c$ .

### Proof of Proposition 3

*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  $\mu(S^2) = 0$  because  $\theta(S^2) = 0$  (see Proposition 1). For short, we write  $\theta_1 = \theta(S^1)$ ,  $\theta_2 = \theta(S^2)$ ,  $\mu_1 = \mu(S^1)$ ,  $\mu_2 = \mu(S^2)$ .

$(\theta_1, S^1)$  satisfy Eq. (44) and (45), or equivalently Eq. (44) and (47). Eq. (44) is written as

$$h_0^{1-\alpha_e} ar_e \left( \alpha_e \theta_1^{\alpha_e-1} - (\alpha_e + \alpha_d) \theta_1^{\alpha_e} \right) = \frac{\alpha_d(x_0 - aX)}{S_1^{\alpha_e}}. \quad (53)$$

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  $(\theta_2, S^2)$  satisfy Eq. (44) and (47). That means they satisfy the first order condition. with  $\mu_2 = 0$ .

The LHS of Eq. (53) is a decreasing function in  $\theta_1$ . Hence  $\theta_1$  is determined uniquely.

When  $x_0 > aX$ , if  $(\theta_2, S^2)$  satisfy Eq. (53), with  $S^2 < S^1$ , then  $\theta_2 < \theta_1$ . In this case,  $(\theta_2, S^2)$  also satisfy Eq. (47), and we have  $\mu_2 = 0$ .

When  $x_0 < aX$ , write Eq. (53) as:

$$h_0^{1-\alpha_e} ar_e \left( \alpha_e \theta_1^{-1} - (\alpha_e + \alpha_d) \right) = \frac{\alpha_d(x_0 - aX)}{(\theta_1 S^1)^{\alpha_e}}. \quad (54)$$

If  $(\theta_2, S^2)$  satisfy Eq. (53), with  $S^2 < S^1$ , then  $\theta_2 > \theta_1$ . As  $x_0 < aX$ , from Eq. (54), we have  $\theta_2 S^2 < \theta_1 S^1$ . Again  $(\theta_2, S^2)$  satisfy Eq. (53) and (47). That implies  $\mu_2 = 0$ .

*Step 2*

Let

$$\tilde{S} = \max\{S_m : S_m \geq S^c, \text{ and } S \leq S_m \Rightarrow \mu(S) = 0\} \quad (55)$$

and

$$\tilde{\tilde{S}} = \inf\{S_M : S_M > S^c, \text{ and } S > S_M \Rightarrow \mu(S) > 0\} \quad (56)$$

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  $\tilde{\tilde{S}} \geq \tilde{S}$ . If  $\tilde{\tilde{S}} > \tilde{S}$ , then take  $S \in (\tilde{S}, \tilde{\tilde{S}})$ . From the definitions of  $\tilde{S}$  and  $\tilde{\tilde{S}}$ , there exist  $S_1 < S$ , and  $S_2 > S$  such that  $\mu(S_1) > 0$  and  $\mu(S_2) = 0$ . But that contradicts Step 1. Hence  $\tilde{\tilde{S}} = \tilde{S}$ . Putting  $\hat{S} = \tilde{\tilde{S}} = \tilde{S}$  leads to the proof.

#### **Proof of Proposition 4**

From Proposition 3, we have  $\mu^c = 0$ . In this case,  $\theta^c$  and  $S^c$  satisfy Eq. (48) 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

$$\frac{a r_e (\theta^c)^{\alpha_e - 1} (S^c)^{\alpha_e} h_0^{1-\alpha_e} \alpha_e}{x_0 + a (r_e (\theta^c)^{\alpha_e} (S^c)^{\alpha_e} h_0^{1-\alpha_e} - X)} = \frac{\alpha_d}{1 - \theta^c} \quad (57)$$

and

$$\left( x_0 + a (r_e (\theta^c)^{\alpha_e} (S^c)^{\alpha_e} h_0^{1-\alpha_e} - X) \right) (1 - \theta^c)^{\alpha_d} = x_0 \quad (58)$$

Computations show that  $\theta^c$  satisfies:

$$\alpha_e \left( 1 - \frac{x_0 - aX}{x_0} (1 - \theta)^{\alpha_d + 1} \right) = \theta (\alpha_d + \alpha_e) \quad (59)$$

If  $x_0 > aX$ , the LHS is a strictly concave function which increases from  $\frac{\alpha_e aX}{x_0}$  when  $\theta = 0$  to  $\alpha_e$  when  $\theta = 1$ . The RHS is linearly increasing, equal to 0 at

the origin and to  $\alpha_d + \alpha_e$  when  $\theta = 1$ . Then, there exists a unique solution  $\theta^c \in (0, 1)$ .

If  $x_0 < aX$ , the LHS is a strictly convex function which decreases from  $\frac{\alpha_e aX}{x_0}$  when  $\theta = 0$  to  $\alpha_e$  when  $\theta = 1$ . The RHS is linear increasing, equal to 0 at the origin and to  $\alpha_d + \alpha_e$  when  $\theta = 1$ . Then, 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,  $\theta^c$  does not depend on  $r_e$ .  $\theta^c$  is positively related to  $a$  if  $x_0 \neq aX$ . With a higher value of the spill-over indicator  $a$  (better social capital and institutional capital), the economy not only invests in new technology earlier but also invests more initially.

Eq. (58) gives:

$$ar_e(S^c)^{\alpha_e} = \left( x_0 \left( \frac{1}{(1 - \theta^c)^{\alpha_d}} - 1 \right) + aX \right) \frac{1}{(\theta^c)^{\alpha_e} h_0^{1 - \alpha_e}} \quad (60)$$

$S^c$  is a decreasing function in  $a$  and  $r_e$ .

**Proof of Proposition 7** Let  $S^s$  be defined by

$$\alpha_d(S^s)^{\alpha_d - 1} x_0 L_d^{*1 - \alpha_d} = \frac{1}{\beta} \quad (61)$$

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  $t \geq T_2$ .

Consider the case where  $0 < S_0 < S^c$ . Obviously,  $\theta_0^* = 0$ . If  $a$  or  $r_e$  are large then  $S^c < S^s$ . If for any  $t$ ,  $\theta_t^* = 0$ , also  $K_{e,t}^* = 0 \forall t$ , and the optimal path  $(S_t^*)_t$  converges to  $S^s$  (Le Van and Dana 2003). But,  $S^c < S^s$ , hence the optimal path  $(S_t^*)_t$  is non decreasing and exceeds  $S^c$  after some date  $T_1$  and  $\theta_t^* > 0$  when  $t \geq T_1$ .

If the optimal path  $(S_t^*)_t$  goes 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 goes to infinity if  $a$  or  $r_e$  are large enough.

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

$$u'(c_t^*) = \beta u'(c_{t+1}^*) H'_s(r_e, S_{t+1}^*) \quad (62)$$

If  $S_t^* \rightarrow \bar{S} < \infty$ , then  $c_t^* \rightarrow \bar{c} > 0$ . From Euler equation, we get

$$H'_s(r_e, \bar{S}) = \frac{1}{\beta} \quad (63)$$

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

$$\begin{aligned} H'_s(r_e, S) &= F'_s(r_e, S) S^{\alpha_d} + \alpha_d F(r_e, S) S^{\alpha_d - 1} \\ &\geq F'_s(r_e, S) S^{\alpha_d} \end{aligned} \quad (64)$$

From the envelope theorem we get:

$$\begin{aligned} F'_s(r_e, S) S^{\alpha_d} &= \\ &\left( ar_e \theta^{*\alpha_e} (h(\mu^* S))^{-\alpha_e} (\alpha_e h(\mu^* S) + (1 - \alpha_e) \mu^* S h'(\mu^* S)) S^{\alpha_d + \alpha_e - 1} \right) \\ &\times L_d^{*1 - \alpha_d} (1 - \theta^* - \mu^*)^{\alpha_d} \end{aligned} \quad (65)$$

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

$$\begin{aligned} H'_s(r_e, S) &\geq L_d^{*1 - \alpha_d} (1 - \theta^* - \mu^*)^{\alpha_d} ar_e \theta^{*\alpha_e} (h^*(\mu S))^{1 - \alpha_e} \alpha_e S^{\alpha_d + \alpha_e - 1} \\ &\geq L_d^{*1 - \alpha_d} (1 - \bar{\zeta})^{\alpha_d} ar_e \underline{\theta}^{\alpha_e} (h^*(0))^{1 - \alpha_e} \alpha_e (S^c)^{\alpha_d + \alpha_e - 1} \end{aligned} \quad (66)$$

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

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

$$H'_s(r_e, S) \geq L_d^{*1-\alpha_d} (1 - \bar{\zeta})^{\alpha_d} ar_e \underline{\theta}^{\alpha_e} (h^*(0))^{1-\alpha_e} \alpha_e \quad (67)$$

and when  $ar_e$  becomes very large, the RHS of inequality (67) will be larger than  $\frac{1}{\beta}$ .

Assume  $\alpha_d + \alpha_e > 1$ . From Eq. (60), the quantity  $ar_e(S^c)^{\alpha_e}$  equals

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

and

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

We have

$$H'_s(r_e, S) \geq L_d^{*1-\alpha_d} (1 - \bar{\zeta})^{\alpha_d} \underline{\theta}^{\alpha_e} (h^*(0))^{1-\alpha_e} \alpha_e \gamma \left( \frac{\gamma}{ar_e} \right)^{\frac{\alpha_d-1}{\alpha_e}}$$

Because  $\alpha_d - 1 < 0$ , when  $ar_e$  is large,  $H'_s(r_e, S) > \frac{1}{\beta}$ .

## 7 Appendix 2: Data

Table 2: Inputs and Technical Progress

**Contributions (in percent) of the Sources of Growth**

	Sample period	Physical capital	Labor	Human capital	Technical progress
<b>(1) Before 1973</b>					
Hong Kong	1966-73	68.37 (9.67)	28.50 (3.10)	3.13 (5.57)	0.00
S. Korea	1960-73	72.60 (11.58)	21.87 (4.14)	5.53 (7.70)	0.00
Singapore	1964-73	55.59 (12.73)	40.18 (7.56)	4.22 (9.17)	0.00
Taiwan	1953-73	80.63 (13.21)	15.45 (2.63)	3.91 (6.73)	0.00
Indonesia	1970-73	73.09 (11.09)	9.37 (2.15)	17.54 (19.50)	0.00
Malaysia	1970-73	59.97 (9.56)	29.99 (4.32)	10.05 (12.64)	0.00
Philippines	1970-73	39.79 (5.12)	49.97 (7.36)	10.24 (11.51)	0.00
Thailand	1970-73	82.11 (10.96)	7.67 (0.57)	10.22 (11.44)	0.00
China	1965-73	85.29 (13.51)	10.36 (3.19)	4.35 (7.01)	0.00
Japan	1957-73	55.01 (11.43)	4.85 (0.82)	1.06 (2.87)	39.09
*G-5	1957-73	41.50 (4.62)	6.00 (4.24)	1.43 (1.70)	51.07
<b>(2) 1974-85</b>					
Hong Kong	1974-85	64.31 (9.58)	32.73 (3.40)	2.96 (5.67)	0.00
South Korea	1974-85	78.08 (13.28)	18.10 (2.83)	3.81 (6.41)	0.00
Singapore	1974-85	64.68 (9.94)	31.72 (3.42)	3.60 (5.48)	0.00
Taiwan	1974-85	78.91 (11.89)	18.12 (2.23)	2.97 (4.98)	0.00
Indonesia	1974-85	77.69 (12.22)	13.55 (2.65)	8.76 (10.20)	0.00
Malaysia	1974-85	61.39 (10.76)	33.61 (4.94)	5.00 (8.15)	0.00
Philippines	1974-85	62.59 (7.29)	29.28 (3.53)	8.13 (8.07)	0.00
Thailand	1974-85	67.53 (8.69)	25.02 (3.55)	7.46 (8.96)	0.00
China	1974-85	80.46 (9.44)	14.64 (2.53)	4.09 (6.37)	0.00
Japan	1974-85	40.65 (6.73)	10.22 (0.93)	0.96 (1.69)	48.17
*G-5	1974-85	36.29 (2.65)	-14.55 (-0.42)	2.53 (1.90)	75.73

In parentheses the average annual rates of growth of each inputs.

Table 2 (*cont.*): Inputs and Technical Progress

**Contributions (in percent) of the Sources of Growth**

	Sample period	Physical capital	Labor	Human capital	Technical progress
<b>(3) After 1986</b>					
Hong Kong	1986-95	41.81 (7.56)	6.46 (0.53)	1.58 (3.10)	50.14
South Korea	1986-95	44.54 (11.90)	14.98 (2.76)	1.75 (4.15)	38.73
Singapore	1986-95	37.01 (8.50)	31.30 (4.32)	1.52 (3.38)	30.17
Taiwan	1986-95	43.00 (9.01)	10.46 (1.34)	1.38 (3.13)	45.16
Indonesia	1986-94	62.79 (8.88)	15.91 (2.31)	5.69 (6.94)	15.61
Malaysia	1986-95	42.87 (8.53)	33.41 (4.83)	3.25 (6.15)	20.47
Philippines	1986-95	52.18 (3.77)	41.63 (2.96)	6.23 (5.09)	-0.03
Thailand	1986-94	51.01 (11.27)	13.32 (2.72)	2.36 (5.25)	33.31
China	1986-95	86.39 (12.54)	10.34 (1.92)	3.27 (4.54)	0.00
Japan	1986-94	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

In parentheses, the average annual rates of growth of each inputs.

\*G-5: France, West Germany, Japan, UK and US

*Source:* Lau and Park (2003)

Table 3: Countries in the Sample of Human Capital

<b>Economies</b>	<b>Range</b>	<b>Economies</b>	<b>Range</b>
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:* Barro and Lee (2000)

Data are calculated every 5 years and some data for 1955 are missing.



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