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The Optimal Structure of Technology Adoption and Creation: Basic Research vs. Development in the Presence of Distance to Frontier

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Abstract

This paper presents a theoretical model and empirical evidence to explain the observation that a country in which the level of technology approaches the technology frontier tends to rely more on technology creation than adoption, and to invest more in basic research than in development. The model shows that technology creation involves both basic and development research processes while technology adoption uses only the latter process. Thus, research and development (R&D) investment in our model involves three different processes: basic research in technology creation, development in technology creation, and development in technology adoption. The results suggest first, that the rate of growth is positively correlated with the level of basic research activities in the technology creation sector, if one country's technology gap with the technology frontier is small enough. Second, an increase in the efficiency of the education system for highly skilled workers raises the level of basic research and the rate of growth. Third, verifying these theoretical results, empirical analyses using panel data of Japan; Republic of Korea; and Taipei, China show that the narrower the technological distance to the frontier, the higher the growth effect of basic R&D, indicating that the share of basic R&D matters for economic growth. Last, these also show that the quality of tertiary education has a significantly positive effect on the productivity of R&D.

I. Introduction

Recently, many economists have insisted that Asian countries in particular—such as the People’s Republic of China, Japan, Republic of Korea (henceforth Korea), and others—should focus more on basic research than technology adoption, and on the supply of skilled workers than unskilled workers, to advance economic growth (Lee 2005 and Suh and Chen 2007). This is because these countries face difficulty obtaining freely available technologies as their technology levels move closer to the technological frontier.¹

In this context, this paper presents a theoretical model and empirical evidence that support the following observation. As an economy’s technological distance to frontier narrows, it relies more on creation than adoption, and also invests more in basic research (or high-skill education) for technology creation than in development research (or low-skill education) for technology adoption. Specifically, the model implies that the narrower a country’s technological distance, the more it induces economic growth to correlate positively with the level of high-skilled human capital and basic research activities for technology creation. It also implies that an increase in the efficiency of an education system increases technology and output growth rates. In addition, we provide relevant empirical evidence for these theoretical predictions using data from Japan; Korea; and Taipei, China.

There are several papers that explore implications similar to ours. Aghion and Howitt (1996) investigate the role of the mix of research and development (R&D) in a Schumpeterian growth model. They also distinguish basic from development research investment, as in our model. In their model, there exist three types of knowledge: general, fundamental, and secondary knowledge. Researchers produce fundamental knowledge

¹ Lee (2005) and Suh and Chen (2007) diagnose problems in the Korean economy and propose policies for developing it as a knowledge-based economy. For example, Suh and Chen (2007) suggest that “Changes in economic environments in the early 1980s induced Korea to embark on serious investments in indigenous research and development. On the one hand, Korean industrial development had reached the stage at which domestic industries found it more difficult to be competitive in the international market because they were reliant on imported technologies and employed domestic labor that was becoming more and more expensive. On the other hand, Korean industries had grown to become potential competitors in the international market, making foreign companies increasingly reluctant to transfer technologies to Korea; thus, it was inevitable that Korea would have to develop an indigenous base for research and innovation. Meeting the challenge required highly trained scientists and engineers as well as financial resources to support R&D activities, which are by nature uncertain and risky” (Suh and Chen 2007, 18).

represented by the number of newly invented product lines using general knowledge, which is nonappropriable and open to the public. The fundamental knowledge is appropriable, but these product lines cannot be used without the invention of their plans through the development process. These plans represent secondary knowledge. While these distinctions and their theoretical implications are similar to ours, we differ from their model in that we study not only the interaction between education and R&D investment, but also the distinction between technology adoption and creation.

Vandenbussche, Aghion, and Meghir (2006) examine the role of human capital composition in a model of technology adoption and innovation. They set up a theoretical model to show that one country's skilled labor has a higher growth-enhancing effect when its technology level is closer to the technology frontier. This is under the assumption that technology creation is a relatively more skill-intensive activity than adoption. They also provide empirical evidence, using a panel dataset covering 19 countries in the Organisation for Economic Co-operation and Development between 1960 and 2000, that as a country moves closer to the technology frontier, tertiary level education becomes increasingly more important for growth than primary and secondary education. Even though the paper's implication for the role of human capital in technology adoption and creation is similar to ours, our model differs from theirs in that it distinguishes the process of research in the dimension of basic and development research. Also our model studies a micro-mechanism showing how a different mixture of unskilled and skilled human capital leads to different opportunities for technological improvement through different channels of technology adoption and creation.

The theoretical part of the paper presents an endogenous growth model economy in which technological progress occurs through two channels of technology adoption and creation. We also assume that technology adoption and creation consist of basic research and development processes. A basic research process creates new basic ideas. In contrast, a development process produces different intermediate goods from available basic ideas, which are used for technological improvements.² These processes of technology adoption and creation are described by Romer's variety expansion model.

Our model actually distinguishes only three processes of R&D investment, instead of four: basic research in technology creation, development in technology creation, and

² This distinction between basic and development research process is very similar to that of Aghion and Howitt (1996), even though our modeling strategy is different from theirs: "Research produces fundamental knowledge, which by itself may not be useful, but which opens up windows of opportunity, whereas the purpose of development is to generate secondary knowledge, which will allow those opportunities to be realized. In this respect the distinction is much the same as that between basic and applied research, between invention and innovation, or between innovation and diffusion. Thus research and development are complementary activities; in order to profit from the fundamental knowledge generated by research a firm must spend resources developing applications, while development by itself would be of no use if there were no fundamental ideas to be developed. We capture this distinction by supposing that each innovation resulting from research consists of a potential line of new products and that each innovation resulting from development consists of a workable plan for producing one of those products" (Aghion and Howitt 1996, 50).

development in technology adoption. This is because the pool of basic research used for adoption is publicly available, so there exists no need for further basic research before adoption can take place. Thus, our model focuses on only three types of innovative R&D: basic research creating new ideas, development research that turns the basic ideas created by the basic research into new intermediate goods, and other development research adopting intermediate goods that already have existed in advanced countries.

In addition, the model economy consists of three types of workers differing in their level of human capital: highly skilled workers for basic research in the creation sector, skilled workers for development activities in the creation sector, and less skilled workers for development activities in the adoption sector.³ The supply of three different types of human capital is determined endogenously.

Our theoretical model shows that economic growth is more positively correlated with the amount of skilled human capital (or highly skilled) and basic research in technology creation when one country's technological distance to frontier is narrower. It also shows that the efficiency of the education system improves the efficiency of basic R&D, and thus increases the output growth rate.

We find empirical evidence supporting these results. Specifically, using the time series data of three East Asian economies, namely Japan; Korea; and Taipei, China, we find the interaction between R&D input structure and distance to technological frontier significantly affects total factor productivity (TFP) growth. As the TFP level of an economy approaches that of the world frontier, basic research becomes relatively more important, and an increase in the share of basic R&D in total R&D expenditure significantly raises the TFP growth rate. We also find that using the time series data of the three countries, the quality of higher education, measured by teacher–pupil ratio of tertiary education, has a positive association with the productivity of R&D expenditures, and thus with TFP growth rates.

The paper is structured as follows. Section II describes the basic setup of the model, and provides the mechanism of demand and supply for different types of human capital and optimal structures of various types of research investment. Section III describes the equilibrium paths of technology and output, and the effects of government policies on them, while Section IV provides empirical evidence that supports the main implications derived from the model. Conclusions follow in Section V.

³ In this way, our model embeds the skill-technology complementarity. There exist several important studies focusing on the role of this complementarity in technological change and economic growth. See Redding (1996), Lloyd-Ellis and Roberts (2000), Basu and Weil (1998), Kim and Lee (2009), and Acemoglu (2001), among others.

II. The Model

The model economy is described by a representative firm and by three different types of workers who differ in their level of human capital (less skilled workers U , skilled workers S , and highly skilled workers H). The firm produces final output by combining three inputs of raw labor, physical capital, and technology. The three types of workers engage in different research activities for technology improvements.

The technology sector consists of technology adoption and technology creation subsectors. In the adoption subsector, development research activities of less skilled workers (U) produce different intermediate goods utilizing freely available basic ideas for technological improvements. They provide these intermediate goods to monopolistic competitive markets. The amount of new basic ideas that flow into the adoption sector in each period is proportional to this country's technological distance to frontier.

On the other hand, in the creation sector, the development activities of skilled workers (S) produce various intermediate goods from the pool of basic ideas for technological improvements. These intermediate goods, which are adapted from corresponding basic ideas, are bought from monopolistic competitive markets. New basic ideas that flow into the creation sector in each period are created by basic research activities of highly skilled workers (H), in addition to spillover from foreign technologies due to the technology gap. The inventor of a new basic idea is assumed to monopolize his profit for one period.

The supply of three different types of workers is endogenously determined. We assume each worker living two periods is born with a certain level of ability, and one unit of time for labor supply in the second period. A worker with greater ability pays less for education. In his first period, through obtaining relevant education, he chooses one of the three types of human capital that differ in the level of skill. The more able he is, the less he pays for the same level of education. In the second period, he works in one of the three different research sectors: development research in the adoption sector, development research in the creation sector, or basic research in the creation sector.

A. Production and Technology

1. Production

The final output of the economy is produced by the Cobb-Douglas technology of

$$Y_t = T_t^\gamma K_t^\nu L_t^{1-\gamma-\nu}, \quad (1)$$

where T_t represents the level of technology and is a function of human capital, K_t the level of physical capital, and L_t raw labor. We assume the final output market is competitive and consists of a unit measure of identical firms. A capital market is

internationally open, and thus the interest rate is exogenously given in the framework of a small open economy. For the sake of simplicity, we also assume that the amount of raw labor (L) is fixed in the economy.⁴

2. Human Capital and Technology

There are three different types of human capital—less skilled workers U , skilled workers S , and highly skilled workers H —that will be used in the adoption and creation sectors. We assume that the total amount of human capital employed for technology adoption and creation is fixed by one.⁵

$$U + S + H = 1 \quad (2)$$

The aggregate technology level is expressed as a summation of technology adoption level, $D_t(U)$, and technology creation level, $C_t(S)$ as

$$T_t = [D_t(U) + \kappa C_t(S)], \quad (3)$$

where $\kappa > 1$. Equation (3) implies that the level of technology is determined by the two sources of technological changes of adoption and creation. It also implies that these two sources do not congest and overlap, because they have different quality levels, aspects, and areas of technological changes.

Based on the Romer's variety expansion model, each technology process is described by

$$D_t(U) = \left[\int_0^{G_{Dt}} x_{Dt}(i)^{\frac{\alpha-1}{\alpha}} di \right]^{\frac{\alpha}{\alpha-1}} \quad (4)$$

$$C_t(S) = \left[\int_0^{G_{Ct}} x_{Ct}(i)^{\frac{\alpha-1}{\alpha}} di \right]^{\frac{\alpha}{\alpha-1}}, \quad (5)$$

where G_{Dt} represents the level of the pool of total basic ideas available for technology adoption at time t , G_{Ct} that available for technology creation, and $\alpha > 1$.

The pool of total basic ideas available in each sector is described as follows. The flow of new basic ideas in the creation sector is due not only to basic research activities of highly skilled human capital (H), but also to technology spillovers, which increase in the technological distance. An innovator, investing a certain amount of highly skilled workers

⁴ The assumption that the amount of total human capital (total R&D investment) is fixed helps focus on the impact of the allocation of human capital on the economy.

⁵ The relationship of equation (2) can be expressed in the efficiency unit measure of workers through education. That is, the total number of efficiency unit of workers (E_t) can increase over time with $U_t + H_t + S_t = E_t$, instead of being fixed by one. However, if the efficiency unit grows at the identical rate with final output, total research investment is still constrained with the fixed amount of research investment intensities, the ratio of research investments to gross domestic product (GDP).

$(u_t(j))$, creates new basic ideas by $Bu_t(j)G_{Ct-1}$.

Then the pool of the total basic ideas of the creation sector (G_C) accumulates over time by

$$G_{Ct} = \{1 + d(\bar{T} - T_t) + BH\} G_{Ct-1}, \quad (6)$$

where $d(\bar{T} - T_t)$ representing the efficiency of the adoption sector is an increasing function in its argument assuming that as the technology level approaches the fixed value of technology frontier (\bar{T}), it monotonically decreases to zero, $\int_{j=0}^1 u_t(j) dj = u_t = H$

(summed over all identical firms whose measure is one), H represents the total supply of highly skilled workers, and B is the efficiency of the creation (research) sector.⁶

The pool of the total basic ideas available in the adoption sector (G_D) accumulates over time by

$$G_{Dt} = \{1 + d(\bar{T} - T_{t-1})\} G_{Ct-1}. \quad (7)$$

One unit of each intermediate good (x_{jt}) is produced using one efficiency unit of human capital (l_{jt}) through the production technology of

$$x_{jt} = l_{jt} \text{ for } j = D, C, \quad (8)$$

where x_{jt} ($j=D, C$) represents intermediate goods in technology adoption ($j=D$) and technology creation process ($j=C$), respectively.

$$\int_0^{G_{Dt}} l_{Dt}(i) di = U, \quad (9)$$

$$\int_0^{G_{Ct}} l_{Ct}(i) di = S. \quad (10)$$

Hence, the adoption sector needs less skilled workers (U) to produce intermediate goods, while the creation sector needs skilled workers (S). The production of intermediate goods represents the development research process. Thus, the levels of less skilled workers (U) and skilled workers (S) imply the total amount of development research investment in the

⁶ B can also represent the success probability of basic research investment to create new ideas for each firm. With the success of basic research investment, the amount of basic idea for technology creation sector of firm j increases by $u(j)G_{Ct-1}$, while that does by zero with the failure, at time t . Then, the total pool for technology creation for the aggregate economy at the end of period t is represented by equation (6) with the success probability B , considering that the amount of basic research investment for any firm j ($u(j) = u = H$) is identical for all firms.

⁷ This expression implies that G_{Ct-1} is freely available at time t , and also represents the technology adoption sector's absorptive capacity of foreign technology spillovers at time t .

adoption and in the creation sector, respectively.

We assume that the intermediate goods markets of the adoption and of the creation sector are monopolistic competitive.

Technology and output levels are represented respectively by

$$T = G_{Ct-1}^{\frac{1}{\alpha-1}} \left\{ (1+d)^{\frac{1}{\alpha-1}} U + \kappa (1+d+BH)^{\frac{1}{\alpha-1}} S \right\}, \text{ and} \quad (11)$$

$$Y = \left\{ G_{Ct-1}^{\frac{1}{\alpha-1}} \left((1+d)^{\frac{1}{\alpha-1}} U + \kappa (1+d+BH)^{\frac{1}{\alpha-1}} S \right) \right\}^{\gamma} K^{\nu} L^{1-\gamma-\nu}, \quad (12)$$

where $d = d(\bar{T} - T_i)$.

Because the market for intermediate goods of the adoption sector is monopolistic competitive, we have $p_D(i) = \frac{\alpha}{\alpha-1} w(U)$, where $p_D(i)$ represents the price of an i -th intermediate good in the adoption sector. From this and $p_D(i) = \frac{\partial Y}{\partial x_D(i)}$, we derive

$$w(U) = \frac{\alpha-1}{\alpha} p_D(i) = \frac{\alpha-1}{\alpha} \frac{\partial Y}{\partial U} = \frac{\alpha-1}{\alpha} \gamma Y \frac{(1+d)^{\frac{1}{\alpha-1}}}{(1+d)^{\frac{1}{\alpha-1}} U + \kappa (1+d+BH)^{\frac{1}{\alpha-1}} S} \quad (13)$$

Similarly, we have $p_C(i) = \frac{\alpha}{\alpha-1} w(S)$, where $p_C(i)$ is the price of an i -th intermediate good

in the creation sector. From this and $p_C(i) = \frac{\partial Y}{\partial x_C(i)}$, we obtain

$$w(S) = \frac{\alpha-1}{\alpha} p_C(i) = \frac{\alpha-1}{\alpha} \frac{\partial Y}{\partial S} = \frac{\alpha-1}{\alpha} \gamma Y \frac{\kappa (1+d+BH)^{\frac{1}{\alpha-1}}}{(1+d)^{\frac{1}{\alpha-1}} U + \kappa (1+d+BH)^{\frac{1}{\alpha-1}} S} \quad (14)$$

Note informally here that the wage share for skilled workers increases in H and B and decreases in d and S .⁸ This is quite intuitive.

The highly skilled worker contributes to the creation of new ideas, which are used to produce intermediate goods in the creation sector, and earns profit π for one period.⁹

⁸ To be more precise, we should take into account the results of comparative static analysis.

⁹ We assume that the property right of a new idea will be transferred to the firm in the next period to simplify the model.

Considering that $\pi = \frac{1}{\alpha - 1} w(S) \frac{S}{G_{Ct}}$, the demand for the highly skilled worker is expressed by

$$w(H) = BG_{Ct-1}\pi = \frac{B}{\alpha - 1} \frac{S}{1 + d + BH} w(S). \quad (15)$$

It implies that the highly skilled worker's wage share is positively associated with B , S , and $w(S)$.

B. Household's Choice of Education and the Allocation of Human Capital

1. Household's Choice of Education

We assume that a unit measure of workers with different abilities lives for two periods. Each worker is born with a certain level of ability that is uniformly distributed on $[0, 1]$. And he is endowed with one unit of time for labor supply in his second period. He decides how much he invests in education in his first period, depending on his ability, education costs, and wage rates for different levels of human capital. Thereby, the type of human capital he owns in his second period will be determined. In the aforementioned way, demand and supply for each type of human capital determine wage rates, various research investments, and thus technology and output growth rates.

We assume that the education cost in the value of the second period to become a skilled workers is $\frac{C_s}{m(a)} w(S)$, while that to become a highly skilled one $\frac{C_H}{n(a)} w(H)$ ¹⁰, where $m(a)$ and $n(a)$ increase in a (worker's ability), and C_s and C_H represent the inefficiency of the education system. We assume that without education (that is, with zero education cost), he will work as a less skilled worker.

With these simplifying assumptions, we can easily derive the critical level of ability of a such that

¹⁰ We are assuming that education process costs resources proportional to the level of knowledge to be delivered which the student's future wage rate is also proportional to. Thus, the tuition for education is proportional to the student's future wage rate.

$$w(S) - \frac{C_S}{m(a)} w(S) > w(U) \Rightarrow \quad (16)$$

$$a > m^{-1} \left\{ C_S \frac{\kappa(1+d+BH)^{\frac{1}{\alpha-1}}}{\kappa(1+d+BH)^{\frac{1}{\alpha-1}} - (1+d)^{\frac{1}{\alpha-1}}} \right\} \equiv a_S^* . \quad 11$$

A worker with the ability higher than or equal to a_S^* will be educated to become a skilled worker by paying the education cost of $\frac{C_S}{m(a)} w(S)$. $m^{-1}(\cdot)$ is the inverse function of $m(a)$, increasing in a .

Similarly, a worker with the ability higher than or equal to a_H^* will be educated to become a highly skilled worker. $n^{-1}(\cdot)$ is the inverse function of $n(a)$, increasing in a .

$$w(H) - \frac{C_H}{n(a)} w(H) > w(S) \Rightarrow a > n^{-1} \left\{ C_H \frac{BS}{BS - (\alpha-1)(1+d+BH)} \right\} \equiv a_H^* . \quad (17)$$

In addition, we assume that with $a_H^* > a_S^*$, in order to join the pool of the highly skilled workers, workers with ability higher than a_H^* must obtain both of two different types of education, one to become skilled workers and the other to become highly skilled ones.

2. Comparative Statics related to the Allocation of Human Capital

From equation (12), we have

$$H = 1 - a_H^* = 1 - n^{-1} \left\{ C_H \frac{SB}{SB - (\alpha-1)(1+d+BH)} \right\} \quad (18)$$

Equations (16) and (18) yield

$$S = a_H^* - a_S^* = 1 - H - m^{-1} \left\{ C_S \frac{\kappa(1+d+BH)^{\frac{1}{\alpha-1}}}{\kappa(1+d+BH)^{\frac{1}{\alpha-1}} - (1+d)^{\frac{1}{\alpha-1}}} \right\} , \quad (19)$$

and

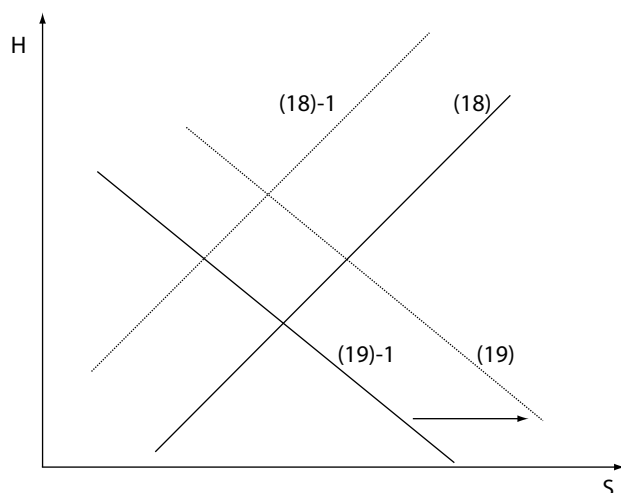
$$U = a_S^* = m^{-1} \left\{ C_S \frac{\kappa(1+d+BH)^{\frac{1}{\alpha-1}}}{\kappa(1+d+BH)^{\frac{1}{\alpha-1}} - (1+d)^{\frac{1}{\alpha-1}}} \right\} . \quad (20)$$

¹¹ If $\frac{1}{\kappa(1+d+BS)^{\frac{1}{\alpha-1}} - (1+d)^{\frac{1}{\alpha-1}}} < 0$, then $a_H^* = 1$.

Now, from equations (18), (19), and (20), we will find relationships among H , S , and U . Equation (18) implies the positive relationship between H and S . And with the assumption that the direct negative effect of an increase in H on S dominates the indirect positive effect on S ,¹² equation (19) implies the negative relationship between H and S .

Equations (18) and (19) yield comparative static results as follows (Figure 1).

Figure 1: Comparative Statics



- (i) As an economy's technology level approaches the technology frontier (a decrease in $(\bar{T} - T_{t-1})$), the curves of (18) and (19) shift to (18)-1 and (19)-1 respectively, thus raising H . And the effect on S depends on the elasticities of these two graphs. With the assumption that S does not change much, equation (20) implies that U decreases.
- (ii) An increase in the efficiency of the education system for highly skilled workers (a decrease in C_H) shifts the curve of (18) leftward as to (18)-1, thus raising H and lowering S . Equation (20) implies that U decreases.
- (iii) An increase in the efficiency of the education system for skilled workers (a decrease in C_S) shifts the curve of (19) rightward as to (19)-1, thus raising H and S . Thus U decreases.

¹² This assumption is reasonable because an increase in H affects S indirectly through increasing the pool of available basic ideas. For this to hold, we can specifically assume that the elasticity of $m(a)$ (η_m) is large enough such that the education system for L to become S or H may be very inefficient. It is consistent with the observation that many countries including East Asian countries are struggling to transform the objective of their education system from enhancing only memorizing skill to enhancing creativity.

- (iv) An increase in the efficiency of the basic research system for highly skilled workers (an increase in B) shifts both the curve of (18) leftward as to (18)-1 and the curve of (19) rightward as to (19)-1, thus raising H still further. The effect on S depends on the elasticities of these two graphs. Equation (20) implies that U decreases.

III. Equilibrium Growth Paths of Technology and Output, and Government Policies

This section describes the equilibrium paths of technology and output, and the effects of government policies on them. The previous model implies that over different generations, the model economy grows through the spillover of technological changes, in other words through the accumulation of general knowledge (G_C).

Equations (11) and (12) together with $\frac{\dot{Y}}{Y} = \frac{\dot{K}}{K} = \frac{\gamma}{1-\nu} \frac{\dot{T}}{T}$ yield¹³

$$\frac{\dot{T}}{T} = \frac{1}{\alpha-1} \frac{\dot{G}_C}{G_C} + (1-Z_C) \left\{ \frac{1}{\alpha-1} \frac{(1+d)}{(1+d)} + \frac{\dot{U}}{U} \right\} + Z_C \left\{ \frac{1}{\alpha-1} \frac{(1+d+BH)}{(1+d+BH)} + \frac{\dot{S}}{S} \right\} \quad (21)$$

Neglecting $\frac{(1+d)}{(1+d)}$ and $\frac{(1+d+BH)}{(1+d+BH)}$, equation (21) gives

$$\frac{\dot{T}}{T} \approx \frac{1}{\alpha-1} (1+d+BH) + (1-Z_C) \left(1 + \varphi_D U + \frac{\dot{U}}{U} \right) + Z_C \left(1 + \varphi_C S + \frac{\dot{S}}{S} \right) \quad (22)$$

where $Z_C = \frac{(1+d+BH)^{\frac{1}{\alpha-1}} \kappa S}{(1+d)^{\frac{1}{\alpha-1}} U + (1+d+BH)^{\frac{1}{\alpha-1}} \kappa S}$, and

$$\frac{\dot{Y}}{Y} \approx \frac{\gamma}{1-\nu} \left\{ \frac{1}{\alpha-1} (1+d+BH) + (1-Z_C) \left(1 + \varphi_D U + \frac{\dot{U}}{U} \right) + Z_C \left(1 + \varphi_C S + \frac{\dot{S}}{S} \right) \right\}^{14} \quad (23)$$

¹³ From the perfect capital mobility condition, $\frac{\partial}{\partial K_t} Y_t = \eta T_t^\gamma K_t^{\gamma-1} L_t^{1-\gamma-\nu} = \frac{\nu Y_t}{K_t} = \bar{r}$, we can easily infer that output and capital grow at the same rate.

¹⁴ At the steady state with $Z_C = 1$ and $d = 0$, $\frac{\dot{Y}}{Y} = \frac{\gamma}{1-\nu} \left\{ \frac{1}{\alpha-1} (1+BH) + (1+\varphi_C S) \right\}$.

The model implies that an economy grows by both the adoption and creation processes. Suppose that initially an economy's growth relies more on adopting technologies than on creating new technologies, due to a lower initial endowment of highly skilled workers. As its technology level approaches the technology frontier, the technology gap ($\bar{T} - T_{t-1}$) decreases over time. This in turn makes the technology adoption process slow down, and increases the level of technology creation. Characterizing the equilibrium growth paths of our model delivers the following three propositions.

Proposition 1: When one country's technological distance to frontier becomes smaller, a marginal increase in highly skilled human capital (basic research investment in the technology creation sector) raises the current economic growth rate more.

(Proof) From equation (12) we derive $\frac{\partial Y}{\partial H} = \frac{Z_c}{\alpha - 1} \frac{B}{1 + d + BH} \gamma Y$. Equation (19) implies that $\frac{\partial}{\partial d}(d + BH) > 0$. Then, with $\frac{\partial Z_c}{\partial d} < 0$, we can easily see that with a lower value of d , a marginal increase in H raises the current growth rate more. Thus, we prove the proposition.

Proposition 2: An increase in the level of basic research activities of the creation sector with the corresponding decrease in development research activities of the adoption sector, to have the fixed amount of total research investment, raises the growth rate. The smaller the technological distance, the higher the corresponding increase in the current growth rate.

(Proof) It is obvious that the maximization of one period's welfare leads to the maximization of the current growth rate given three state variables of G_{Ct-1} . For the maximization of one period growth rate, we can easily derive the social marginal benefit for a marginal increase in each type of worker as:

$$w''(U) = \frac{\partial Y}{\partial U} = \frac{\alpha}{\alpha - 1} w(U) \quad (P1)$$

$$w''(S) = \frac{\partial Y}{\partial S} = \gamma Y \frac{\kappa(1 + d + BH)^{\frac{1}{\alpha-1}}}{(1 + d)^{\frac{1}{\alpha-1}} U + \kappa(1 + d + BH)^{\frac{1}{\alpha-1}} S} = \frac{\alpha}{\alpha - 1} w(S) \quad (P2)$$

$$w''(S) = \frac{H}{\alpha - 1} \frac{B}{1 + d + BS} w''(H) \quad (P3)$$

By comparing (13)-(15) with (P1)-(P3) and based on equation (16), we can easily see that the transfer of one marginal agent from development research activities of the adoption sector to those of the creation sector does not change the social marginal benefit net of marginal cost, in the framework of one period growth maximization. Thus the growth

rate of income does not change. Note that in the market equilibrium where the private welfare is maximized satisfying (13)-(15), the private marginal benefit of the transfer of a marginal agent equals the private marginal cost including education cost. On the contrary, the transfer of one marginal agent from development research activities of the technology creation to basic research activities of the technology creation will raise the growth rate

by $\left(\frac{B}{\alpha-1} \frac{S}{1+d+BH} - 1 \right) \frac{1}{\alpha} \gamma \frac{\kappa(1+d+BH)^{\frac{1}{\alpha-1}}}{(1+d)^{\frac{1}{\alpha-1}} U + \kappa(1+d+BH)^{\frac{1}{\alpha-1}} S}$, as we can see from equation

(17) and (P3).¹⁵ Thus, we can easily show from Result (a) of the comparative static analysis that with the lower value of d , these transfers increase the growth rate more. It is because a decrease in d increases H , while it decreases U and $d+BH$.¹⁶ Thus the proof completes.

Result (d) of the comparative static analysis and the relationship of

$\frac{\dot{Y}}{Y} = \frac{\gamma}{1-\nu} \left\{ \frac{1}{\alpha-1} (1+BH) + (1+\varphi S) \right\}$, at the steady state with $Z_C = 1$ and $d = 0$, show

that an increase in the efficiency of education system (B) raising the efficiency of basic research investment increases steady state output growth rates. In addition, its impact on the current income growth on the transitional path is described by:¹⁷

Proposition 3: An increase in the efficiency of education system (B), raising the efficiency of basic research investment, increases the steady state output growth rate as well as the current growth rate on the transitional path. The smaller the technological distance, the larger the increased current income growth rate.

(Proof) The latter part of the proof goes as follows. Equation (12) yields

$$\frac{\partial Y}{\partial B} = \frac{Z_C}{\alpha-1} \frac{H}{1+d+BH} \gamma Y > 0. \text{ Equation (19) implies that } \frac{\partial}{\partial d}(d+BH) > 0. \text{ Thus, with } \frac{\partial Z_C}{\partial d} < 0, \text{ we prove the proposition.}$$

¹⁵ If we consider the education cost as the time opportunity cost of highly skilled labor, then the increase in growth rate will be zero. However, the increase in income growth rate of the transfer from adoption sector to the basic research of creation sector is identical with that to the development research of the creation sector.

¹⁶ Note here that we assume that S does not change much, even though comparative static Result (a) shows that the effect of a decrease in $(\bar{T} - T_{t-1})$ on S depends on the elasticities of the two graphs of (18) and (19).

¹⁷ On the transitional path toward the steady state, from equation (23) we can infer that when $Z_C > 0.5$ the proposition holds, neglecting the effect of changes in $\frac{\dot{S}}{S}$ and $\frac{\dot{U}}{U}$.

IV. Empirical Evidence

Now, we implement empirical tests to verify whether the main results of this paper are supported by the data. Specifically, we verify whether the implications of propositions 1, 2, and 3 are consistent with the panel data of the three East Asian economies.

A. Composition of R&D Investment and Economic Growth

According to propositions 1 and 2, as the TFP level of a developing country approaches that of the world frontier, basic research investment becomes relatively more important than development investment. Now, we divide R&D into only two different categories, “basic research” and “applied research and development” due to the lack of data. Next we attempt to identify how each type of R&D interacts with distance to frontier in determining long-run GDP or TFP growth rates.¹⁸ Before conducting empirical tests, we need to estimate major variables first, i.e., TFP and distance to the frontier of Japan; Korea; and Taipei,China.

1. Estimating TFP

In order to estimate TFP and the distance to the frontier of each country, we are assuming a Cobb-Douglas type aggregate production function, which is used widely in growth literature, as follows.

$$Y_j = T_j K_j^{\alpha_j} L_j^{1-\alpha_j} \Leftrightarrow y_j \equiv \frac{Y_j}{L_j} = T_j \left(\frac{K_j}{L_j} \right)^{\alpha_j} = T_j k_j^{\alpha_j}, \quad (24)$$

where T is the level of TFP, k capital stock per worker, L the number of workers, α capital share of national income, and subscript j country. The variables are computed from Penn World Table (PWT) version 6.2; Y is GDP (*rgdch*pop*), and L is obtained from GDP divided by GDP per worker (*rgdpwok*).

Capital stock K is estimated through a perpetual inventory method using the formula of

$$K_t = K_{t-1} + I_t - \delta K_{t-1} \quad (25)$$

where I represents investment ($ki \cdot GDP$) and δ the depreciation rate set to be 6%.

The capital stock for the initial year is computed by

$$K_0 = \frac{I_0}{g_{0-10} + \delta} (1 - \delta) + I_0 \quad (26)$$

¹⁸ In the time series data of advanced countries, the share of basic research tends to increase and that of development to decrease, whereas the share of applied research is more or less stable over time. Thus, it seems that applied research does not actively interact with the distance to frontier, and our focus is on the relative importance between basic and development research in the process of technological progress.

where g_{0-10} is the average growth rate of GDP for the first 10 years.

Using these data, each country's TFP level T is obtained from the formula of

$$T_j = \frac{y_j}{k_j^{\alpha_j}}. \quad (27)$$

Here, capital share α_j can be simply assumed to be some constant number such as 0.3, based on the stylized fact that in most countries labor share (1-capital's share) is in the range of 0.65–0.80 (Gollin 2002). However, in order to take into account possible differences in the aggregate production function among the countries, we estimate capital share of income for each country by estimating labor share using the following relationship of¹⁹

$$\text{Labor share} = \frac{\text{Corporate Employee Compensation}}{\text{GDP} - \text{Indirect Taxes} - \text{OSPUE}} \quad (28)$$

where OSPUE is “Operating Surplus, Private Unincorporated Enterprises.” This assumes that the share of labor income in OSPUE is the same as that in the corporate sector, allowing for the existence of noncorporate capital income. The reason for this kind of adjustment is that the income share of “employees” does not include labor income of self-employed people, and therefore, the income share of employees tends to understate the true labor share.

The data for estimation of equation (28) has been obtained from the national accounts published by each economy's government. Note that the labor share of the United States (US) has also been estimated to compute the US' TFP proxying the technological frontier.²⁰

The result of the estimation using equation (28) is given in Table 1, where the labor share of each country is presented. This table also shows standard deviations of the estimates and p-values for the hypothesis that labor share is constant. Standard deviations are fairly small compared to the level of labor share in each country, and the p-values are close to zero in all cases. Therefore, one can say that in each country labor share can be regarded as constant over time.

Table 1: Labor Share of Income in US; Japan; Korea; and Taipei,China

	Labor Share	Standard Deviation	p-value
US	0.6959	0.0072	0.000
Japan	0.6864	0.0163	0.000
Korea	0.6919	0.0189	0.000
Taipei,China	0.6913	0.0266	0.000

Note: Labor share for the US, Japan, and Korea is the average of 1980–2003. Taipei,China's labor share is the average of 1981–2003. p-values are for the hypothesis that $\beta=0$ in the following specification: $a = a_0 + \beta t + \varepsilon$ where t is time.

¹⁹ See Bernanke and Gurkaynak (2001) and Gollin (2002) for details.

²⁰ For national account data see the websites of the US Bureau of Economic Analysis (www.bea.gov); Japan Statistics Bureau (www.stat.go.jp); Korea National Statistics Office (www.nso.go.kr); and Taipei,China's Statistical Bureau (eng.stat.gov.tw).

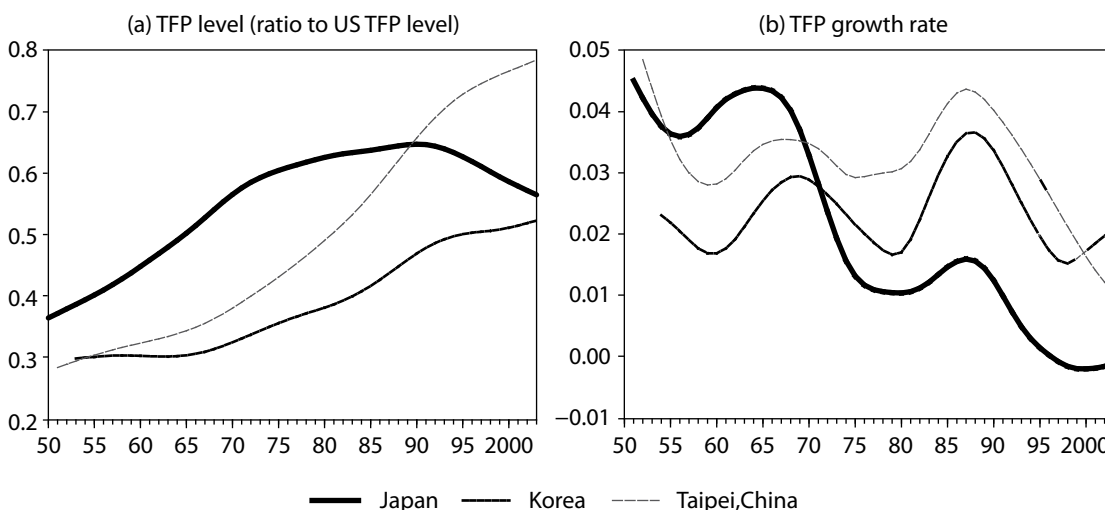
2. Trends in Major Variables

Using the labor share in Table 1, the TFP of each economy has been computed. Figure 2 shows the trend in TFP level as a percentage of the US' TFP level and growth rates from 1950 to 2003.²¹ TFP level as a percentage of the US TFP level, which is labeled *A* here, shows the distance to the world frontier; as *A* gets bigger the distance to the frontier becomes narrower.

Although Japan; Korea; and Taipei,China all have narrowed the distance to the US' technology level (or the world frontier), ever since the late 1990s, Japan's distance to the US has been widening. As for TFP growth rates, Korea and Taipei,China show no significant trends, while Japan shows a decreasing trend.

On the other hand, Figure 3 depicts the trends in R&D inputs of the three East Asian countries for 1970 to 2003.^{22 23} Figure 3(a) shows that R&D intensity, or total R&D expenditure as a percentage of GDP, for the three countries all increased continuously. However, in Figure 3(b), basic research expenditures as a share of total R&D show no definite trend.

Figure 2: TFP Levels and TFP Growth Rates of Japan; Korea; and Taipei,China



TFP = total factor productivity.

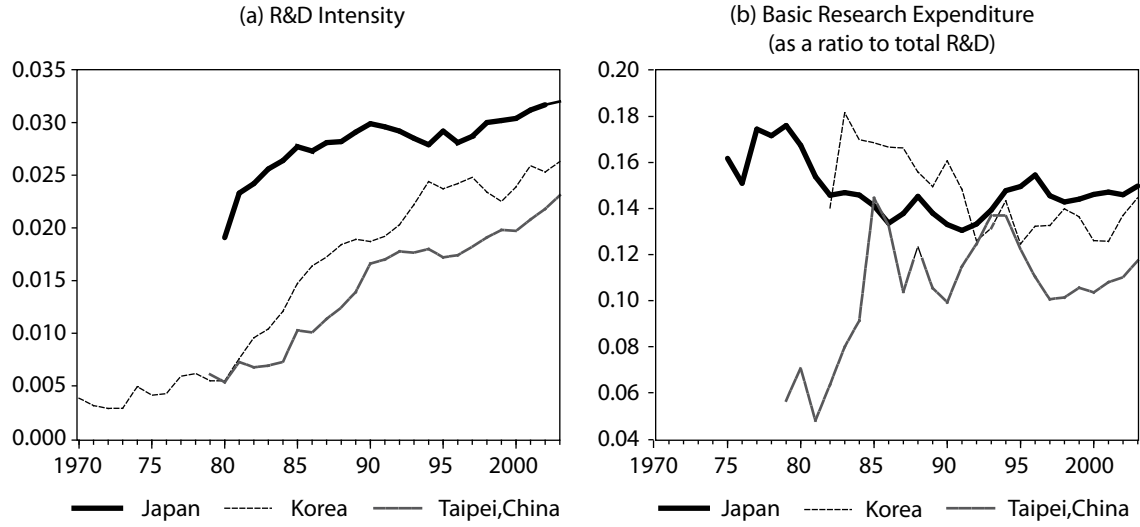
Source: Authors' calculation, smoothed using HP-filter.

²¹ The TFP data for Korea starts from 1953 and for Taipei,China from 1952.

²² The R&D intensity of Japan starts from 1980 and those for Taipei,China starts from 1979. The basic research data for Korea starts from 1982; Japan from 1975; and Taipei,China from 1979.

²³ The R&D composition data for Taipei,China seems to be a little problematic, as various sources with different time spans show different figures around 1995. However, analyses without Taipei,China's data do not alter the qualitative results of this paper.

Figure 3: R&D Intensity and Basic Research Expenditures



Sources: Japan: *Science and Technology Indicators 2008* and its database (National Institute of Science and Technology Policy 2008).
Korea: National Statistics Office database.
Taipei, China: *Statistical Yearbook of the Republic of China 2006* and its database for updated data (DGBAS 2006).

3. Empirical Analysis

To analyze how the interaction between R&D input structure and distance to technological frontier affects economic growth, we set up the following hypothesis in such a way that is consistent with Propositions 1 and 2.

Hypothesis 1: *As the distance to technological frontier narrows, the growth effect of basic research increases, while the growth effect of applied and development research decreases.*

This hypothesis means that as a country's TFP level approaches the frontier, new knowledge creation plays a more important role for TFP growth than knowledge adoption, hence the basic research for the creation of new knowledge becomes more important for economic growth. To test this hypothesis, assume the following basic model where TFP growth rates are affected by R&D structure, which interacts with the distance to frontier.

$$g_{jt} = \beta x_{B,jt} A_j + X'_{jt} \gamma + \varepsilon_{jt} \quad (29)$$

where $A_j = \frac{\text{TFP of country } j}{\text{TFP of the frontier (= TFP of the US)}}$

where g is TFP growth rate (\dot{T}/T) and x_B is the expenditure on basic research as a ratio to total R&D. A represents TFP level as a ratio to the world frontier proxied by the US TFP level; a higher A indicates a closer distance to the world frontier. X is the vector of other variables that may affect TFP growth. Here, subscript j and t represents country and period, respectively.

In this model, $x_B A$ represents the interaction between basic research and relative TFP level (or the inverse of the distance to frontier).²⁴ If our hypothesis is true—the higher the relative level of TFP, the greater becomes the growth effect of basic research—the coefficient of $x_B A$ in (29), β , will be positive.

In various specifications considered in this paper, X includes such variables as R&D intensity, the distance to the frontier, etc. One example of the specification is

$$g_{jt} = \beta x_{B,jt} A_{jt} + \gamma_{0,j} + \gamma_1 x_{jt} + \gamma_2 A_{jt} + \gamma_3 year_t + \varepsilon_{jt} \quad (30)$$

where γ_0 is a constant and x total R&D expenditure share in GDP. “year” indicates time, which is included to consider possible trends in TFP growth rates.

We also consider the following specification where the interaction between the inverse of distance to the frontier and basic research as a percentage of GDP, which is $x_B x$.

$$g_{jt} = \beta x_{B,jt} x_{jt} A_{jt} + \gamma_{0,j} + \gamma_1 A_{jt} + \gamma_2 year_t + \varepsilon_{jt} \quad (31)$$

As equation (31) ignores investment in applied R&D and development, we can also consider the following specification that explicitly includes basic research as a percentage of GDP, $(1 - x_B)x$.

$$g_{jt} = \beta x_{B,jt} x_{jt} A_{jt} + \gamma_{0,j} + \gamma_1 (1 - x_{B,jt}) x_{jt} A_{jt} + \gamma_2 A_{jt} + \gamma_3 year_t + \varepsilon_{jt} \quad (32)$$

The estimation results for equations (30), (31), and (32) are reported in Table 2. Note that pooled ordinary least squares (OLS) with country fixed effects has been used for the estimation. Fixed effects are applied to consider country specific factors that may affect TFP growth rates.

Table 2, column (1), which is the result for specification of equation (30), shows that the coefficient for Ax_B is positive and statistically significant, implying that as a country's relative level of TFP increases, the positive growth effect of the basic research share becomes greater. In addition, the coefficient of x is positive and statistically significant, supporting the R&D-based growth theory that predicts a higher R&D intensity is associated with a higher TFP growth rate. One can also see that relative level of TFP A is negatively related to TFP growth, which is consistent with the intuition that as a country gets closer to the frontier, growth rates tend to slow down.

²⁴ Here g and A are smoothed using an HP-filter to remove the factors related to business cycles.

Columns (2) and (3), which represent specifications in (31) and (32) respectively, show the interaction between the relative level of TFP (A) and expenditures on basic research as a percentage of GDP ($x_B x$) instead of the basic research share among total R&D. Results show that those two variables, A and $x_B x$, interact positively with each other, implying that basic research becomes more important as the economy approaches the frontier.

Table 2: TFP Growth and R&D Input Structure: Japan; Korea; and Taipei,China

Dependent Variable: g	(1)	(2)	(3)
$x_B A$	0.291 (4.75)***		
$x_B x A$		16.431(3.50)***	16.803(3.36)***
$(1 - x_B)x A$			-0.214(-0.23)
x	2.051 (5.37)***		
A	-0.099 (-5.14)***	-0.055(-2.58) **	-0.050(-1.64)*
$year$	-0.002 (-9.33)***	-0.001 (-8.12)***	-0.001 (-6.25)***
Constant	3.539(9.45)***	2.842(8.22)***	2.779(6.27)***
within	0.75	0.65	0.65
R^2 between	0.71	0.90	0.91
overall	0.15	0.12	0.11
No. of obs.	71	71	71

* indicates a 10% significance level, ** 5%, and *** 1%, respectively.

Note: Estimation is based on pooled OLS with country fixed effects.

Table 3 presents the results for the specifications similar to Table 2, but uses different data. The data used in Table 3 are computed under the assumption that labor share is assumed to be identical across countries at 0.7. In this case, the results are almost the same as in Table 2, showing that they are not sensitive to the parameter values of labor share.

Table 3: TFP Growth and R&D Input Structure (labor share = 0.7)

Dependent Variable: g	(1)	(2)	(3)
$x_B A$	0.059 (4.66)***		
$x_B x A$		15.713(3.54)***	15.898(3.35)***
$(1 - x_B)x A$			-0.103(-0.12)
x	2.063 (5.37)***		
A	-0.092 (-5.07)***	-0.050(-2.55)**	-0.048(-1.72)*
$year$	-0.002 (-9.41)***	-0.001 (-8.16)***	-0.001 (-6.45)***
Constant	3.584(9.53)***	2.922(8.26)***	2.890(6.48)***
within	0.75	0.65	0.65
R^2 between	0.67	0.93	0.93
overall	0.12	0.12	0.12
No. of obs.	71	71	71

* indicates a 10% significance level, ** 5%, and *** 1%, respectively.

Note: Estimation is based on pooled OLS with country fixed effects.

B. Quality of Education and Productivity of R&D

Now, related to Proposition 3, we explore the issues regarding how quality of education affects productivity of R&D, using the data for the three East Asian economies. For this, we set up the following hypothesis in such a way that is consistent with Proposition 3.

Hypothesis 2: *As the quality of education improves, the growth effect of (basic) R&D increases.*

This hypothesis implies that as a country's quality of education improves, the productivity of R&D also improves to accelerate the speed of knowledge creation (and adoption) and economic growth. Therefore, the quality of education and R&D intensity interact positively in determining the TFP growth rate. To test this hypothesis, consider the following basic model where TFP growth rates are affected by R&D intensity, relative level of TFP, and interaction between the quality of education and (basic) R&D.

$$g_{jt} = \beta x_{B,jt} edu_{jt} + X'_{jt} \gamma + \varepsilon_{jt} \quad (33)$$

where variables are defined in the same way as equation (24), except that edu is the quality of education. Here, the quality of education is proxied by the inverse of the number of students per teacher in tertiary education. Note also that edu is lagged by 5 years; this is because there are time lags between college education and economic activities of college graduates.²⁵

We can consider the following specifications that take into account the effects of the interaction between education and basic R&D as well as other relevant variables.

$$g_{jt} = \beta_1 x_{B,jt} edu_{jt} + \beta_2 edu_{jt} + \gamma_{0,j} + \gamma_1 x_{jt} + \gamma_2 A_{jt} + \gamma_3 year_t + \varepsilon_{jt} \quad (34)$$

$$g_{jt} = \beta x_{B,jt} edu_{jt} + \gamma_{0,j} + \gamma_1 x_{jt} + \gamma_2 A_{jt} + \gamma_3 year_t + \varepsilon_{jt} \quad (35)$$

One can also consider the following variations, in which the interaction between education and total R&D intensity is taken into account.

$$g_{jt} = \beta_1 x_{jt} edu_{jt} + \beta_2 edu_{jt} + \gamma_{0,j} + \gamma_1 x_{jt} + \gamma_2 A_{jt} + \gamma_3 x_{B,jt} A_{jt} + \gamma_4 year_t + \varepsilon_{jt} \quad (36)$$

$$g_{jt} = \beta_1 x_{jt} edu_{jt} + \beta_2 edu_{jt} + \gamma_{0,j} + \gamma_1 A_{jt} + \gamma_2 x_{B,jt} A_{jt} + \gamma_3 year_t + \varepsilon_{jt} \quad (37)$$

The results of pooled OLS with country fixed effects are summarized in Table 4. According to columns (1) and (2), which reflect specifications in equations (34) and (35),

²⁵ Analyses with no time lags or other time lags such as 4 years produce quite similar results. So, this exercise is not sensitive to the lag length of education variables.

education quality positively interacts with basic research, meaning that higher quality of education improves the growth effect of basic research. Columns (3) and (4), which are the results for specifications in equations (36) and (37), show that this result applies not only to basic research but also to total R&D intensity. Moreover, columns (3) and (4) also identify the positive interaction between basic research share and the relative level of TFP which was already shown in Tables 2 and 3. Table 5 shows that the analyses with the data generated from the assumption that labor share is 0.7 also produce similar results.

Table 4: TFP Growth and the Interaction between Education and R&D

Dependent Variable: g	(1)	(2)	(3)	(4)
$x_B \cdot edu$	1.494 (3.12)***	1.797(4.00)***		
edu	0.209(1.67)*			
$x \cdot edu$			12.725(3.88)***	14.788(5.14)***
x	1.332 (3.07)***	1.411(3.22)***	0.612(1.29)	
A	-0.036 (-1.95)*	-0.050(-2.96)***	-0.061(-3.31)***	-0.043(-3.61)***
$x_B A$			0.161(2.80)***	0.157(2.73)***
year	-0.002 (-9.87)***	-0.002 (-9.58)***	-0.002(-10.16)***	-0.002(-11.60)***
Constant	3.636(9.97)***	3.549(9.68)***	3.701(10.30)***	3.423(11.85)***
within	0.85	0.84	0.86	0.86
R^2 between	0.94	0.99	0.99	0.93
overall	0.20	0.16	0.20	0.17
No. of obs.	64	64	64	64

* indicates a 10% significance level, ** 5%, and *** 1%, respectively.
Note: Estimation is based on pooled OLS with country fixed effects.

Table 5: TFP Growth and the Interaction between Education and R&D (labor share=0.7)

Dependent Variable: g	(1)	(2)	(3)	(4)
$x_B \cdot edu$	1.504 (3.14)***	1.818(4.03)***		
edu	0.215(1.73)*			
$x \cdot edu$			13.194(4.04)***	15.172(5.28)***
x	1.337 (3.09)***	1.408(3.21)***	0.592(1.25)	
A	-0.033 (-1.91)*	-0.045(-2.90)***	-0.056(-3.27)***	-0.039(-3.57)***
$x_B A$			0.152(2.78)***	0.150(2.73)***
year	-0.002 (-10.00)***	-0.002 (-9.68)***	-0.002(-10.36)***	-0.002(-11.86)***
Constant	3.682(10.10)***	3.584(9.79)***	3.762(10.50)***	3.492(12.11)***
within	0.85	0.85	0.86	0.86
R^2 between	0.93	0.99	0.99	0.93
overall	0.19	0.14	0.19	0.16
No. of obs.	64	64	64	64

* indicates a 10% significance level, ** 5%, and *** 1%, respectively.
Note: Estimation is based on pooled OLS with country fixed effects.

V. Conclusion

This paper first presents an endogenous growth model where, as an economy's technology level approaches the technology frontier, it tends to rely more on technology creation than adoption, and to invest more in basic research than development and applied research. The model shows that as one country's technology gap with the technology frontier becomes narrower, an increase in the level of basic research investment for technology creation, with the corresponding decrease in development research investment for technology adoption, raises TFP growth rate more. It also implies that an increase in the efficiency of an education system or of a basic research system increases technology and output growth rates.

Second, this paper also empirically shows that, using panel data of Japan; Korea; and Taipei,China, as their technological distance to frontier narrows, the growth effect of basic R&D increases. This empirical fact indicates that the share of basic R&D matters. Panel data for the three countries also show that the quality of tertiary education has a significantly positive effect on the productivity of R&D.

In future research, we would introduce dynamic features into the model by including different vintages of basic ideas, human capital accumulation, and saving and physical capital accumulation. On this dynamic model, we could apply calibration and simulation techniques. Even though this extended model provides more detailed dynamic features of the model, the main implications would not change much.

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About the Paper

Joonkyung Ha, Yong Jin Kim, and Jong-Wha Lee present a theoretical model and empirical evidence to explain the observation that a country in which the level of technology approaches the technology frontier tends to rely more on technology creation than adoption, and to invest more in basic research than in development. The results suggest that the rate of growth is positively correlated with the level of basic research activities in the technology creation sector, if one country's technology gap with the technology frontier is small enough. Verifying these theoretical results, empirical analyses using panel data of Japan; Republic of Korea; and Taipei, China show that the narrower the technological distance to the frontier, the higher the growth effect of basic R&D, indicating that the share of basic R&D matters for economic growth.

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