# INFORMATION SPILLOVER AND ECONOMIC DEVELOPMENT

by

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## Abstract

This paper explores a new aspect of the relationship between backwardness and growth, \information spillover". If solving problems is a source of economic growth, then knowing which problems have been solved is per se valuable. A backward country will concentrate its problem-solving e®orts on those problems that have been solved abroad. For countries with an intermediate level of human capital, this e®ect could be strong enough for them to grow faster than more advanced countries in the short run. However, for countries with low human capital, the same information is not as valuable and they will grow slowly or will even stay stagnant. Since it is not the absolute, but the relative human capital levels (of information receiver and provider) that determine growth rates, this model predicts a great variety of economic performance among backward countries.



JEL No.(), (O00), (O33)

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# 1 Introduction

Simply by looking at the economic performance of di®erent countries in the past several decades, one sees the following :

(1) Taking the U.S. as the leading country, after 1950 some countries (mostly in western Europe) enjoyed a higher growth rate than the U.S., and it seems there was homogenization in terms of per capita income within this group.

(2) A few years later, several countries started to grow at an even faster rate than the more advanced group. However, at this time the income gap between these countries and the leading group remains substantial.

(3) Most other countries grew slowly and their per capita income level at 1960 varied considerably.

(4) Several countries essentially displayed no growth; they tend to be the poorest countries since the beginning of this century.

The ¯rst two sets of countries form the so-called \convergence club", which draws many economists' attention. In order to understand convergence, we have to detect the driving force behind it, i.e., the advantage, in terms of growth rate, of backwardness. Since only a fairly restricted set of countries are in this club, this advantage should not be advantage per se. Under this criterion, diminishing marginal return on physical capital is predestined to fail. Another often used and well accepted advantage of backwardness is technology di®usion. New technology, in this story, is invented in the leading country and embodied in some kind of blueprint or menu that can be acquired by the followers at some lower cost.[1] However, the great and persistent disparity in technology level across countries seems to suggest that technology transfer may not be as easy as assumed in those models. Among many, Parente and Prescott (1994), and Basu and Weil (1998) try to explain what makes it di±cult.[2] It is noteworthy that although in their story technology transfer is no longer immediate { a modi¯cation of Solow's (1957) extreme assumption, the conception of knowledge/technology is still transferable.

This paper departures from this line of literature by pushing the assumption to another extreme, i.e., knowledge/technology is not transferable. This assumption partly re°ects the argument that technology is often embedded in organizational structures (¯rms, institutions, or countries).[3] Under this point of view, complete technology transfers must accompanied by transfers of institutional arrangements, which are generally considered di±cult. Also this assumption stems from the discomfort with the implicit assumption underlying complete transferability, namely all involved techniques can be well de¯ned and clearly articulated, like a theorem. If this were the case, then any marginal change on the learning curve should be able to be attributed to some speci¯c technological advance, and any ¯rm or plane in the technology-matured industry should not go through the same learning process. Therefore, it seems reasonable to assume there are tacit elements involved in those producing activities

[1] For example, see Barro and Sala-i-Martin (1995) Ch 8.

[2] Studying the textile industry, Clark (1987) suggests that local culture may play an important role. Parente and Prescott (1994) posit the existence of a country-speci¯c barrier to technology adoption. Basu and Weil (1998) assume that technologies are speci¯c to particular combinations of inputs.

[3] For this line of argument, see Nelson (1981) and Nelson and Wright (1992).

that display unexplained and repeated pattern of learning. For those kinds of activities, how well they can be transferred must depend on to what extent an adopter is able to ¯gure out those elements. Foe simplicity, I assume away the part of knowledge/technology that can be well articulated, i.e., can be transferred, and only focus on the tacit part.

Under this assumption of non-transferability, is there a force driving convergence? Do advanced countries do anything for the backward countries? My answer is still yes! Put it shortly, the advantage that followers enjoy is knowing what is achievable. Fermat's so-called \last theorem" provides an interesting example. If Fermat did not claim so, it is dubious that there are so many mathematicians trying to solve that problem. In other words, Fermat's claim changes the way that followers allocate their resources (mostly their time). In this paper, an individual country's technology advance comes from solving problems, technical or non-technical. The information that knowing some certain problem has been solved elsewhere will help it more accurately evaluate the chance of solving this problem and thus, is valuable. (If country X can do this, why not me?) By focusing on those problems that have been solved by others, a backward country may enjoy a higher chance of solving them itself and therefore outgrow the more advanced countries. Note again that the content of information is just knowing which problem has been solved, but not how exactly it is solved.

It is not the case that every country values a certain piece of information equally. If higher human capital means greater probability of solving problems, as I assume in this paper, then it is the human capital level that decides how well a country can take advantage of the information spillover. The argument that \If you can do it, why not me?" makes sense only when relevant countries have relatively similar human capital levels. If their human capital levels vary in a great deal, then the fact that some problem has been solved in the high-human-capital country says little about the chance of solving this problem for the other low-human-capital country since there is too much that one can do but the other cannot. Simple as it is, this argument has some interesting implications. First, \technology gap" is not an advantage per se as many have assumed.[4] A large technology gap between two countries may be attributed to the large di®erence in their human capital levels which implies, according to this paper, the information that the technology-backward country can use is less valuable. Secondly, an individual country will optimally choose its information source, namely the country with relatively similar human capital. Hahn (1995) studies Korea's technology adoption during 62-92 period and ¯nds that Korea adopted Japanese technologies as much as U.S. technologies, even though the U.S. industries were recognizes as leaders in many ¯elds for most of the periods. Why did Korea not adopt technologies exclusively from the U.S.? This paper suggests that Korea may subjectively feel that it is easier to ¯gure out the tacit parts contained in the Japanese technologies. Thirdly, as the previous U.S.-Japan-Korea example shows, middle country (like Japan) does play a role in the world economy. It may take advantage of the information revealed from the more advanced country (like U.S.), and at the same time, provide valuable information for the more backward country (like Korea). Therefore the world is no longer dichotomous as, for

[4] In their pioneer paper, Nelson and Phelps (1966) assumes that the rate of increase of technology is propotional to the \gap".

example, innovation-imitation model describes; and term like "advanced" or "backward" should not be used in their "absolute" sense. Finally, notice that it is the similarity of countries' human capital that decides how valuable each country's information is, which in turn decides their technology growth rates. Hence, this paper predicts the simple relationship between growth rate and "absolute" human capital level could be highly non-linear.

This article is organized as follows. In Section 2, I develop a basic model in which there is no information spillover. Information spillover is introduced in Section 3 and its implications on convergence are presented. Section 4 contains some discussions about this model. Conclusions are in Section 5.

## 2 The Basic Model

Consider a world consisting of N countries. Each country contains one infinite-lived representative agent. The only interaction among countries is pure information spillover which will be introduced in the next section. The focus of this section is to describe a single, closed economy and to study its representative's behavior.

### 2.1 Model Layout

Preference: There is only one final good. The representative consumes this good only at the end of each period. His preference over consumption streams is $\sum_{t=0}^{\infty} \beta^t c_t$ where $c_t$ is the consumption at date t and $\beta$ is the discount factor.

Production: For each date t, the output ($y_t$) depends on the current technology level ($A_t$) the representative is using and the amount of time he devotes to producing activity

($l_t$). More specifically,

$$y_t = A_t \cdot l_t.$$

Since there is no reason to defer consumption, we must have $c_t = y_t$.

Endowment: The representative is endowed with one unit of time each period. There are two activities, producing and problem-solving, to which he can allocate his time. He may be willing to undertake the problem-solving activity, at the expense of current output, in the hope of enhancing the technology level in the future.

Problems: There are an infinite number of problems associated with producing this final good. Let $\Psi$ be the set of these problems. This set contains not only "hard" problems like engineering, but also "soft" ones like management. The representative is entitled to pick one problem for each date and his next-period technology level goes up by a constant factor $\lambda\,(>1)$ if this problem is solved and remains the same otherwise. For example, let $A_t$ be the technology level he is using during date t and $\psi_t$ be the problem he picks. Then

$$A_{t+1} = \begin{cases} \lambda A_t & \text{if } \psi_t \text{ is solved} \\ A_t & \text{otherwise} \end{cases}.$$

Notice that, together with the production function, this setup implies that even if $\psi_t$ is solved, the technology level during date t is still $A_t$. That is, the improved technology is not available until next period. To see how this assumption simplifies the analysis, see the discussion following eq. (2) and footnote 6. Problems in $\Psi$ are assumed to be identical ex ante and independent of each other. I will return to this assumption soon.

Knowledge: Call $K = [0; 1]$ the knowledge space which contains all the knowledge. By "all the knowledge", I mean knowledge that has or has not been found. Representative $i$'s knowledge (human capital), $K_i$, is just a subset of $K$ and is exogenously fixed in the model. I put a subscript $i$ to emphasize that, in this paper, representatives differ from each other in their knowledge. Let $\mu$ be the Borel measure on $K$. We can define the size of representative $i$'s knowledge by $S_i = \mu(K_i)$. Since I treat each piece of knowledge as equally important, we can use $S_i$ as a measure of representative $i$'s human capital level.

Solutions: Each problem in $\Phi$ has exactly one solution which is an element in $K$. Given any problem $\phi_j$, I assume that people have the same prior belief, denoted by $\mu_j$, about the location of its solution. Furthermore, for simplicity's sake I assume that $\mu_j$ is i.i.d. uniform distribution on $K$. (Therefore, $\mu_j = \mu\ \forall j$.) This assumption rules out some interesting cases like "problem $\phi_j$ is more difficult than problem $\phi_k$" or "solving problem $\phi_j$ would help to solve problem $\phi_k$".

Problem-solving: Problem-solving activity is modeled as searching activity. More specifically, representative $i$ tries to solve problem $\phi_j$ by searching for its solution within his knowledge set $K_i$. Therefore, problem $\phi_j$ is potentially solvable for representative $i$ only if its solution is in $K_i$. Otherwise, it's unsolvable for him. Searching takes time. Let $\alpha$ be the searching speed, which is identical across all the representatives. That is, if one spent $\Delta\tau$ time on searching, he was able to search $\alpha \cdot \Delta\tau$ "area" in his knowledge set. Since the prior belief is a uniform distribution, there is no reason why one wants to search a certain area first. In other words, he is doing a "blind search".

Before getting into the representative's optimization problem, let me emphasize the role of human capital in this paper. Similar to the idea of Nelson and Phelps (1966) and Romer (1990), human capital in this model enters the production function by facilitating technological progress. Unlike some models[5], this kind of set-up implies that it is the level, not the growth of human capital entering growth accounting. By noticing this difference, Benhabib and Spiegel (1994) empirically support this view.

## 2.2 Optimization

Given the initial technology level $A_0$ and his knowledge set, the representative tries to maximize his expected discounted utility by optimally allocating his time into two activities — producing and problem-solving. Conceptually, the representative has to choose between these two activities at each point in time. However, since the agent consumes only at the end of each date, any plan that puts producing ahead of searching within one period can be changed by switching their order without being worse off. Therefore, we can study only the plans that always put searching activity first, and the decision variable is just the maximal time he would like to spend on searching during each date.

Given the rate of searching speed ($\alpha$) and the representative's knowledge size ($S$); let $v_\alpha(A; S)$ be his maximal expected lifetime utility when the state variable — the technology

[5] For example, Mankiw, Romer, and Weil (1992) treat human capital as an ordinary input. In Lucas (1988), higher human capital means more "effective labor".

level at the beginning of the date | is A: Then

$$v_\alpha(A;S) = \max_{0\le\tau\le\frac{S}{\alpha}} \{(1-\tau\alpha)[(1-\tau)A + \beta v_\alpha(A;S)] + \tau\alpha[\int_0^\tau (1-z)A\frac{\alpha}{\tau\alpha}dz + \beta v_\alpha(\lambda A;S)]\}. \quad (1)$$

The first term in eq. (1) is that, given the maximal time he would like to spend on searching ($\tau$), the probability he will not find the solution is $(1-\tau\alpha)$ and in this case, he will produce $(1-\tau)A$ in the current period and the technology level will remain the same at the beginning of the next period. The second term is, given he is able to find the solution, the expected current-period production $\int_0^\tau (1-z)A\frac{\alpha}{\tau\alpha}dz$ and the state variable for next period becomes $\lambda A$. Also notice that $\frac{S}{\alpha}$ is the time needed for the individual to search all his knowledge. If $\frac{S}{\alpha} < 1$, then the maximal time he can search is bounded by his knowledge; otherwise, it is bounded by his endowed time | 1. I assume that searching speed is high enough ($\alpha > 1$) such that the latter situation would never happen. Therefore, we must have $\frac{S}{\alpha} < 1$.

To solve $v_\alpha(A;S)$, notice that this function should be homogeneous of degree 1 in A since if we double the technology level, the expected lifetime utility should double simply by using the same plan. Suppose $v_\alpha(A;S) = h_\alpha(S)\cdot A$. Substituting it into eq. (1), we can get

$$h_\alpha(S)A = \max_{0\le\tau\le\frac{S}{\alpha}} \{(1-\tau\alpha)(1-\tau) + \alpha\frac{1-(1-\tau)^2}{2} + \beta(1-\tau\alpha+\tau\alpha\lambda)h_\alpha(S)\}A. \quad (2)$$

Since the RHS of eq. (2) is convex in $\tau$, we must have a corner solution. That is, his optimal decision is either he not to solve the problem at all, or to search until he finds the solution or exhausts his knowledge. This result is intuitive. Chop each date into a great deal of tiny, equal-length intervals. Either the prize or the cost for searching any interval is the same. However, conditioned on the failure of the previous search, searching in the latter time interval will have higher chance of success. Therefore, once he starts searching, he will not declare failure until he is certain this problem is unsolvable for him.[6]

Substituting these two corner values into (2) and solving for $h_\alpha(S)$; one can get

$$h_\alpha(S) = \max\left\{\frac{1}{1-\beta}; \frac{1-\frac{S}{\alpha}+\frac{S^2}{2\alpha}}{1-\beta[1+(\lambda-1)S]}\right\}. \tag{3}$$

The two terms in parentheses correspond to the two extreme cases, "never try" and "try his best", respectively. The solution to (3) depends on the values of parameters $\alpha$ and $\lambda$. Fix $\lambda$. Intuitively, if $\alpha$ is very small, which means the opportunity cost for engaging in search activity is very high, the representative should never spend his time on problem-solving no matter how big his knowledge set is. On the opposite, if $\alpha$ is very big, then he should always try his best to solve problems since the opportunity cost is low. However, neither case is very interesting. Notice that, as I mentioned earlier, the searching setup has the implication that earlier failure would increase the chance of success for later search. Therefore, if one's knowledge is very limited, he will not be able to do much "later" search so that searching is not worthwhile due to low probability of success. In other words, there is some "minimal capacity" of knowledge such that one will try to solve problems only if his size of knowledge exceeds this level. To have this more interesting case, I need to make the following assumption:

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[6] Recall that I assume the improved technology is not available until next period. Suppose it is available immediately after the solution is found; then we need to multiply the second term in (2) by $\lambda$. Under this assumption, we need $\lambda < 2$ to ensure (2) is convex in $\tau$. This additional assumption is needed since the prize for searching those tiny intervals is now decreasing. For simplicity, I prefer the original assumption.

Assumption 1: $\frac{1-\beta}{2\alpha\beta} < \lambda - 1 < \frac{1-\beta}{\alpha\beta}$.

Under this assumption, one can easily show that there exists a unique $S^* \in (0, 1)$ such that

$$h_\alpha(S) = \begin{cases} \frac{1}{1-\beta} & \text{if } S < S^* \\ \frac{1 - \frac{S}{\alpha} + \frac{S^2}{2\alpha}}{1-\beta[1+(\lambda-1)S]} & \text{if } S \geq S^* \end{cases}. \tag{4}$$

In fact, $S^* = 2 - \frac{2\alpha\beta(\lambda-1)}{1-\beta}$. Furthermore, one can show that the required minimal capacity ($S^*$) gets lower when searching is faster ($\alpha \uparrow$), payoff is larger ($\lambda \uparrow$), or the representative is more patient ($\beta \uparrow$). The economic interpretations for these results are obvious.

Notice that when $S = S^*$, the expected lifetime utility for trying to solve a problem only once is

$$\begin{aligned} (1 - S^*)[(1 - \tfrac{S^*}{\alpha})A + \tfrac{\beta A}{1-\beta}] + S^*[\textstyle\int_0^{\frac{S^*}{\alpha}} (1 - z)A\frac{\alpha}{S^*}dz + \frac{\beta\lambda A}{1-\beta}] \\ = \frac{A}{1-\beta}. \end{aligned} \tag{5}$$

The equality in (5) implies that when $S = S^*$, there is no difference between "not trying" and "trying one's best" at each date. For $S > S^*$, the "capacity" has been great enough to make searching worthwhile.

We can also calculate the expected growth rate. Apparently, $S^*$ serves as a "threshold" in this model.[7] If one's knowledge is very limited ($S < S^*$), he will devote all his time to production, so the technology level can never change. In this case, there is no growth. Otherwise, the technology level, as well as the output level, grows at an expected rate $g(S) = (\lambda - 1)S$. Figure 1 shows the expected lifetime utility and expected growth rate

[7] Many economists conjecture that there is a threshold on human capital such that economies below this level will stagnate in underdevelopment traps. A popular argument behind it is increasing social returns to scale in the accumulation of human capital. For example, see Azariadis and Drazen (1990).

under di®erent S given the initial technology level $A_0$.

Given S, the expected output level at date t can be approximated by

$$
\begin{aligned}
E[y_t(S)] &\approx e^{g(S)t} \cdot [1 - \xi(S)]A_0 \\
\Longrightarrow \log E[y_t(S)] &\approx g(S)t + \log[1 - \xi(S)]A_0;
\end{aligned}
\tag{6}
$$

where $\xi(S)$ is the expected time spent on searching each date.[8] Figure 2 plots (6) for three di®erent sizes of knowledge, $S_1 > S_2 > S^* > S_3$.

# 3 Information Spillover

In the previous section, I showed that countries with higher human capital level tend to enjoy both higher per capita income level and higher growth rate. That is, there is no convergence. However, this conclusion no longer holds in a world with information spillover. The information that "country i has solved problem $\phi_j$" is valuable to other countries since now they know the solution to problem $\phi_j$ is in $K_i$. By focusing on those problems that have been solved by the more advanced countries, backward countries may outgrow the advanced in the short run. Unfortunately, the high growth rate is not sustainable since the valuable information is depletable. In the long run, the human capital level still determines the growth rate. I formalize these ideas in Section 3.1.

This model also suggests that countries would optimally choose their information source. For country i, information generated from countries with similar human capital level is most valuable since it is very possible that country i can solve those problems as well. An

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[8] $\xi(S) = \begin{cases} 0 & \text{if } S < S^* \\ \frac{S}{\alpha} - \frac{S^2}{2\alpha} & \text{if } S \geq S^* \end{cases}.$

immediate implication is that it is not always the best to target the most advanced country. Therefore, a dichotomous view that divides countries into only two groups (advanced versus backward) is not able to depict the whole picture. In Section 3.2, I show what would happen in the case where there are more than two countries in the world.

I begin this section by defining the information set. Suppose there are N countries in the world and they are ordered by their representatives' knowledge sets, $K_1 \supseteq K_2 \supseteq \cdots \supseteq K_N.$ This also implies $S_1 > S_2 > \cdots > S_N.$ Let $\Omega_{it} \subset \Omega$ be the set of problems that have been tried by country i before the end of date t and among them, let $\Omega^*_{it} \subset \Omega_{it}$ be the set of those that have been solved. The key assumption for the information spillover story is that $K_i; \Omega_{it}; \Omega^*_{it};$ $\forall i$ are known to each country. Let $I_t = \{\{S_i\}_{i=1}^N; \{\Omega_{it}\}_{i=1}^N; \{\Omega^*_{it}\}_{i=1}^N\}$ be the information set available to all countries at the end of date t.[9] [10] We can also define $D_{jit} \equiv \Omega^*_{it} \setminus \Omega_{jt}$ to be the set of problems that have been solved by country i but not tried by country j. Notice that, for those problems in $D_{jit}$, since country j has more information about their solutions (in $K_i$), $D_{jit}$ is the part of information from country i that is valuable to country j.

## 3.1 Two Countries

In this subsection, I assume there are only two countries (N=2) in the world. To make this world interesting, I need $S_1 > S^*$ (but $S_2 \gtrless S^*$). There is no information spillover until the end of date $T_1$. Since $S_1 > S^*$, from Section 2, the productivity in country 1 would have grown

[9] In the original draft, I assumed $I_t = \{\{K_i\}_{i=1}^N; \{\Omega_{it}\}_{i=1}^N; \{\Omega^*_{it}\}_{i=1}^N\}$. Under this old assumption, it is possible that a country with high human capital wants to "redo" problems that other low-human-capital countries failed to solve.

[10] Assuming some time lag may be more realistic, but it will not change the results significantly.

before $T_1$, but country 2 may not. If country 2 did grow, I assume that, for simplicity, all the problems solved by country 2 before $T_1$ had also been solved by country 1, i.e. $\Omega^*_{2T_1} \subset \Omega^*_{1T_1}$. Otherwise, $D_{12T_1}$ is not empty and country 1 will use this valuable information first. As I mentioned above, $D_{21T_1}$ is the part of valuable information for country 2, more specifically, country 2 will have a greater chance ($\frac{S_2}{S_1} > S_2$) to solve problems in it. Therefore, country 2 would pick problems from $D_{21T_1}$ first if it ever tries to solve any. Before redoing the exercise in Section 2, note that now we have another state variable $D_{21T_1}$ which would be very troublesome. To avoid this problem, I assume, unrealistically, that $D_{21T_1}$ is infinite at this moment; I will return to this later. Let $\hat{v}_\alpha(A, S_2)$ be the maximal expected discounted utility when the technology level is A after information becomes available. Following (1), we can write

$$\hat{v}_\alpha(A, S_2) = \max_{0 \le \tau \le \frac{S_2}{\alpha}} \left\{ \left(1 - \frac{\tau\alpha}{S_1}\right)\left[(1-\tau)A + \beta\hat{v}_\alpha(A, S_2)\right] + \frac{\tau\alpha}{S_1}\left[\int_0^\tau (1-z)A\frac{\alpha}{\tau\alpha}dz + \beta\hat{v}_\alpha(\lambda A, S_2)\right]\right\}. \tag{7}$$

Define $\hat{S}_2 \equiv \frac{S_2}{S_1}$ and $\hat{\alpha} \equiv \frac{\alpha}{S_1}$. Eq. (7) can be rewritten as

$$\hat{v}_\alpha(A, S_2) = \max_{0 \le \tau \le \frac{\hat{S}_2}{\hat{\alpha}}} \left\{ (1 - \tau\hat{\alpha})\left[(1-\tau)A + \beta\hat{v}_\alpha(A, S_2)\right] + \tau\hat{\alpha}\left[\int_0^\tau (1-z)A\frac{\hat{\alpha}}{\tau\hat{\alpha}}dz + \beta\hat{v}_\alpha(\lambda A, S_2)\right]\right\}. \tag{8}$$

Comparing (8) with (1), we can conclude

$$\hat{v}_\alpha(A, S_2) = v_{\hat{\alpha}}(A, \hat{S}_2); \tag{9}$$

that is, the economic performance in country 2 will look as if its representative has size of knowledge $\hat{S}_2 = \frac{S_2}{S_1}$ and searches at a rate of speed $\hat{\alpha} = \frac{\alpha}{S_1}$. The reason it appears to be searching faster is, given a certain probability of success, the searching time needed is now less. Accordingly, the minimal capacity for growth in case of no information spillover ($S^*$) changes:

$$S^{**} = 2 - \frac{2\alpha\beta(\lambda - 1)}{1 - \beta}.$$[11]

Note that $S^{**}$ is the critical value for $\hat{S}_2$: The minimal capacity for country 2 under information spillover is

$$\hat{S} = S_1 S^{**} = 2S_1 - \frac{2\alpha\beta(\lambda - 1)}{1 - \beta} < S^*. \tag{10}$$

The expected growth rate of country 2 now becomes

$$\hat{g}(S_2) = g(\hat{S}_2) = \begin{cases} 0 & \text{if } \hat{S}_2 < S^{**} \\ (\lambda - 1)\hat{S}_2 & \text{if } \hat{S}_2 \geq S^{**} \end{cases}$$

or

$$\hat{g}(S_2) = \begin{cases} 0 & \text{if } S_2 < \hat{S} \\ (\lambda - 1)\frac{S_2}{S_1} & \text{if } S_2 \geq \hat{S} \end{cases}. \tag{11}$$

Notice that $\hat{S} < S_1^2$.[12] Therefore, depending on its human capital level, country 2 may grow faster (if $S_2 > S_1^2$), slower (if $\hat{S} < S_2 < S_1^2$), or not at all (if $S_2 < \hat{S}$). Only in the first case is, information spillover able to generate convergence. In Figure 3, $S_2$ takes three values, $S_{2x}$, x = I, II, III, corresponding to these three possible cases.[13]

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[11] Under the assumption in Section 2, $\lambda - 1 > \frac{1-\beta}{2\alpha\beta}$ still holds but it may not be less than $\frac{1-\beta}{\alpha\beta}$. In this case, $S^{**} = 0$.

[12] $\hat{S} - S_1^2 = (2S_1 - S_1^2) - \frac{2\alpha\beta(\lambda-1)}{1-\beta} < 1 - \frac{2\alpha\beta(\lambda-1)}{1-\beta} < 0$. The first inequality holds because the first term is strictly increasing if $S_1 \in (0, 1)$. The second one comes from assumption 1.

[13] $S_1^2$ is not necessarily greater than $S^*$ as shown in Figure 3. More precisely, the three possible values for $S_2$ that I discuss are: $S_{2I} > \max\{S_1^2, S^*\}$, $\hat{S} < S_{2II} < \min\{S_1^2, S^*\}$, and $S_{2III} < \hat{S}$.

However, the set $D_{21T_1}$ is not infinite. Unless $S_2$ is too small to utilize this information, country 2 will pick one problem in $D_{21\cdot}$ every period. On the other hand, country 1 keeps "producing" valuable information into $D_{21\cdot}$ at the rate of $S_1$ piece per date. Apparently, the information in $D_{21\cdot}$ is "consumed" by country 2 at a faster rate than it is supplemented. Therefore, sooner or later, country 2 will use up all the valuable information from country 1's experience. How will this fact change our previous analysis? Of course, $\hat{\vartheta}(A;S_2)$ is overstated. However, the minimal capacity for country 2 to grow ($\hat{S}$) is still right by the similar argument as the one following (5). Therefore for $S_2 \in (\hat{S};S_1)$; country 2 will grow at an expected rate $(\lambda - 1)\frac{S_2}{S_1}$ before the date at which $D_{21\cdot}$ first becomes empty, say $T_2$. After $T_2$, if country 2 does not try to solve problems before $T_1$ ($S_2 < S^*$), then it will do problem-solving only when there is new valuable information coming in. In this case, the expected growth rates of countries 1 and 2 are $(\lambda - 1)S_1$ and $(\lambda - 1)S_2$ respectively. Notice that country 2's growth rate drops from $(\lambda - 1)\frac{S_2}{S_1}$ to $(\lambda - 1)S_2$ after $T_2$. If country 2's size of knowledge is greater than $S^*$, that is, it will try to solve problems itself even without information spillover, the analysis becomes more complicated for two reasons. One is since country 2 may succeed on solving new problems, country 1 could also benefit from country 2 occasionally. The second reason is there could be strategic concern. Namely, since information is valuable, countries may want to strategically wait for it. At this moment, I am going to ignore the strategic concern and only focus on what are the expected growth rates for both countries in the case of mutual information spillover. I will briefly discuss the strategic behavior in the next section.

In the Appendix, I derive the expected growth rates when there is mutual information spillover. Applying those results, we can get the expected growth rates for both countries after date $T_2$. They are

$$
\begin{aligned}
g(S_1, S_2) &= (\lambda - 1)\left[S_1 + \frac{S_2(1 - S_1)^2}{1 - S_1 S_2}\right] \equiv (\lambda - 1)[S_1 + \Delta_{12}] \\
g(S_2, S_1) &= (\lambda - 1)\left[S_2 + \frac{S_2(1 - S_1)(1 - S_2)}{1 - S_1 S_2}\right] \equiv (\lambda - 1)[S_2 + \Delta_{21}].
\end{aligned}
\tag{12}
$$

Notice that:

(1) Since $\Delta_{12} > 0$ and $\Delta_{21} > 0$, both countries grow faster than when there is no information spillover.

(2) Since $\Delta_{21} > \Delta_{12}$, country 2 benefits more from country 1 than country 1 from country 2.

(3) For country 2, when $S_1$ goes up, there are two effects working in the opposite directions. The beneficial effect is that now country 2 can benefit from country 1 more often since the chance of country 1 producing valuable information gets higher. The adverse effect is that the information becomes less valuable since the gap between their human capital levels gets larger. The fact that $\frac{\partial \Delta_{21}}{\partial S_1} < 0$ suggests the second effect outweighs the first one.

(4) On the contrary, when $S_2$ goes up, there is no adverse effect working on country 1's growth rate. Therefore we have $\frac{\partial \Delta_{12}}{\partial S_2} > 0$.

(5) Since $g(S_2, S_1) - (\lambda - 1)\frac{S_2}{S_1} = -\frac{S_2(1 - S_1)^2}{S_1(1 - S_1 S_2)}(\lambda - 1) < 0$, country 2's growth rate drops after date $T_2$.

(6) Since $g(S_1, S_2) - g(S_2, S_1) = \frac{(1 - S_2)(S_1 - S_2)}{1 - S_1 S_2}(\lambda - 1) > 0$, country 1 enjoys a higher

expected growth rate in the "long run". [14]

Depending on the amount of country 2's knowledge, we can study its expected logarithm of output level over time. Using the three possible values of $S_2$ displayed in Figure 3, Figures 4 and 5 show their long-term economic performance accordingly.

## 3.2 Multiple Countries

An important implication drawn from the previous subsection is that, if possible, it is always (weakly) better to use the information from the country with a smaller size of knowledge than from the one with a larger size. This is because, in a sense, a country with a smaller knowledge size can do a better job of "screening" the problems.

Suppose now we have three countries. The relationship between country 3 and 2 is similar to the one between country 2 and 1. We can also derive the minimal capacity ($\tilde{S}$) for country 3 to grow. Very similar to $\hat{S}$, $\tilde{S} = 2S_2 - \frac{2\alpha\beta(\lambda - 1)}{1-\beta} < \hat{S}$. Therefore, if $S_3 \in (\tilde{S}, \hat{S})$, since $S_3 < \hat{S}$, country 3 will not pick problems in $D_{31\cdot}$ directly. That is, for country 3, information revealed from country 1 is useless because, in a sense, country 1 is too "smart" to learn from. However, information from country 2 is valuable since $S_3 > \tilde{S}$. In this case, although country 1 (the most advanced) does not (directly) help country 3 to grow, country 2 ( the middle) does. This is the interpretation of "learning from country X's growing experience" in this paper.

Although country 3 could outgrow country 2, its growth rate has to drop below country

[14] I use the term "long run" to emphasize that the valuable information is exhaustable. I put a quote there because the human capital level of each country is still held fixed.

2's eventually and the difference in their output level enlarges over time. The reason is exactly the same as before. In Figure 6, I assume that $S_2 > \max\{S^*; S_1^2\}$ and $S_3 \in (\bar{S}; \hat{S})$; $S_3 < S_2^2$: Under this setup, country 3 will not grow until $T_1$ and it will never use information from country 1. At $T_2$, country 3 may or may not have used up the information from country 2, but eventually, its growth rate has to drop to $\frac{S_3}{S_2}$ times country 2's growth rate. Notice that between $T_1$ and $T_2$, the middle country displays the highest growth rate. That is, if we put growth rate on the vertical axis and per-capita income level on the horizontal axis, we can get a familiar bell shape. However, this result depends heavily on the knowledge sizes we pick.

Once country 3 starts to grow, it sets a lower minimal capacity of knowledge for its followers. If $K_i$ and $K_{i+1}$, $\forall i = 1; \ldots; N - 1$ do not differ significantly, this transmission mechanism will continue so that all countries (except those with no knowledge at all) can grow. However, if $S_{i+1}$ is less than the minimal requirement set by some country i, then the transmission breaks down and countries $i + 1; \ldots; N$ will stay poor forever. The conclusion that "thresholds" would be kept pushing downward is noteworthy. One might think that since world technology becomes more and more sophisticated, poor countries nowadays would need to reach higher human capital level to be able to escape from low equilibrium. Chen (1999) reports nine Latin American and Asian countries' threshold years (the year that each country started growing) and their threshold human capital levels (the human capital level at threshold year), and finds that these two variables are negatively correlated. In other words, the threshold value on human capital level gets lower for countries that started growing at later date. The transmission mechanism provided in this model is consistent with her result.

# 4 Discussion

In this section, I am going to further discuss some features of this model and relate them to the existing literature.

1. Availability of technology and technology gap

In his seminal paper, Solow (1957) shows that a major part of productivity growth should be attributed to technology progress. In his interpretation, technology is a public good { i.e., something that is readily available and free of charge. Under this interpretation, whatever makes cross-country di®erence, either in living standard or long-run growth rate, is not technology. The way to avoid this counter-intuitive conclusion must rest on making technology less public. Then why it is not public and through what channel it can be public (to the adopting country) become major concerns.

One way to make technology less public is to emphasize that technology is to some extent complementary to some inputs. The speci¯c input could be physical goods. For example, in Grossman and Helpman (1991), better technology takes the form of expending variety or rising quality of intermediate goods. Therefore, in order to use this new technology, a backward country must acquire these goods ¯rst { through trade or imitation. Instead of physical goods, technology may be complementary to human capital. Due to lack of human capital, although new technology is available, it may not be ready to use for backward countries. One way for them to accumulate human capital is to increase \personal contact" with people in the advanced countries. Sending students out, inviting foreign technicians in, and encouraging trade[15] are examples. Some researchers emphasize that sometimes one can accumulate his human capital only through actually doing the job { i.e., learning-by-doing. Since the present model, to some extent, features learning-by-doing process, I will come back to this point soon.

The major departure of the present model from the literature mentioned above is that new technology is not available { there is no way to \see" solutions found by other countries so that countries must solve problems by themselves. Admittedly pushing the assumption to another extreme, this model focuses on the case where { as some economists[16] stress { technology is tacit or embedded in organizational structures. Technology of this kind is usually considered di±cult to transfer and hence technology gap results. However, this paper shows even so, backward countries may still bene¯t from information spillover so that convergence can still happen.

2. Trade and growth

Although this paper only deals with non-transferable technology, degree of openness may still have some impact on countries' growth rates. Trade de¯nitely provides channels of personal contacts and knowing new production, organizational methods, and thus facilitates

[15] Trade could increase the number of contacts which in turn, facilitate the °ow of ideas. See Grossman and Helpman (1991a).

[16] For example, see Nelson (1981), Nelson and Wright (1992).

information °ows. Therefore a relatively closed economy is not able to take full advantage of information spillover and tends to grow slower. Furthermore, since the value of information varies across its source country, trading partner is also important. This model suggests that, in order to enjoy high growth rate on technology, countries should trade with those countries with slightly higher human capital.[17]

3. Learning-by-doing

In his pioneer paper, Arrow (1962) states \Learning can only take place through the attempt to solve a problem and therefore only take place during activity.". The question is: why cannot one learn how to solve the problem beforehand? One possible answer is, as this paper stresses, the technology (knowledge) involved is tacit. If so, whether or how fast a country's productivity can grow should depend on its ability of solving problems. However, in the literature, learning-by-doing is usually modeled as automatic. Therefore persistent technology gap must be explained by a persistent time-lag that di®erent countries started to engage in some certain technology. For example, in Young (1991) and Stokey (1991), due to trading with advanced countries, backward countries postpone the timing of engaging in better technology.

Although this model predicts learning curve would depend on producers' human capital levels, since their human capital is assumed to be exogenously given, they do not really \learn". Also this simple model does not capture the features that many other emphasize,

[17] When international learning is in concern, it is usually argued that technology-advanced countries are ideal trade partners. See Coe, Helpman and Ho®maister (1997) and Chuang (1998).

like bounded learning-by-doing or learning-by-doing spillover.

4. Why do backward countries not always adopt technologies from the leading country?

Hahn (1995) studies Korea's technology adoption during the 62-92 period and ¯nds that Korea adopted Japanese technologies as much as U.S. technologies, even though the U.S. industries were recognized as leaders in many ¯elds for most of the periods. Why did Korea not adopt technologies exclusively from the U.S.? One possible answer is that U.S. is technology-leading only in the aggregate sense. If the conception of technology can be dissected as piece-by-piece, very narrow-de¯ned technologies, those pieces of technologies that Korea adopted from Japan may not be inferior at all. Another possible answer is that Japanese technologies were thought to be easier due to smaller technology gap between Japan and Korea, therefore Korea was willing to adopt inferior technologies. Notice that for both answers, \country" (either Japan or U.S.) is really not a concern. A more appropriate question may be \Did Korea always adopt state-of-art technologies?" or \Should Korea ever adopt inferior technologies?". As long as Korea is able to adopt some piece of technology, which country is its supplier does not matter.

However the conception of technology could be a package which consists of pieces of elements that may and may not be narrowly de¯ned. One reason is that the productivity of some industry in one country may depend on the social infrastructure of that country. Costello (1993) studies the productivity growth for ¯ve industries in six countries and ¯nds that productivity growth is more correlated across industries within one country than across countries within one industry. Her results suggest that a substantial fraction of changes in industry-level productivity can be attributed to nation-speci¯c factors. If so, it seems reasonable to put a \country tag" on technology and ask which country's technology is ideal for a backward country to adopt from.

In my model, the information revealed from some country is conceptually more similar to treating technology as a package. To the question \Why do backward countries not always adopt technologies from the leading country?", this model implies a backward country is willing to focus on the package revealed from a non-leading country not because some speci¯c problem in that package is easier, but the whole package is on average easier.

5. Is Technology gap an advantage per se?

It has been an old idea that there is some kind of relationship between technology gap and productivity growth. In their pioneer work, Nelson and Phelps (1966) hypothesizes that productivity growth rate positively depends on the technology gap. Starting from a theoretical setup, Hahn (1995) compares the technology investments (including R&D and technology adoption) made by Japan and Korea in the past three decades. His result suggests that the relationship between the bene¯ts from technology adoption and technology gap could be inverse U-shaped. One question we can ask is whether technology gap itself has direct e®ect on productivity growth or technology adoption. If yes, why? If no, what exactly is the indirect e®ect?

Another interesting question is which technology gap we are talking about. Is it the gap between the technology level of the adopting country and the world technology or the technology supplying country? In Nelson and Phelps' paper, it is the former. But in Hahn's paper, the technology gap for Korea is measured by the productivity di®erence between Korea and Japan which was not on the technology frontier during the period studied.

In this paper, the size of set $D_{jit}$ is the technology gap between country i and country j at time t. A large size of this set (large gap) can have two interpretations. One interpretation is this set is large because country j's human capital level is far below country i's. Then through time, the technology gap between these two countries becomes large. Another interpretation is although the di®erence of their human capital levels is small, there just has not been enough time for country j to improve its productivity due to, perhaps historical reasons. Obviously, we would expect divergence in the ¯rst case but convergence in the second one. Therefore, a large gap is not an advantage or disadvantage for backwardness per se. Furthermore, this model implies an appropriate concept for technology gap in the context of productivity growth should be between the receiving country and the supplying country, not the world.

6. A non-dichotomous world

The arguments in the previous two points have an important implication: a country can be both information receiver (from the more advanced countries) and supplier (for the more backward countries) at the same time. Therefore, the world in this model is no longer dichotomous (advanced v.s. backward) { a feature that growth models emphasizing technology di®usion usually have.[18] The dichotomy in these models stem from the dichotomy of the qualitatively di®erent behaviors { the advanced do innovations and the backward do imitations. Assuming imitating cost as a function of technology gap { a gap between imitating country and technology frontier { will not change the essence of this dichotomy and hence, is not able to capture the whole picture of this model.

In the literature, only few models have the feature that middle countries play a role. Nakajima (1999) tries to explain the catchup in turn phenomena by constructing a multi-country international trade model in which learning-by-doing and invention are the sources of growth. In his model, due to trade, a fast-growing middle country deprives the poorest country's chance to improve productivity through learning-by-doing. Therefore the growth rate of the poorest country is actually depressed in a multi-country world. Basu and Weil (1998) emphasizes the idea of \appropriate technology" by limiting the learning-by-doing spillover e®ect to a particular range of input combinations. A middle country[19] will have positive e®ect on the poorest country if they are \close" enough. If the middle country is instead closer to the most advanced country, the growth rate of the poorest country will be depressed due to less learning-by-doing spillover.

## 7. Patent racing

[18] For example, see Grossman and Helpman (1991) Ch. 11 and Barro and Sala-i-Martin (1995) Ch. 8.

[19] In their model, countries di®er in their saving rates. In the steady state, growth rate will (weakly) positively depends on the saving rate. Therfore middle country in their model means country with middle saving rate.

The idea that knowing others' technological break-through itself is valuable can be found in the patent racing literature. Choi (1991) points out in a multi-stage patent race, ¯rm that having technological break-through in the early stage sends two messages to its rival: one is now the technology gap is larger, the other is the problem at that stage is not that di±cult after all. When the second e®ect is strong enough, the technology-laggard ¯rm would choose continuing the race instead of dropping o®.

8. Strategic behavior

In section 3, countries with human capital level higher than the threshold ($S^¤$) are assumed to solve new problems when there is no valuable information available. In other words, countries are assumed not to behave strategically. However, since one country's problem-solving activity is helpful for other countries to reassess their probability of success, other countries might strategically choose to wait for the arrival of new information. Taking this strategic concern into account, the analysis becomes much more complicated. Suppose there are only two countries, one possible Nash equilibrium is that one country always tries to solve new problems and the other country always waits for new information, and the former country is not necessarily the one with higher human capital level. If there are more than two countries, not only countries may strategically choose not to solve new problems, but also they may choose not to use valuable information immediately { because this information may be re¯ned by other users.

# 5 Conclusion

In this paper, I build a model where people use their knowledge to solve problems; this is assumed to be the only source of economic growth. If people get to know what problem has been solved by whom, then solving a new problem would have some positive e®ect on others, since they can more accurately evaluate their probabilities of success. By focusing on this information spillover e®ect, I get the following main results:

(1) How strong this e®ect is, and hence how fast a country can grow, would depend on the relative human capital levels of information receiving and providing countries. A laggard country can grow faster or slower than the more advanced countries, or even stay stagnant.

(2) Therefore, countries would optimally choose their information source. It is not always best to use information revealed from the most advanced country, and countries in the middle group play an important role in the world economy.

(3) Since valuable information is exhaustible, fast growing due to information spillover is only a short-run phenomenon. In the long run, countries' technology levels and living standards are still ranked by their human capital levels.

The last point is actually more a caveat than a conclusion. Will all countries eventually reach the same human capital level so that convergence prevails? One cannot answer this question without explicitly spelling out how human capital is accumulated. However, the present analysis does shed some light on this question. The bene¯t from acquiring an additional amount of human capital is high for countries that are having \good" information source. Therefore, if the marginal cost does not depend on human capital levels, countries that are expecting fast growth, even though in the short run, will have higher incentive to accumulate human capital. This implies, in the long run, that we may observe multiple groups,[20] and countries within each group have the same human capital level. To prove this conjecture, a formal model that endogenizes human capital accumulation is certainly needed and I leave it to future study.

[20] Quah (1993) studies the dynamics of per capita income distribution across 118 countries. He concludes that countries in the world tend to cluster into two extreme (rich and poor) groups.

# A Appendix

Suppose there are only two countries, 1 and 2, in the world, $K_2 \subset K_1$ and $S_1 > S_2 > S^*$. From Section 2, since both countries' sizes of knowledge are greater than the minimal requirement for growing ($S^*$), they will try to solve problems even without information spillover. This means after depleting valuable information from country 1, country 2 will pick a problem from $\Phi$ and try to solve it itself. Therefore, country 1 will get some useful information if country 2 had succeeded. In this Appendix, I'll try to derive their expected growth rates.

In a situation where both countries can benefit from each other, it must be the case that one country will pick the problem just solved by the other country on the very next date. Therefore $D_{21t}$ (or $D_{12t}$) contains at most one element for any date. In other words, $|D_{ijt}| = 0$ or $1; \forall t; \{i; j\} = \{1; 2\}; i \neq j$; so the state space $s = \{(|D_{21}|; |D_{12}|)\}$ contains only four elements. Let $s_1 = (0; 0)$; $s_2 = (1; 0)$; $s_3 = (0; 1)$; $s_4 = (1; 1)$. The meaning of, say $s_2$, is one piece of valuable information for country 2 but none for country 1. The pertinent transition function for this situation can be represented by a Markov matrix $\Pi$; where

$$\Pi = \begin{bmatrix} (1-S_1)(1-S_2) & S_1(1-S_2) & (1-S_1)S_2 & S_1S_2 \\ (1-S_1) & S_1 & 0 & 0 \\ (1-S_2) & 0 & S_2 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}.$$

The meaning of, say the second row, is that when the state is $s_2$; country 2 will try to use that valuable piece of information (i.e., try to solve the problem just solved by country 1) and country 1 will randomly pick a new one from the pool $\Phi$. Whether country 2 succeeded or not, there is no valuable information for country 1. Therefore, states $s_3$ and $s_4$ will not happen for the next date and the probabilities of $s_1$ and $s_2$ will depend on whether country 1 fails or succeeds in solving its problem.

There is a unique invariant distribution $p^*$ associated with $\Pi$ and $p_i^*$ $(i = 1, 2, 3, 4)$ is the long-term average probability of state $s_i$. We can easily show that

$$p^* = \left(\frac{(1-S_1)(1-S_2)}{(1-S_1S_2)^2}, \frac{S_1(1-S_2)^2}{(1-S_1S_2)^2}, \frac{(1-S_1)^2S_2}{(1-S_1S_2)^2}, \frac{S_1S_2(1-S_1)(1-S_2)}{(1-S_1S_2)^2}\right).$$

For countries 1 and 2, the probabilities of success under different states can be represented by a $2\times4$ matrix $\Omega$,

$$\Omega = \begin{bmatrix} S_1 & S_1 & 1 & 1 \\ S_2 & \frac{S_2}{S_1} & S_2 & \frac{S_2}{S_1} \end{bmatrix},$$

where the first (second) row is for country 1 (2) and the $i$th column represents under state $s_i$. For example, $\Omega_{13}$ means under $s_3$ (where country 1 has one piece of valuable information but country 2 does not), country 1 can definitely solve it since the solution is in $K_2$, which is a proper subset of $K_1$. Then the expected growth rate for each country is just

$$\begin{bmatrix} g(S_1, S_2) \\ g(S_2, S_1) \end{bmatrix} = (\lambda - 1)\cdot\Omega\cdot p^{*-1} = (\lambda - 1)\cdot\begin{bmatrix} S_1 + \frac{S_2(1-S_1)^2}{1-S_1S_2} \\ S_2 + \frac{S_2(1-S_1)(1-S_2)}{1-S_1S_2} \end{bmatrix}.$$

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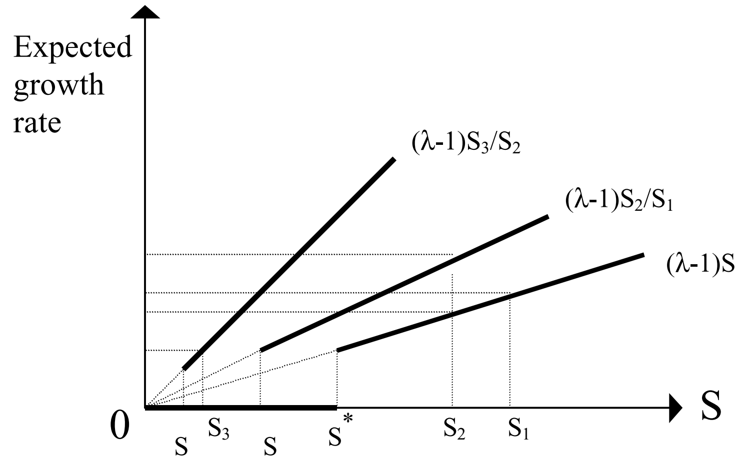



Fig. 6a

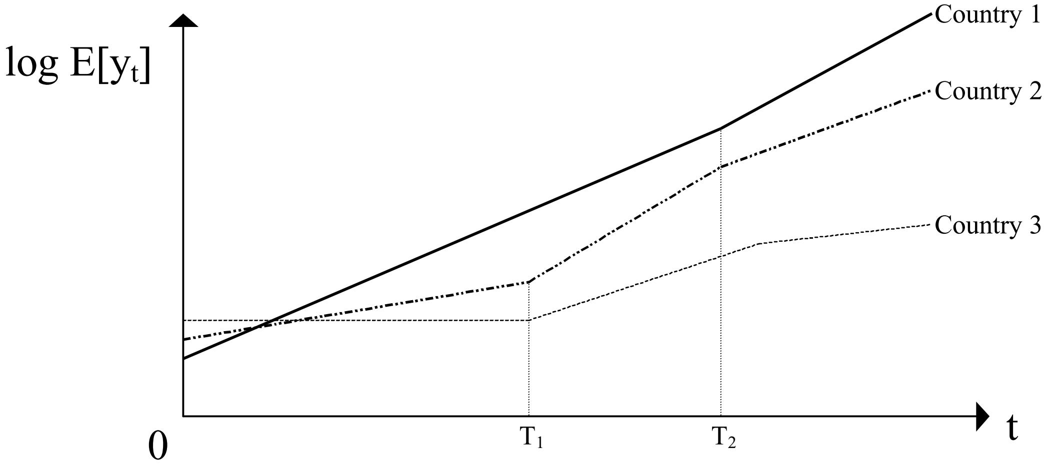



Fig. 6b

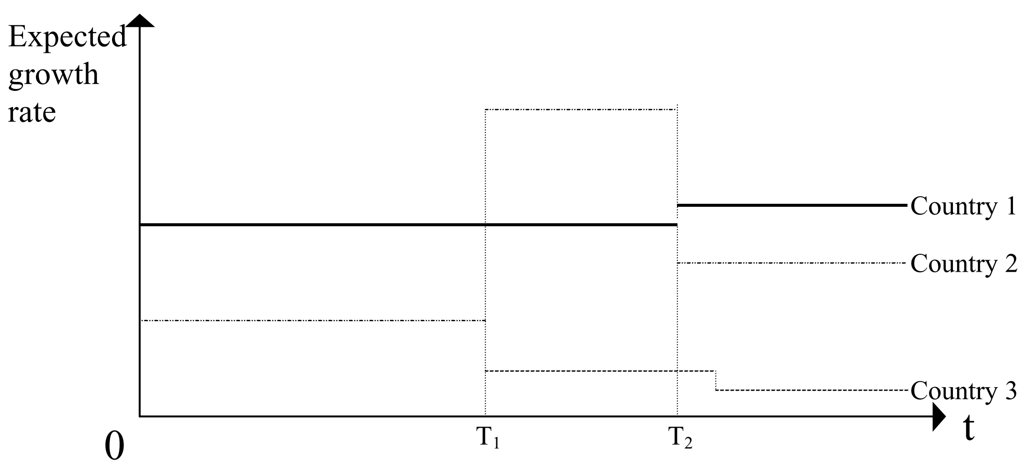



Fig. 6c

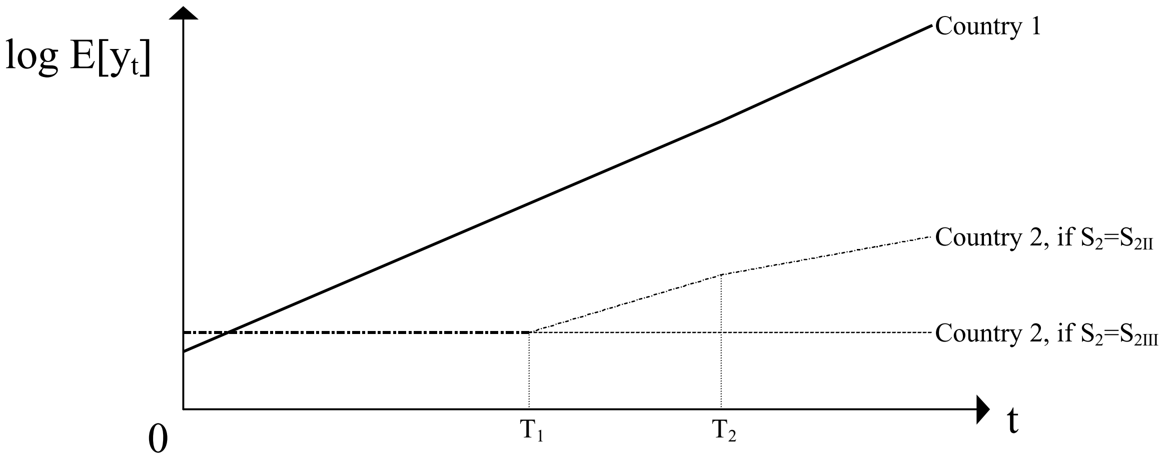



Fig. 5a ($S_2$=$S_{2II}$ or $S_{2III}$)

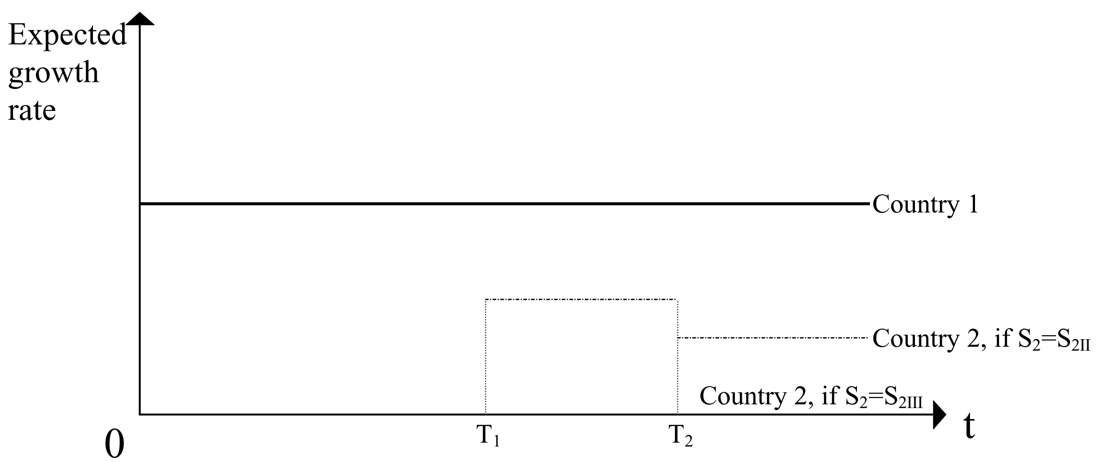



Fig. 5b ($S_2$=$S_{2II}$ or $S_{2III}$)

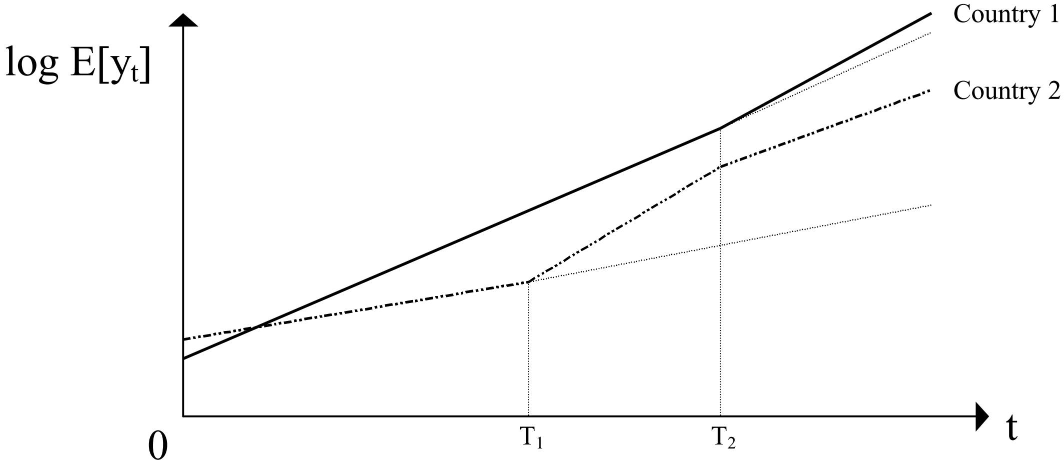



Fig. 4a ($S_2$=$S_{2I}$)

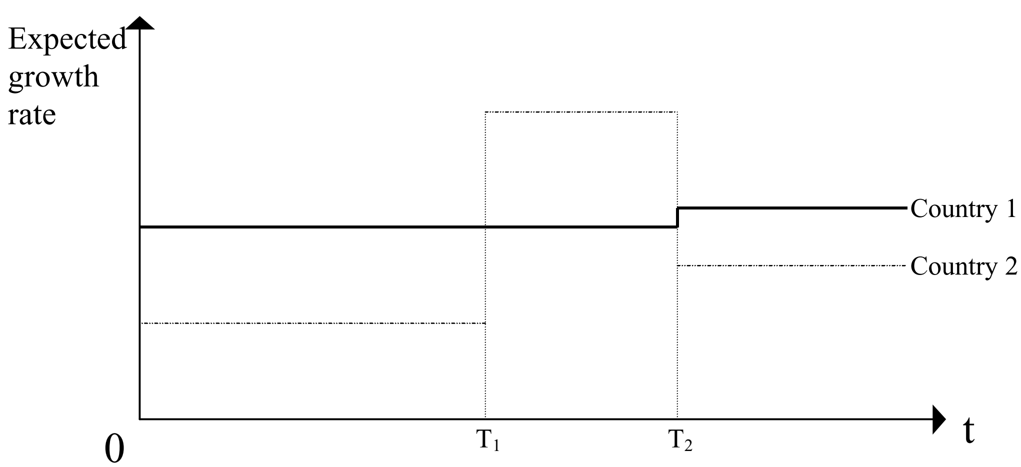
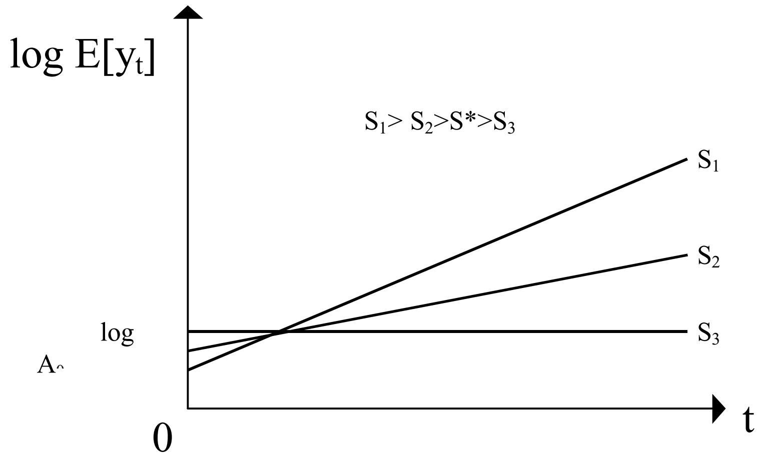
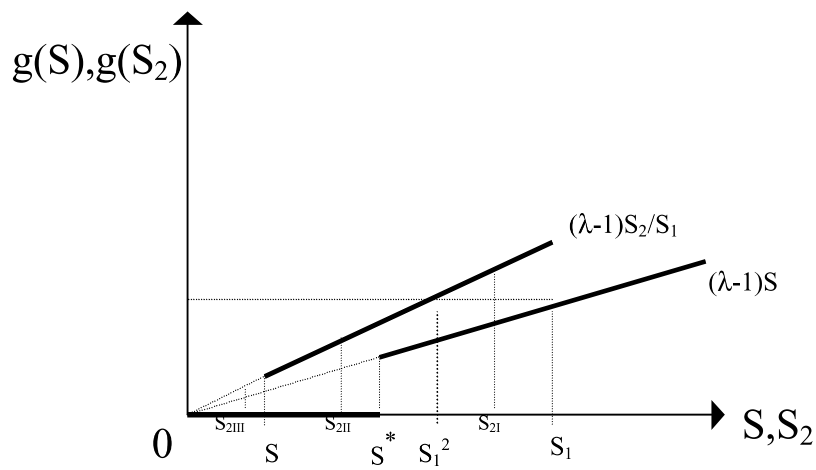



Fig. 4b ($S_2$=$S_{2I}$)



log E[y_t]
S1> S2>S*>S3
S1
S2
S3
log
A^
0
t


Fig. 2



g(S),g(S2)
(λ-1)S2/S1
(λ-1)S
S2III
S2II
S2I
0
S
S*
S1 2
S1
S,S2


Fig. 3

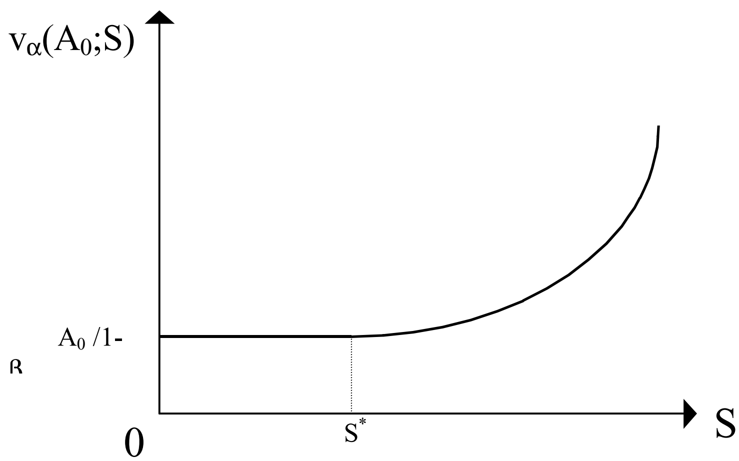



Fig. 1a

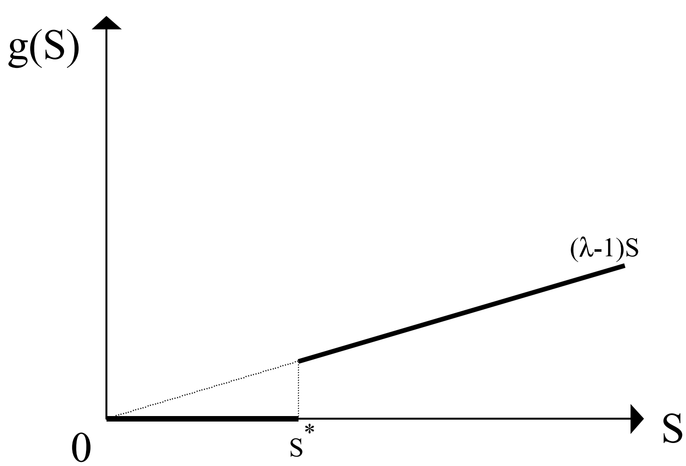



Fig. 1b