Technology Adoption, Human Capital, and Growth Theory

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Abstract

This paper explores a model in which growth is determined by a combination of human capital and technology adoption. At the heart of the model is the notion of "contiguous knowledge" – the idea that knowledge spreads out a certain distance. Because of this property of knowledge, a developing country can adopt existing technology only when it is sufficiently close to the technological frontier. The nature of the model is optimistic in that technology gaps present an opportunity for developing countries that are relatively close to the frontier to achieve rapid growth through technology adoption. Unlike the neoclassical growth model however, the predictions of the model are rather pessimistic for countries that are far away from the frontier making them unable to take advantage of imitation. As a result, the model is able to account both for rapid growth episodes as well as economic stagnation.

JEL Classification: O31, O40

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1. Introduction

Recent work on economic growth has focused on explaining the striking variation in growth rates and income levels among nations. Much of the research undertaken deals with identifying potential growth engines and explaining their role in the development process. For a number of years the literature was divided into two classes of models: the first class was based on the notion that factor accumulation alone can account for the observed cross–country income dispersion, whereas the second class was centered around the idea that technical change is the primary source of economic growth.[1] This division became less visible after the emergence of an alternative class of models in which both factors of production, such as physical and human capital, as well as technological progress are necessary engines in the development process.[2]

Following this new class of models, we construct a model in which growth is determined by a combination of human capital and technology adoption. At the heart of the proposed model is the notion of "contiguous knowledge" – the idea that knowledge can only be disseminated a certain distance, therefore limiting the benefits of relative backwardness. Contiguous knowledge is motivated by the notion that countries that are sufficiently close to the technological frontier can grow rapidly thus taking full advantage of the benefits of technology adoption.[3] However, countries that are far away from the frontier are unable to adopt existing technologies. In the context of an example, contiguous knowledge would suggest that it is doubtful that an Ethiopian farmer will benefit from the latest advances in animal genetics, or an Indian doctor from the latest innovations in laser surgery, or a Nepalese shopkeeper from the latest innovations in computerized inventory control. It is more likely that the real beneficiaries of new technologies are people of developing countries closer to the frontier.

One of the primary results of the model is that it can account for rapid growth episodes as well as economic stagnation. The nature of the model is optimistic in that technology gaps present an opportunity for developing countries that are relatively close to the frontier to achieve rapid growth

[1] The pioneer papers for the former and later classes of models are Lucas (1988) and Romer (1990) respectively. Following the lead of these pioneer papers we have consequently experienced an explosion of papers exploring and extending these models in many directions. For a nice review of these models see Klenow and Rodríguez-Clare (1997).

[2] Growth models that include physical and human capital accumulation combined with technological progress include Eicher (1996) and Bils and Klenow (forthcoming).

[3] Technological adoption refers to a country's ability to imitate, or adopt, existing technologies. The notion of technological adoption can be traced back to the work of Veblen (1915). Renewed interest in the importance of technology adoption (mainly at the inter–industry level) was shown by Schumpeter (1961) and a group of other economists who expanded upon Schumpeter's work. The first attempt to present adoption in a formal setting was made by Nelson and Phelps (1966), who developed a simple dynamic model which examined the impact of technology lags on the growth performance of developing countries. Recent attempts that explore technology adoption and link it to human capital and growth include Benhabib and Spiegel (1994), Parente and Prescott (1994) and Segerstrom (1999), just to name a few.

through technology adoption. Unlike the neoclassical growth model however, the predictions of the model are rather pessimistic for countries that are far away from the frontier making them unable to take advantage of imitation. In this respect, the model is consistent with empirical evidence (i.e. Durlauf and Johnson (1995) and Quah (1997)) suggesting that middle–income countries, such as Turkey, Brazil and Thailand, are converging, whereas low–income countries, such as Ethiopia, Haiti, and Yemen, are stagnant showing no promise for rapid growth.

This paper is related to existing work both in its aim and modelling framework. The model developed here is based on the R&D–based framework pioneered by Romer (1990) and extended by Barro and Sala–i–Martin (1995, 1997) to allow for technological adoption. Other papers that are conceptually similar to ours include Romer (1993) who investigates the proposition that idea gaps are an integral part of income dispersion across countries, Eicher (1996) and Rodriguez–Clare (1996) who develops rich models in which both human capital and R&D activity are endogenous, and Restuccia (1997) who develops a dynamic model with schooling and technology adoption. Probably, closer to our model is Benhabib and Spiegel (1994) who investigate an explicit law of motion of technology with both innovation and adoption. Our model differs from the above mentioned models, in that due to the notion of contiguous knowledge, the relationship between technology adoption (and growth) and relative backwardness is *not* monotonically positive but quadratic.

The remainder of the paper is organized as follows. Section 2 describes the economic environment of the model. Of particular interest in this section is the proposed law of motion of technology which is the driving force of the model. Section 3 investigates the steady–state and transitional dynamics properties of the model. Section 4 discusses the primary implications of the model, and suggests empirical tests of the proposed theory. Section 5 concludes.

2. The Model

We examine a two–country model in which one country is the technological leader (named country L), and the other is the technological follower (named country F). The leader is defined as the country which has the highest per capita income level and the highest level of technology. The follower is a country which lags the leader in both per capita income and technology. The leader country is assumed to spend a substantial amount of resources in R&D and devotes no resources in adopting foreign technologies. In contrast, the follower spends most of its resources in adopting and assimilating already existing technologies, and use only limited resources in re–inventing.[4]

[4]This assumption is motivated by micro and macro evidence supporting the idea that the cost of imitation is much lower than the cost of innovation (i.e. see Ozawa (1966), Teece (1977), and Mansfield, Schwartz and Wagner

An implicit assumption of the model is that innovations can be converted into a communicable form and transferred to the follower. Finally, it is assumed that the leader does not receive any compensation (i.e. royalties) for the use of its technologies in poorer nations, and does not seek to produce abroad.

The leader and follower countries are assumed to operate under the same economic environment; the main difference between the two countries is the way by which they obtain their production technologies. The technological leader only innovates, whereas the technologically backward country mostly imitates. Given this simplified framework, we can characterize a model economy that represents both the advanced as well as the developing economies. Following closely Romer (1990) and Barro and Sala–i–Martin (1997), our model economy consists of three sectors. First, there exists a final–good sector, which is perfectly competitive and produces a single homogenous consumption good. The production of the final good requires the use of a portion of the total amount of human capital and a variety of intermediate goods. Second, there exists an intermediate–goods sector, which supplies a variety of inputs to the final–good producers. The intermediate–goods sector consists of monopolistic producers of differentiated products. Firms producing intermediate goods will not be willing to produce under conditions of perfect competition because the production of intermediate goods requires manufacturing costs plus an up–front investment in R&D. In other words, an intermediate–goods producer can raise sufficient revenues to pay for production cost as well as for the cost of carrying out the necessary research for developing (or adopting) a design only by selling the input at a price with a mark–up on the marginal cost of production. The model then requires that the intermediate–goods producer be an imperfect competitor that can recover investments made in R&D. Incorporating monopolistic competition into the intermediate–goods sector reflects the nonrival nature of technology (a property that, in general, does not hold in the final–goods market). Technology in this model is “nonrival good” in the sense that its use by one firm does not limit its use by others. Third, there exists an R&D sector that supplies the intermediate–goods producer with different designs and blueprints. One can imagine this third sector as being the R&D department of the intermediate–goods firms. For this sector it is assumed, as in Dixit and Stiglitz (1977), that there exists free entry in the intermediate–goods market which results in the elimination of profits in a present value sense.

Since the two countries studied here are subject to the same economic structure, we will proceed by examining a model economy which resembles the same characteristics in both the leader and follower countries.

(1981)). In addition, Helpman and Hoffmaister (1997) report that in 1990 industrial countries accounted for 96% of the worlds R&D expenditure. Given the above evidence our model assumes that the follower does not (or better can not) innovate but can re–invent existing technology.

2.1. Final–Good Sector

Perfectly competitive firms produce a single nondurable final good by combining human capital with a series of intermediate goods X_i, where $i \in [0, A]$. Human capital in this model is used in the production of goods (H_Y) and the production of designs (H_A). Human capital used in the production of both goods and designs equals the aggregate level of human capital that is assumed to be fixed ($H_Y + H_A = H$). Following Ethier (1982), the number of intermediate goods used in the production of the final good reflects the technological level of a country. Technological advancement takes the form of an endogenous increase in the range of intermediate goods. The production function of the final good in country j (either L or F) is given by

$$Y_j = B_j(H_{Yj})^{1-\alpha} \int_0^{A_j} (X_{ij})^{\alpha}\, di,\ B_j > 0,\ 0 < \alpha < 1, \tag{2.1}$$

where Y_j is output in country j, B_j is a positive productivity parameter that may represent a variety of things (i.e. government policy), H_{Yj} is the portion of human capital used in the production of the final good, A_j is technology given by the number of intermediate goods used in the production of final good, X_{ij} is the amount of intermediate good i used in the production of final good, and α is intermediate–goods share.

The additive separability of X_{ij} is an important property of this production function. It implies that discoveries of new intermediate goods do not make any existing discoveries obsolete, and that no particular intermediate good is necessary for the production of the consumption good (each intermediate good is useful regardless of whether other intermediate goods are available). Under conditions of perfect competition final–good producers maximize their instantaneous profits

$$\Pi_j = Y_j - w_{H_{Yj}} H_{Yj} - \int_0^{A_j} (P_i X_{ij})\, di, \tag{2.2}$$

where P_i is the price of the intermediate good i in terms of final good, and $w_{H_{Yj}}$ is the human capital wage rate in country j in terms of final good. Taking the consumption good as the numeraire, final–good producers choose inputs so that their marginal products equal input prices (i.e. $MPX_{ij} = P_i$). It is straightforward to verify that the first–order conditions of the above maximization problem imply the following relations:

$$X_{ij} = H_{Yj} \left(\frac{B_j \alpha}{P_i} \right)^{\frac{1}{1-\alpha}} \tag{2.3}$$

$$w_{H_{Yj}} = (1-\alpha) B_j (H_{Yj})^{-\alpha} \int_0^{A_j} (X_{ij})^{\alpha}. \tag{2.4}$$

Equation (2.3) is the demand curve of input i. This demand function is what the intermediate–goods producers take as given to maximize profits. Equation (2.4) gives the human capital wage rate.

2.2. Intermediate–Goods Sector

The production function of intermediate goods is assumed to be the same as the production function specified in equation (2.1). Introducing a new production function for the manufacturing of intermediate goods would only complicate the algebra without changing the results qualitatively.[5] Given this simplifying assumption, each unit of intermediate goods can be exchanged for one unit of final good. As discussed previously, producers of intermediate goods are assumed to be monopolistic competitors who choose the profit maximizing prices of intermediate goods.[6] In principle, input producers are expected to be unwilling to produce under competitive market conditions. This is because the manufacture of an input requires a start–up cost of innovating (or adopting) a new design. This investment in a blueprint can only be recovered if profits in each date are positive for a certain period in the future.

Since the producer of variety i of intermediate goods is assumed to be a monopolistic competitor, s/he solves the following maximization problem at each period:

$$\max_{P_i}(P_i - 1)X_{ij}\ , \tag{2.5}$$

or substituting equation (2.3), the demand function, into (2.5) s/he will be solving the following problem

$$\max_{P_i}(P_i - 1)H_{Yj}\left(\frac{B_j\alpha}{P_i}\right)^{\frac{1}{1-\alpha}}. \tag{2.6}$$

After taking the derivative with respect to price and setting it equal to zero, it is straightforward to derive the solution of this maximization problem as

$$P_i = \frac{1}{\alpha}. \tag{2.7}$$

The profit–maximizing price chosen by the monopolistic competitor represents a markup, $1/\alpha$, on the marginal cost of manufacturing intermediate goods, which is equal to 1. Notice that the price chosen by the monopolistic competitors is constant (therefore $P_i = P$) which makes our problem symmetric. Also notice that this price is taken as given by the final–good producers (price takers).

Substituting equation (2.7) into equation (2.3) yields the explicit demand function

$$X_{ij} = X_j = \alpha^{\frac{2}{1-\alpha}}H_{Yj}(B_j)^{\frac{1}{1-\alpha}}. \tag{2.8}$$

[5] For discussions concerning the production function of intermediate goods see Dixit and Stiglitz (1977), and Ethier (1982).

[6] For a comprehensive discussion of the properties of imperfect competition in various frameworks see Matsuyama (1995).

We can now substitute the explicit demand for inputs into the production function of the final good and due to the symmetry of the problem ($\int_0^{A_j} X_{ij}^{\alpha}\, di = A_j X_j^{\alpha}$) we get the output level

$$Y_j = \alpha^{\frac{2\alpha}{1-\alpha}} A_j (B_j)^{\frac{1}{1-\alpha}} H_{Yj}. \tag{2.9}$$

Finally, we need to examine the present value of the returns from the production of intermediate–goods. Given the instantaneous interest rate r_j, the present value of the net returns form sales of intermediate goods to the final–good sector is given by

$$V_j(t) = (P-1)X_j \int_t^{\infty} e^{-r_j(\eta - t)}\, d\eta, \tag{2.10}$$

and in steady state where the interest rate r^{ss} is constant,[7]

$$V_j(ss) = \frac{(P-1)X_j}{r_j^{ss}}. \tag{2.11}$$

Substituting the profit–maximizing price and the demand curve given by (2.7) and (2.8) respectively into equation (2.10) gives the explicit present value as a function of the human capital used in the production of final goods H_{Yj}, the productivity parameter B_j, the factor share α and the interest rate r_j as follows:

$$V_j(t) = (1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}} H_{Yj} (B_j)^{\frac{1}{1-\alpha}} \int_t^{\infty} e^{-r_j(\eta - t)}\, d\eta, \tag{2.12}$$

and in steady state,

$$V_j(ss) = \frac{(1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}} H_{Yj} (B_j)^{\frac{1}{1-\alpha}}}{r_j^{ss}}. \tag{2.13}$$

2.3. Research and Development Sector

It is assumed that the R&D sector provides intermediate–goods producers with patents or blueprints under competitive conditions. It is possible that R&D is produced either by specialized firms which sell their products to the intermediate–goods market, or by R&D departments within the intermediate–goods firms. Following Romer (1990) and Grossman and Helpman (1991), the competitive market of blueprints implies free entry in the intermediate goods–sector and the consequent elimination of profits in a present–value sense. That is, monopolistic competitors decide whether to produce an intermediate good based on the cost of the blueprint and comparing it to the discounted net revenues from sales of the intermediate good. Any intermediate–goods producer can pay the cost of blueprint, to secure the net present value $V(t)$ given in equation (2.12). By

[7] Even though the interest rate at time η is not constant, as argued later on, it is constant at steady state.

using an arbitrage argument, we get the cost of a blueprint at each point in time as

$$\phi_j = (1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}} H_{Yj}(B_j)^{\frac{1}{1-\alpha}} \int_t^{\infty} e^{-r_j(\eta-t)}\, d\eta, \tag{2.14}$$

where ϕ_j is the cost of R&D in country j.[8] Then by differentiating both sides of (2.14) with respect to time gives

$$r_j = \frac{(1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}} H_{Yj}(B_j)^{\frac{1}{1-\alpha}}}{\phi_j} + \frac{\dot{\phi}_j}{\phi_j}, \tag{2.15}$$

which in steady state is given by

$$r_j^{ss} = \frac{(1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}} H_{Yj}(B_j)^{\frac{1}{1-\alpha}}}{\phi_j^{ss}}. \tag{2.16}$$

Equation (2.16) shows an inverse relationship between interest rate r_j and the cost of R&D ϕ_j.[9]

What remains to be described is the production process of new varieties of intermediate goods (blueprints). This requires the specification of a law of motion that determines how the intermediate–goods set expands in both the leader and the follower countries. We consider the implicit specification

$$\dot{A}_j = Q\left[H_{Aj},\ A_j,\ f\left(\frac{A_j}{A_L}, b\right)\right],\ 0 < \frac{A_j}{A_L} < 1,\ 0 < b < 1, \tag{2.17}$$

where the following conditions hold:

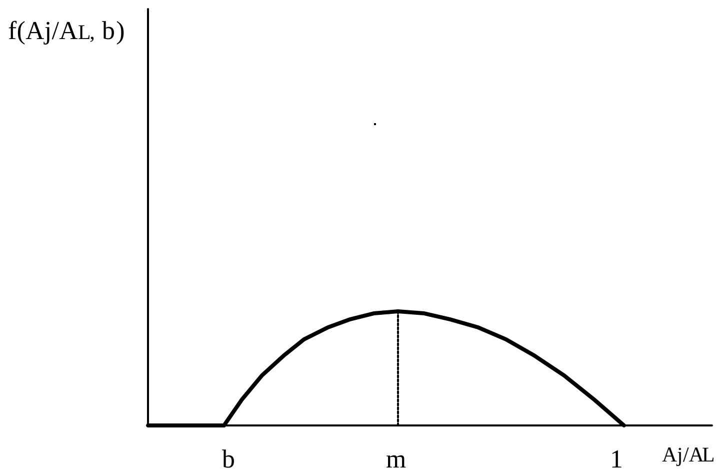
1. $Q\left[0,\ A_j,\ f\left(\frac{A_j}{A_L}, b\right)\right] = 0$
2. $Q_{H_{Aj}} > 0$
3. $Q_{A_j} > 0$
4. $\begin{cases} f_{\frac{A_j}{A_L}} > m,\ \forall\ \frac{A_j}{A_L} < m < 1 \\ f_{\frac{A_j}{A_L}} < m,\ \forall\ \frac{A_j}{A_L} > m > 0 \end{cases}$
5. $\begin{cases} f\left(\frac{A_j}{A_L}, b\right) = 0,\ \forall\ 0 < \frac{A_j}{A_L} \leq b \\ f\left(\frac{A_j}{A_L}, b\right) > 0,\ \forall\ b < \frac{A_j}{A_L} < 1 \end{cases}$

The assumption $0 < \frac{A_j}{A_L} < 1$ restricts the model from leap–frogging (which is an interesting possibility but not the focus of this paper). Condition 4 implies an inverted U–shaped quadratic adoption term, whereas condition 5 secures that the adoption term is economically feasible (i.e. it is nonnegative). Figure 2.1 provides an illustration of the adoption term $f(\frac{A_j}{A_L}, b)$.

[8] Equation (2.14) states that the cost of R&D in the follower country is bid up so that the intermediate-goods producers are indifferent between producing a new intermediate good and not producing at all.

[9] As we show later on, our model implies that $\frac{\dot{\phi}_j^{ss}}{\phi_j^{ss}} = 0$, and therefore ϕ_j^{ss} is constant.

Figure 2.1: Illustration of the quadratic technology adoption function



An explicit specification that is consistent with the above implicit law of motion of technology is given by the equation

$$\dot{A}_j = \left[\delta H_{Aj} A_j + (1-\delta) H_{Aj} \left(-\left(\frac{A_j}{A_L}\right)^2 + (1+b)\frac{A_j}{A_L} - b \right)\right], \ 0 \leq \delta \leq 1, \qquad (2.18)$$

where H_{Aj} is the human capital employed in the R&D sector in country j ($\forall\ j = F, L$), and δ is the fraction of R&D human capital employed in the innovation process. Human capital engaged in the R&D sector is employed in both the innovation process and the adoption process with the feasibility constraint $H_{Aj(\text{ Innov})} + H_{Aj(\text{Imm})} = H_{Aj}$.

Equation (2.18) is inspired by a similar specification suggested by Benhabib and Spiegel (1994) which implies that technical change depends both on innovation and imitation. The first term on the RHS of equation (2.18), $\delta H_{Aj} A_j$, represents the innovation process and indicates that human capital contributes to growth through facilitating domestically produced intermediate–goods. The second term on the RHS of equation (2.18) represents the imitation process and is the heart of our proposed law of motion of technology. In general, this term attempts to capture the benefits of "relative backwardness" by introducing the ratio $\frac{A_j}{A_L}$ in the law of motion of technology.[10] Unlike existing technology specifications in which the imitation process, $\frac{A_j}{A_L}$, enters in a linear form, our specification favors a quadratic (hump–shaped) imitation term. This is motivated by the notion of "contiguous knowledge" which asserts that knowledge is diffused only a certain distance. Because

[10]The relative backwardness hypothesis, pioneered by Findlay (1978), states that the rate of technological progress in a relatively backward country is an increasing function of the gap between its own level of technology and that of the advanced country.

of this property, a developing country can adopt existing technology and grow rapidly only when it is sufficiently close to the technological frontier.[11]

One of the interesting features of the proposed specification is that it represents the law of motion of technology for both the leader and follower countries. Notice that equation (2.18) implies that in the leader country $\dot{A}_L = \delta H_{AL} A_L$.[12]

2.4. Consumer Problem

We close the model by presenting the consumer problem which is assumed to be identical in both economies. Each economy is assumed to have a large number of identical consumers and zero population growth.

Consumers seek to maximize the following constant elasticity of substitution utility function:

$$U_j = \int_t^\infty \left(\frac{c_j^{1-\theta} - 1}{1-\theta} \right) e^{-\rho t}\, dt, \tag{2.19}$$

where $\theta > 0$ is the inverse of the intertemporal elasticity of substitution, and $\rho > 0$ is the discount rate. For simplicity, the preference parameters θ and ρ are assumed to be the same in both countries. The consumer's budget constraint is given by

$$\dot{z(t)} + c(t) = w(h_Y + h_A) + r(t)z(t), \tag{2.20}$$

where $z(t)$ is the total asset holdings of consumers, c is consumption, w is real wage, h_Y is the portion of human capital allocated in the production of final good, h_A is the portion of human capital allocated in the production of technology, and r is the real interest rate. The optimal paths for consumption and investment can be chosen by solving an optimal control problem. The *current–value Hamiltonian* and the first order conditions associated with the household's problem are given as follows:

$$\mathcal{H} = \left(\frac{c(t)^{1-\theta} - 1}{1-\theta} \right) + \mu(t)[w(h_Y + h_A) + r(t)z(t) - c(t)] \tag{2.21}$$

$$c(t)^{-\theta} = \mu(t) \tag{2.22}$$

$$\dot{\mu(t)} = \rho\mu(t) - r\mu(t). \tag{2.23}$$

[11] I thank an anonymous referee whose comments on the notion of "contiguous knowledge" improved the paper substantially.

[12] This is easily shown by setting $j = L$ and noticing that the quadratic term collapses to zero. As will be discussed later on we also set $\delta = 1$ to reflect that all capital is now devoted to the R&D activity.

Differentiating (2.22) with respect to time and substituting in (2.23), yields the growth rate of consumption

$$g_j = \frac{\dot{c}}{c} = \frac{1}{\theta}(r_j - \rho), \tag{2.24}$$

where g_j is a balanced–growth path (i.e. C_j, Y_j, A_j all grow at rate g_j, as will be shown in the next section).

3. Cost of R&D and the Long–Run Equilibrium

This section is concerned with the cost of R&D in the follower and leader countries, and the characterization of the steady state and transitional path implied by the model.

3.1. The Leader Country

The law of motion of intermediate goods in the leader country depends only on the stock of human capital and the stock of domestic technology, not on the technological gap. That is, in the case of the leader, the adoption term in equation (2.18), $(1-\delta)H_{Aj}\left(-\left(\frac{A_j}{A_L}\right)^2 + (1+b)\frac{A_j}{A_L} - b\right)$, is now zero.[13] Also, the assumption that the leader is always on the technological frontier implies that the country can only innovate (*not* imitate). This requires that all of human capital in R&D sector is employed in the innovation task (i.e. $H_{AL(\text{Innov})} = H_{AL}$) and therefore $\delta = 1$. Equation (2.18) is then reduced to,

$$\dot{A}_L = H_{AL}A_L. \tag{3.1}$$

Given that human capital is the only input in the production of technology, all revenues received from sales of designs to the intermediate–goods producers go to human capital wages, w_{H_A}. In addition, we assume that R&D firms operate under perfect competition and pay human capital its marginal product. Taking the derivative of the production function of blueprints given by equation (3.1) with respect to human capital gives

$$w_{H_A} = \phi_L A_L, \tag{3.2}$$

where ϕ_L is the cost of technology production in the leader country. An arbitrage condition implies that in equilibrium human capital engaged in either the final good sector, or the R&D sector will

[13]Notice that replacing A_j with A_L in the adoption function implies that

$$(1-\delta)H_{Aj}\left[-\left(\frac{A_j}{A_L}\right)^2 + (1+b)\frac{A_j}{A_L} - b\right] = 0.$$

receive equal wages (i.e. $w_{H_Y} = w_{H_A}$). Therefore, using equations (2.4), (2.9) and (3.2) gives,

$$\phi_L = (1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}}(B_L)^{\frac{1}{1-\alpha}}. \tag{3.3}$$

We can then derive the interest rate r_L, by substituting equation (3.3) into (2.16)[14]

$$r_L = \alpha H_{YL}. \tag{3.4}$$

Equation (3.4) states that, interest rate in the technological leader depends only on the level of domestic human capital.

3.2. The Follower Country

We next derive explicitly the effects of the law of motion given by (2.18) on the follower country. Following the same steps as before we obtain

$$w_{H_A} = \phi_F \left[\delta A_F + (1-\delta)\left(-\left(\frac{A_F}{A_L}\right)^2 + (1+b)\frac{A_F}{A_L} - b\right)\right], \tag{3.5}$$

where ϕ_F is the cost of technology production in the follower country. An arbitrage condition (i.e. $w_{H_Y} = w_{H_A}$) combined with equations (2.4), (2.9), (3.5), and condition 5 of the technology adoption term given in section 2.3 obtains the cost of R&D in the follower country as,

$$\phi_F = \begin{cases} (1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}}(B_F)^{\frac{1}{1-\alpha}}, & \forall\ 0 < \frac{A_i}{A_L} \leq b,\ \delta = 1 \\ \\ \dfrac{(1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}}(B_F)^{\frac{1}{1-\alpha}}}{\left[\delta + (1-\delta)\frac{1}{A_F}\left(-\left(\frac{A_F}{A_L}\right)^2 + (1+b)\frac{A_F}{A_L} - b\right)\right]}, & \forall\ b < \frac{A_i}{A_L} < 1. \end{cases} \tag{3.6}$$

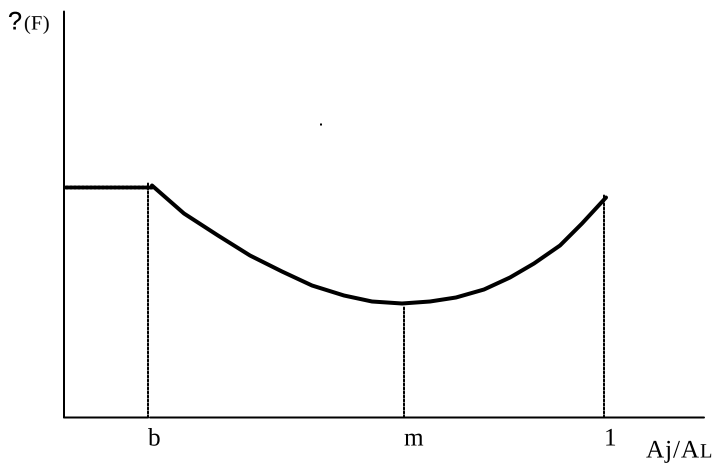
There are several points worth noting here. First, notice that when the follower country is far away from the technological frontier (i.e. $0 < \frac{A_i}{A_L} \leq b$), adoption of existing technologies is not possible and therefore the follower country is forced to only invent (or more appropriately re–invent) technology; this in turn implies a high cost of R&D.[15] Second, for intermediate technology gaps (i.e. $b < \frac{A_i}{A_L} < 1$) the cost of R&D is now a quadratic (U shape) function of the relative backwardness term, $\frac{A_F}{A_L}$.

Figure 3.1 illustrates the technology cost for the follower country. The cost function ϕ_F is constant for large technology gaps. However, after some point, b, the cost of R&D starts declining

[14] Notice that unlike the interest rate in the follower country that is constant only at steady state, the interest rate of the leader, r_L, is constant at all time. Equation (3.3) shows that the cost of innovation ϕ_L is also constant at all time.

[15] Since the follower country far from the frontier does not imitate, it is reasonable to assume that $\delta = 1$ which requires that all of its human capital in R&D sector is employed in the re-invention task and none of it in the imitation task.

Figure 3.1: Illustration of the relationship between R&D cost and technology gap



reflecting the benefits from adoption. When the technology gap between the leader and follower countries reaches point m, the cost is at its minimum. After point m technology cost starts increasing reflecting the gradual saturation of adoption opportunities and heavier reliance on innovation.

We can finally derive interest rate r_F, by substituting equation (3.6) into (2.15) as follows:[16]

$$r_F = \alpha H_{YF}\left[\delta + (1-\delta)\frac{1}{A_F}\left(-\left(\frac{A_F}{A_L}\right)^2 + (1+b)\frac{A_F}{A_L} - b\right)\right] + \frac{\dot{\phi}_F}{\phi_F}. \tag{3.7}$$

According to the above equation, interest rate in the technologically follower country depends crucially on both the country's domestic stock of human capital and the technology gap.

3.3. The Steady State

In this section, we are concerned with the steady–state properties of the model. We start by showing that in steady state there exists a balanced–growth path.

The resource constraint of country j is given by

$$Y_j = C_j + \phi_j \dot{A}_j + A_j X_j. \tag{3.8}$$

Following Barro and Sala–i–Martin (1995, Chapter 6) we assume that intermediate goods X_j are nondurable (rather than durable assumed by Romer (1990)). Using this approach reduces the state

[16]In transition, interest rates include both dividends and capital gains. Dividends is given by the term $\alpha H_{YF}\left[\delta + (1-\delta)\frac{1}{A_F}\left(-\left(\frac{A_F}{A_L}\right)^2 + (1+b)\frac{A_F}{A_L} - b\right)\right]$, and capital gains by the term $\frac{\dot{\phi}_F}{\phi_F}$. Notice that capital gains do not exists in steady state and are present only in transition.

variables to only one, A_j. Equation (3.8) states that income, Y_j, equals consumption, C_j, plus investment in designs, $\phi_j \dot{A}_j$, plus investment goods, $A_j X_j$. We then rewrite equation (3.8) by substituting equations (2.9), (2.18), (3.6), and (2.8). Using that $A_L^{ss} = A_F^{ss}$ and ϕ^{ss} is a constant (see subsequent discussion), simple algebra reveals that $C = \zeta A$, where ζ is also a constant. It then follows that $g_{C_j}^{ss} = g_{A_j}^{ss}$. Equation (2.9) implies that in steady state, $g_{Y_j}^{ss} = g_{A_j}^{ss}$. Therefore, there exists a balanced–growth equation

$$g_{Y_j}^{ss} = g_{C_j}^{ss} = g_{A_j}^{ss}. \tag{3.9}$$

We are now ready to derive and characterize the steady–state growth of the model. We make the simplifying assumption that in steady state $A_F^{ss} = A_L^{ss}$; that is, in steady state the follower converges to the technology frontier. With this assumption we secure that $g_{A_L}^{ss} = g_{A_F}^{ss}$ and that the cost of R&D is constant in steady state (i.e. $\frac{\dot{\phi}_j^{ss}}{\phi_j^{ss}} = 0$) which seem to be reasonable and consistent with observation.[17]

Using equations (2.16), (2.18), (2.24), and the restriction $H_{Yj} + H_{Aj} = H_j$ obtains the world balanced growth path

$$g_W^{ss} = \frac{1}{\alpha + \theta}(\alpha H_W - \rho). \tag{3.10}$$

Equation (3.10) is by construction identical to the balanced–growth path in Romer (1990). Long–run growth in both the follower and leader countries then depends on the stock of human capital, the preference parameters θ and ρ, and the factor share α.

It is well–known that the scale effects exhibited by equation (3.10) have been criticized by Jones (1995) who in turn proposes a semi–endogenous model that is scale–free. Jones' findings about scale effects is the center of on going debate, which certainly has not reached a consensus (see Dinopoulos and Thompson (1999) for a survey of recent contributions to this debate). The proposed model's steady state depends crucially on the law of motion of technology given by equation (2.18). Changing the model assumptions slightly, i.e. $\frac{\dot{H}_j}{H_j} = n$, and modifying the R&D equation (2.18) to $\dot{A}_j = \left[\delta H_{Aj}^{\lambda} A_j^{\psi} + (1-\delta) H_{Aj}^{\lambda} \left(-\left(\frac{A_j}{A_L}\right)^2 + (1+b)\frac{A_j}{A_L} - b\right)\right]$ would result in a common balanced growth path that is identical to that of Jones', $g_W^{ss} = \frac{\lambda n}{1-\psi}$, where λ introduces diminishing returns to human capital, n is human capital growth, and ψ is a technological externality. Another way to eliminate scale effects and retain endogenous growth is suggested more recently by Howitt (2000). Even though worth–noting, none of the these extensions changes the model predictions qualitatively.

[17] In particular, notice that by totally differentiating equation (2.18) gives $g_{A_L}^{ss} = g_{A_F}^{ss} \left[\frac{2-(1+\alpha)\left(\frac{A_L}{A_F}\right)}{1-\alpha\left(\frac{A_L}{A_F}\right)^2}\right]$. By assuming that $A_F^{ss} = A_L^{ss}$ we obtain $g_{A_L}^{ss} = g_{A_F}^{ss}$. In addition, by using the same assumption reduces equation (3.6) to $\phi_L^{ss} = (1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}}(B_F)^{\frac{1}{1-\alpha}}$, and equation (3.7) to $r_F^{ss} = \alpha H_{YF}$.

3.4. Transitional Growth

This section is concerned with the transitional dynamics properties implied by the proposed model. It is shown that although in steady state there exists a world growth rate common to both countries, in transition follower countries can potentially achieve higher growth rates than the leader and can eventually converge to the steady state. This is clearly due to the potential of technological backwardness (the potential for adoption) presented to *some* follower countries. According to our model the potential for adoption can not be realized by countries that are far away from the frontier; an argument consistent with the notion of contiguous knowledge. By means of a simulation exercise we study some of the aspects of the transitional path of countries that are sufficiently close to the technology frontier and therefore can adopt. We show that the convergence trajectory for the technology adopting countries obeys a quadratic path. Finally, we perform a sensitivity analysis which demonstrates how changes in the initial technology gap, $\frac{A_F(0)}{A_L(0)}$, and the threshold parameter, b, influence transitional growth.

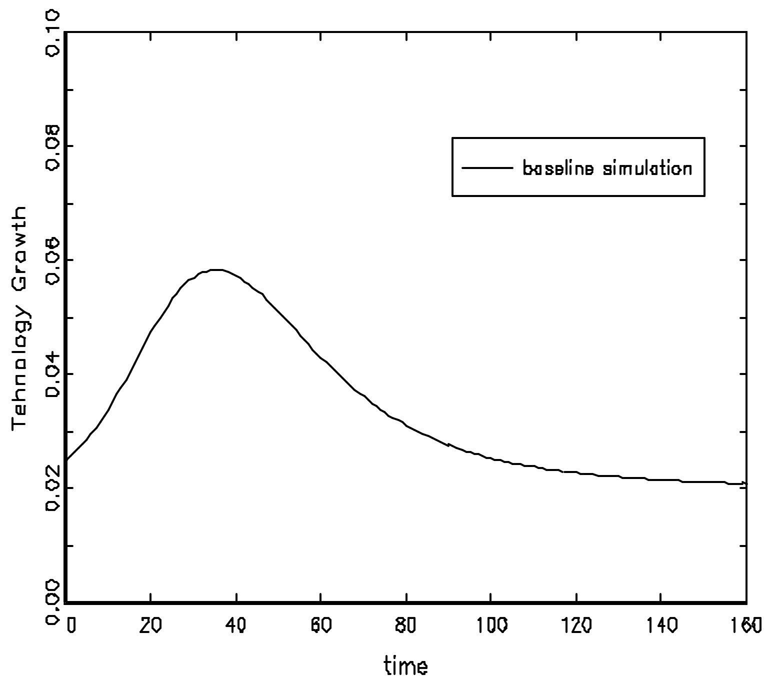
Our model implies that outside the steady state, countries can be positioned into two technology growth trajectories according to their technological backwardness (i.e. their technology level relative to the technological frontier). In particular, the model suggests that if the follower country's technology gap, $\frac{A_F}{A_L}$, is below the threshold parameter, b, then the country is restricted only to "re–inventing the wheel" and therefore behave according to equation $g_{AF}(t) = H_{AF}(t)$. As we will discuss more extensively in the next section, growth in these economies is a function of only domestic human capital therefore the transitional path of technology growth is constant (as human capital is a constant in our model).

More interesting are the off–steady–state properties of countries that have a technology gap which is above the threshold parameter b, and therefore are capable to adopt existing technologies. In particular, we investigate the dynamics of the R&D equation (2.18) by running a simulation exercise. In this exercise we assume that the steady–state world growth rate is given exogenously, i.e. $g_W^{ss} = 0.02$, to approximately match the average per capita growth rate of the U.S. over the postwar period. We set the baseline initial technology gap to $\frac{A_F(0)}{A_L(0)} = 1/10$, which implies that the frontier is 10 times greater than domestic technology in the follower country. Consistent with condition 5, $f\left(\frac{A_i}{A_L}, b\right) > 0$, $\forall\ b < \frac{A_i}{A_L} < 1$, we set $b = 0.095 < \frac{A_F}{A_L}$. Finally we set $\delta = 0.1$, and $H_A = 0.2$.[18] Figure 3.2 illustrates the transitional path of technology growth resulting from our baseline simulation exercise.

Notice that we have chosen the values of technology gap ($\frac{A_F(0)}{A_L(0)} = 0.1$) and the threshold parameter ($b = 0.095$) to be very close to each other. This is done so that our baseline simulation

[18]Experiments with other sets of baseline parameters do not change the results qualitatively.

Figure 3.2: Transitional Path of the Technology Adopting Countries



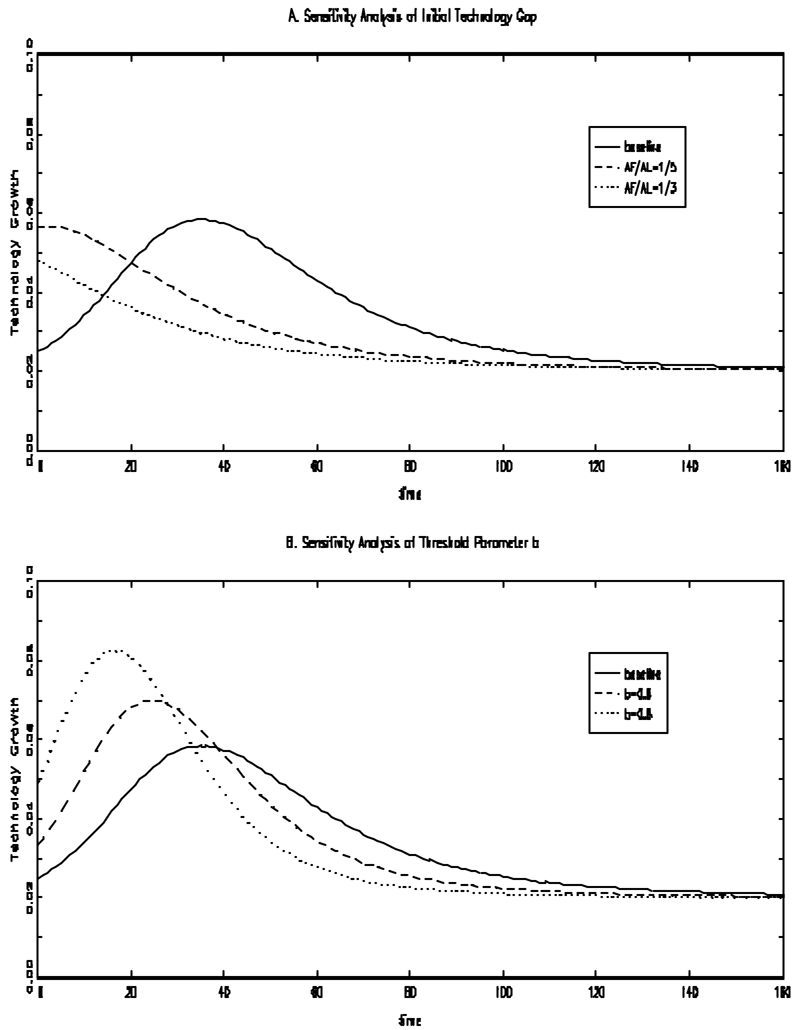
captures the transitional path of a follower country that is just sufficiently close to the frontier so that it can adopt. Consistent with the adoption cost function illustrated in figure (3.1), the transitional path is hump–shaped picking at about period 40 and then converging slowly to the steady state. The inverted U shape path is the result of the lower cost of R&D that is achieved not at the beginning of the convergence process but later on when technology gap is at a medium–range.

An interesting issue in our analysis is to determine the transitional paths of countries that either start with different technology gap levels (i.e. they are closer to the frontier than our baseline economy), or they are faced with different values for the threshold parameter b. Next we perform a sensitivity analysis of the initial technology gap, $\frac{A_F(0)}{A_L(0)}$, and the threshold parameter, b. Figure (3.3) illustrates the effect of different values of these parameters on transitional growth.

Figure 3.3A reveals that everything else being equal, a technology gap decrease from 1/10, to $1/5,$ to 1/3, shifts the whole transitional dynamic path to the left. Obviously in such case convergence to the steady–state growth is faster and this is primarily because the initial gap to the frontier is smaller. Figure 3.3A suggests that countries with moderate technology gaps are the ones that are favored by the quadratic transitional path and experience highest growth.

Figure 3.3B illustrates the behavior of the transitional path for different values of the threshold

Figure 3.3: Sensitivity Analysis of Initial Technology Gap and Threshold Parameter b



parameter b. It is not clear what the value of this parameter is, as there are no existing empirical estimates for it. Therefore our simulation exercise provides some evidence on the way b influences the transitional path of a country that has the potential to adopt (i.e. $b < \frac{A_i}{A_L} < 1$). The main finding here is that, everything else being equal, the smaller the value of b the more skewed to the right the transitional path becomes attaining maximum growth rates early on. The intuition for this result is that the smaller the value of the threshold parameter b, the smaller the cost of imitation early on and the larger the potential of technology adoption and growth in transition.[19]

[19] The fact that maximum growth rates are higher with lower values of b is due to the minimum cost of imitation (at point m in figure (3.1)) which works out to be a positive function of parameter b.

4. Discussion of the Model

This section discusses the primary predictions and implications of the model. The model presented here is consistent with the notion of "contiguous knowledge" which argues that technology can spread a certain distance. This idea of technology diffusion is in contrast to the prevalent in the literature notion of "relative backwardness" which suggests that the rate of adoption (and growth) is a positive and monotonic function of relative technology gap. More precisely, relative backwardness implies that the very poor countries are the ones with most potential to adopt, whereas contiguous knowledge implies that while very poor countries will remain stagnant because of their inability to imitate, middle income countries which are sufficiently close to the frontier technology will benefit the most from progress at the cutting edge.

The driving force of our model is equation (2.18) which differs from existing R&D equations in that it includes a quadratic term. The motivation for using a quadratic rather than a linear R&D equation is that countries can initiate only if conditions are sufficiently similar. The quadratic adoption term in equation (2.18) has two key features. First, it introduces a threshold parameter (b) which dictates whether a follower country can adopt or not. As will be discussed later on, this makes our model consistent with threshold arguments present in the growth literature. Second, it introduces a technology adoption mechanism for the follower countries which are capable of adopting. This mechanism is consistent with our proposed notion of contiguous knowledge.

Is our theory a realistic theory of economic growth and development? Is our model able to explain some of the regularities observe in the data? It is argued that the notion of contiguous knowledge is consistent with many aspects of economic development. It is further argued that the proposed model generates a more realistic story of technology dissemination that is consistent with stagnation and growth miracles. Contiguous knowledge would suggest that it is not likely that poor uneducated peacants can learn much from a frontier technology, whereas it is more likely that factory technicians and engineers in developing countries maybe the real beneficiaries of new technologies. That is, the technology adoption capacity of a country depends crucially on how familiar is the frontier technology to the adopting country. This seems to be consistent with evidence indicating that virtually all high growth developing countries have been exposed to technologies that are at least related to the cutting edge technology.

Our model is consistent with the observation that many less developed economies have remained stagnant over the course of the last half century. In our model, follower countries below the threshold parameter, b, can only re–invent technology and therefore their growth is limited to only being a function of the level of existing human capital. Given that in LDCs human capital is at very low levels the model predicts that growth in these countries is very low and therefore consistent with divergence. The model is also consistent with rapid growth experiences and moderate stable growth. According to our R&D equation, middle income countries like Turkey, Brazil, and Thailand, can benefit the most from cutting edge progress which is consistent with evidence. As the transitional dynamics analysis has revealed, along the convergence path developing countries that close the gap face a higher imitation cost and therefore adoption becomes more difficult pushing growth rates lower towards the steady state. This is also consistent with evidence which suggests that countries very close to the frontier technology, such as the U.K., Germany, and Japan, do not experience rapid but rather moderate and stable growth rates.

Our theory of contiguous knowledge is indeed a threshold theory, and therefore is consistent with current theoretical work including the Schumpeterian model of Howitt (2000), and the Twin Peaks model of Quah (1996). Moreover, evidence from Durlauf and Johnson (1995), Quah (1997), and Duffy and Papageorgiou (2000), provide support that different countries may belong to different "convergence clubs." This too is consistent with our proposed model.

A natural question is whether we can actually test this theory of contiguous knowledge. The first approach to empirically testing our theory is by following Benhabib and Spiegel (1994) who have tested a similar R&D equation to our equation (2.18). It is easy to use their approach by adding a quadratic adoption term to their reduced form specification and estimating the coefficient of this quadratic term.[20] The sign, magnitude and robustness of such estimate will potentially reveal empirical evidence for or against the proposed theory.

As mentioned above our theory actually suggests that there exists a technology gap threshold which determines whether countries will converge to the steady state or they will remain stagnant. Therefore, an alternative approach to empirically testing our hypothesis is to follow recent work by Hansen (forthcoming) on threshold estimation and sample splitting.[21] The empirical test would then be to write a Benhabib and Spiegel–type specification, as suggested in the first approach, and then use the quadratic technology term to test for threshold arguments. Both of these empirical exercises are worthy of serious investigation but are left for future research as they are beyond the focus of this paper which is primarily theoretical.

[20] In particular, Benhabib and Spiegel (1994) use ordinary least squares to estimate the equation

$$\Delta Y = a_0 + a_1 H_i + a_2 H_i (y_{max}/y_i) + a_3(K_T - K_0) + a_4(L_T - L_0) + \varepsilon,$$

where a_j $(j = 1, ..., 4)$ are estimated coefficients, capital letters denote logarithms, ΔY is change in output, y_i is per capita income of country i, y_{max} is the per capita income of the leader, H is human capital, K is physical capital, and L is labor. We could modify the above reduced form equation by adding the quadratic term, $a_5 H_i (y_{max}/y_i)^2$, and obtain a coefficient estimate for a_5.

[21] Hansen develops a statistical theory for threshold estimation in the regression context. For a discussion on his estimation technique for panel and cross-sectional data see Hansen (1999, 2000).

5. Conclusion

This paper explores a model in which growth is determined by a combination of human capital and technology adoption. The model presented differs from existing models, in that the relationship between technology adoption and relative backwardness is *not* monotonically positive but quadratic.

At the heart of the paper is the notion of "contiguous knowledge" asserting that knowledge can be diffused only a certain distance. The real implication of this property of technology adoption is that it is not possible for countries that are far away from the frontier to take advantage of existing technologies and grow rapidly. In contrast, developing countries that are closer to the frontier possess sufficient know–how that allows them to adopt existing innovations and grow fast thus converging to the income level of the technology leader.

Contiguous knowledge is implicitly a threshold argument. That is, countries below a technology–gap threshold are not capable of adopting existing technologies whereas countries above this technology–gap threshold find it easier to adopt existing technologies and grow rapidly. Therefore as argued above, the predictions of the model are consistent both with economic miracles as well as economic disasters.

Our model is rather optimistic in nature, but unlike the neoclassical growth model, only for those countries that are technically proficient to take advantage of existing technologies. We interpret the implications of the model to mean that middle income countries have the potential for rapid growth, whereas poor countries have to depend only on their domestic innovation (which in many cases is nil) and grow at low growth rates. If indeed technology is the main determinant of future growth as many experts expect, then our model predicts continuous increase in the per capital income gap between developed and less developed countries.

The implication of this paper for future research is twofold: First, the notion of contiguous knowledge is worthy of further investigation. Obvious extensions include endogenizing human capital thus making the definition of knowledge broader. Second, empirical investigation of contiguous knowledge is promising especially in light of recent work by Hansen (forthcoming) on sample splitting. An interesting empirical question would be whether we could split a sample of countries based on a quadratic technology gap term using recent datasets on R&D, such as the one in Coe, Helpman and Hoffmaister (1997) which includes data for 77 developing countries. Another empirical exercise worth considering is a Benhabib–Spiegel type regression analysis using a quadratic (rather than a linear) technology term.

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