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EDUCATION AND TECHNOLOGY ADOPTION IN A SMALL OPEN ECONOMY: THEORY AND EVIDENCE

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We develop a simple open-economy growth model in which productivity growth and education influence each other, and use it to empirically address issues of causality between them. Technology adoption fostered by human capital and economic openness determines productivity growth; the framework allows us to evaluate whether the effects of these two variables on growth documented in previous cross-country regression studies carry over to a simultaneous system closely allied to a model. This model implies that an increase in openness will stimulate technical change but, for empirically plausible values of the intertemporal elasticity of substitution, it will cause a decrease in the level of education. The empirical analysis specifies productivity growth and human capital as endogenous variables and finds evidence broadly consistent with the theory—openness and education stimulate productivity growth, and there is a negative effect of this growth on human capital accumulation.

Keywords: Human Capital Accumulation, Productivity Growth, Simultaneous Equation Regressions

1. INTRODUCTION

There is a wide array of studies in the growth literature that examine the role of human capital in growth. Likewise, the effect of economic openness on output and productivity growth has also received widespread attention. This paper takes the position that these related ideas, which typically have been studied in isolation, need to be addressed in a unified framework. There is compelling theoretical motivation to do so. Increased openness, by facilitating technology adoption, fosters productivity growth and this anticipated growth affects the incentives to acquire education; similarly, an increase in the level of education affects the incentives to adopt complementary technologies. Given the simultaneity of influences, there

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is also a strong empirical motivation to allow for the possibility that productivity growth and education simultaneously affect each other, and study issues of causality.[1]

Toward this end, this paper synthesizes ideas from two related strands of growth literature that have mostly remained separate—the human capital literature [as exemplified by Lucas (1988)], and the technical change literature [as exemplified by Romer (1990)]—to develop a simple model of growth in an open economy. The empirical contribution is a study of the causal relationship among openness, productivity growth, and education in a simultaneous-equation framework that is closely motivated by the model.

The production sector is similar to the ones in Romer (1990, 1994). Technology is captured by an ever-increasing variety of intermediate goods used in final-good production. A new intermediate good first has to be adapted to the local environment by incurring a fixed cost. It is assumed that all physical capital needed to manufacture intermediate goods has to be rented from advanced countries at a given world interest rate and is subject to a tariff levied by the local government. Technology is thus embodied in capital imported from advanced countries.

To model human capital accumulation, the model of Stokey (1991) is followed. Finite-lived agents are situated in a dynasty with continuously overlapping generations. Each agent acquires education initially, and then supplies human capital to final-good firms later. Motivated by incompleteness in global human capital markets that arises from moral hazard, we assume education has to be financed locally. For similar reasons, we also assume that the adoption costs have to be borne locally. Hence, the interest rate that agents use in discounting future benefits of education and that adopting firms use in discounting their profits is the endogenously determined domestic rate.

The model is most applicable to non-technology-producing countries that have the opportunity to acquire technologies available in advanced countries by importing capital from them, but are required to develop local educational and technological "infrastructure" to exploit these technologies. The incentives to acquire education and to invest in new technologies interact. The level of human capital and the tariff rate affect the growth rate by affecting the profits from adopting new technologies—the former positively and the latter negatively. The growth rate, in turn, influences the education decision of agents through the effective discount rate.

The focus is on the stationary equilibrium, where the growth rates of technology, output, and consumption, and the level of schooling are constant. The model implies that increased openness will stimulate technical change, but the effect on education depends on the intertemporal elasticity of substitution. When this elasticity is less than unity, the increase in the rate of costly technology adoption, caused by the increased openness, induces an even greater increase in the equilibrium local borrowing and lending rates, thereby increasing the discount factor relevant to the education decision; this will cause the level of education to *decrease*. If the elasticity is greater than unity, the level of education will increase. An elasticity less than one seems to be the empirically plausible value, and therefore there is reason to believe that any increase in growth, *ceteris paribus*, is likely to cause a decrease in the level of education. This result holds whether human capital directly enters the specification for adoption or not.

Motivated by the theory, we specify a simultaneous-equation regression system with TFP growth rates and the level of human capital as endogenous variables. The evidence is in favor of openness and human capital stimulating productivity growth and a negative effect of this growth on education. The stationary version of the model analyzed here is silent on how opening up the economy might preferentially affect the returns to relatively more skilled labor; this is a limitation it shares with most representative-agent models of human capital and growth. The negative coefficient on growth when the dependent variable is overall schooling need not be inconsistent with an increase in skilled wages when an economy opens up.[2]

Our aim is not to argue that the elasticity of intertemporal substitution alone affects returns to education in the context of technology adoption. There is a huge literature that has studied the interplay between technology and the return to education, and identified the skill bias of technical change, and the importance of cognitive ability in a changing environment, among several others, as influential factors.[3] Nevertheless, it is of interest that a model constructed with elements of technology and human capital found in standard growth models exhibits the above-mentioned dependence on this elasticity. Likewise, an empirical caveat might be in order. Other policies could affect growth in conjunction with openness. In the choice between using a wide array of unmodeled policy variables in the empirical analysis versus using only those that have a tight connection with the model developed, we have chosen the latter, with its attendant strengths and weaknesses.

There is a large literature that connects trade policy to growth through its impact on technological change; see, for instance, Grossman and Helpman (1992). The literature that focuses on human capital and growth is equally large. In the interest of space, we survey only a few of the more directly related studies here.

In the models of Tamura (1992, 1996), human capital accumulation affects the level of technology through an external effect on the extent of the market, and thus on the division of labor. The heterogeneity in human capital plays a critical role in these models. We abstract from heterogeneity in our model in order to derive equilibrium conditions simple enough to be taken to data; the link between technology and human capital is through the final-good production function. Eicher (1996) models technical change arising in a serendipitous fashion during the process of human capital accumulation. The use of skilled labor to absorb new technology increases the cost of teachers, thus affecting the incentive to acquire education. In our model, technology adoption is intentional and occurs in a sector different from education; the cost of adoption affects the incentive to acquire education through the interest rate. Apparently, the type of education that Eicher focuses on is university education, which is capable of giving rise to technological change as a byproduct, whereas the education envisioned here is general, and complementary to capital goods in production. In the model by

Acemoglu (1998), the increase in skilled labor increases the "market" size over which adoption costs can be amortized and spurs technological change. Eicher and Acemoglu focus on recent trends in the skill premium and skilled labor supply, whereas we focus on general educational attainment over longer periods.

Barro et al. (1995) study an open-economy version of the neoclassical model and argue that it conforms with convergence evidence only if "an economy can borrow to finance only a portion of its capital, for example, if human capital must be financed by domestic savings." This is precisely the assumption we make in our open-economy model. In a model that features capital–skill complementarity, Stokey (1996) finds that inflows of physical capital alone cause rapid increase in the accumulation of human capital, whereas full integration with a larger neighbor causes little change in the accumulation. Only the small-open-economy case is studied here, and it is shown that increased capital imports *can* cause a greater level of education to be acquired. Unlike her model, ours has growth in the long run.

In our model, in the spirit of Romer (1990), a stationary *level* of human capital is connected to long-run growth. A more recent example is Tamura (2001), who posits an accumulation technology that has constant returns to scale in parental human capital, so that a fixed learning time is consistent with growth. Our implicit assumption that the later-generation students are taught about the latest technologies is akin to a human capital stock (an unobservable quantity that cannot be readily proxied) growing without bound as in Lucas (1988). However, our model is not consistent with the stance that *growth* in observed schooling is responsible for long-run growth. Even with increasing life expectancy, one would be hard-pressed to argue that schooling years can increase forever without hitting a mortality constraint.

As mentioned earlier, there are several empirical studies that consider the above issues of interest separately. Unlike our study, most have used single-equation regressions where issues regarding causality have been hard to pin down, or instrumented regressions that focus on one aspect of the problem. As in the case of the theoretical literature, space considerations limit the extent of our survey.

One strand of this literature examines the effect of human capital and investment on growth, and convergence effects in growth; Barro (1991) is the original influence. Mankiw et al. (1992) find that human capital proxied by school enrollment has a positive effect on end-of-period income as well as the growth rate. Benhabib and Spiegel (1994) use data on human capital *stocks* and find that the growth in this stock is not related to growth in output; however, they find a positive role for the level of stock on TFP growth, which provides support for the level hypothesis discussed earlier. We use stock levels as well, but rely on the more recent studies of Klenow and Rodriguez (1997) and Bils and Klenow (2000) for our theoretical specification of the human capital function as well as for data; these studies construct human capital stocks using Mincerian regressions.[4] Our finding that the stock of human capital is positively associated with TFP growth concurs with that of Benhabib and Spiegel, though our results are obtained in a simultaneous-equation framework. However, we do not find the positive "reverse" channel between growth and schooling that Bils and Klenow do. While concluding, we speculate on the reasons for this difference.

A second strand examines the effect of economic openness on output and productivity growth; most of these also include human capital as a regressor. These studies differ primarily in the proxies they use for openness. Lee (1993) uses tariff rates and black-market premia, and Lee (1995) uses the ratio of imported to domestically produced capital goods; both find that openness increases growth. Sachs and Warner (1995) construct their own (binary) index of openness based on several trade-related indicators. Edwards (1998) uses nine different proxies and also conducts a principal-components analysis to conclude that the positive relation between openness and TFP growth is robust. The black-market premium (BMP), an inverse index of openness, is one such significant measure. The BMP also figures in the panel data analysis from Harrison (1996), who finds it significantly influencing growth. Of the various measures, only for the BMP is a Granger causality test from openness to GDP growth significant—but not for the other way around—which minimizes problems of endogeneity; we rely mainly on this proxy.[5] We find the same negative association between BMP and growth that she finds. She also finds a nonrobust association between openness and returns to schooling—lower for primary education and higher for secondary; we explicitly model schooling to shed theoretical and empirical light on this issue. Our use of instruments for BMP, robustness checks with an alternative measure of openness, and the close alliance to a fully specified model for empirical analysis should address some of the skepticism voiced by Rodriguez and Rodrick (1999) about this literature.[6]

The rest of this paper is organized as follows. In Section 2, the model is developed. The stationary growth path is analyzed in Section 3; the effect of a decrease in tariff rate on the equilibrium rate of technical change and the level of education is studied and theoretical robustness explored. The data are described and the regression results are presented in Section 4. Section 5 concludes.

2. MODEL ECONOMY

2.1. Technology Adoption and Production

The production sector is similar to that of Romer (1990, 1994). Technological progress is captured as the adoption of new intermediate goods used in production, for which blueprints have been developed elsewhere. A single final good is produced using a continuum of available intermediate goods, $x(i)$, $i \in [0, N]$, and human capital. The instantaneous production function is

$$Y = A\left[\int_0^N x(i)^{1-\alpha}\, di\right] H^{\alpha}, \tag{1}$$

where A is a constant productivity parameter and H is the aggregate quantity of

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human capital hired. The final good firm solves

$$\max_{x,H} A\left[\int_0^N x(i)^{1-\alpha}\,di\right]H^\alpha - \int_0^N p(i)x(i)\,di - wH,$$

taking as given the price function, p, and human capital rental rate w; x is chosen from the space of piecewise continuous, bounded functions. The final good is the numeraire. The first-order conditions imply the following factor demands:

$$x(i) = \left[\frac{p(i)}{A(1-\alpha)}\right]^{-1/\alpha} H, \forall i, \tag{2}$$

with the rental rate for human capital satisfying $w = \alpha AN[x(i)/H]^{1-\alpha}, \forall i$.

Each intermediate good is produced by a monopolistically competitive firm. The firm buys the blueprint for manufacturing the intermediate good from the adoption sector at a price of P_N.[7] This gives the firm the know-how to make the good, and also grants it an infinitely lived exclusive right to manufacture the good. Each unit of any intermediate good requires η units of (general) physical capital.

Assumption 1. All physical capital used in the production of intermediate goods has to be imported (presumably from more advanced countries).

The advantages of this assumption are: (i) It makes the domestic household's accumulation problem simpler; (ii) it gives content to the notion of openness toward ideas and technologies by assuming that all technology is embodied in imported capital; and (iii) it allows us to *index* openness by tariffs that are imposed on imported capital.[8]

The firm faces the economywide demand given by equation (2). Its revenues are therefore given by $A(1-\alpha)x(i)^{1-\alpha}H^\alpha$. We assume that the firm faces a (constant) worldwide rental rate of capital r_w, and that the local government imposes a tariff rate τ on imported capital; therefore, the effective cost of capital is $(1+\tau)r_w$.[9] Firm i's problem is $\max_{x(i)} A(1-\alpha)x(i)^{1-\alpha}H^\alpha - \eta(1+\tau)r_w x(i)$. The first-order conditions imply a marked-up price for an intermediate good of

$$p = \frac{\eta(1+\tau)r_w}{1-\alpha},$$

and[10]

$$\left[\frac{x(i)}{H}\right]^\alpha = \frac{A(1-\alpha)^2}{\eta(1+\tau)r_w}. \tag{3}$$

Given the common rental rate and aggregate human capital in the economy, the quantity of intermediate good produced is independent of its index, which is henceforth suppressed. Using the expression for p in the firm's objective function implies instantaneous profits of

$$\pi = A\alpha(1-\alpha)x^{1-\alpha}H^\alpha. \tag{4}$$

The total flow of factor income abroad is $r_w \eta N x$; using this in the production function, one can see that the capital-to-output ratio is directly proportional to the rental flow-to-output ratio. Using imports-to-output as a proxy for the latter, we find that in a cross section of 79 countries the growth rates of imports-to-output and growth rates of capital-to-output for the 1960–1985 period are positively correlated (the correlation coefficient is 0.235). The level correlation across 93 countries is higher, at 0.346. This lends some plausibility to Assumption 1.

The blueprint of an intermediate good has to be adapted to local conditions before it can be used in production. We assume that there is a fixed cost of F units of good, *per worker*, for each new blueprint adopted.[11] Since these technologies have been developed elsewhere, not using human capital as a factor of production in their local adoption is not a serious omission; it is done for simplicity and is essentially conservative. Later, we argue that adding human capital to the adoption specification does not qualitatively change the results. If we denote the number of workers by L, the zero-profit condition for the adoption firm implies that the cost of blueprint P_N is given by $P_N(t) = FL(t)$.

Assumption 2. The adoption costs have to be financed locally.

These projects are located in the LDC and are therefore not amenable to continuous monitoring by foreign investors. Therefore, it is reasonable for foreign firms to expect equity participation by local partners. As Telesio (1979, p. 14) notes in the context of licensing technologies in countries where the investment climate is unfavorable, "Expropriation is probably less likely to occur if there is only a minority foreign position or no foreign ownership at all in a local enterprise than if it is controlled by a foreign investor."[12] Indeed, to get a more applicable sample and find a strengthening of the relevant empirical effects, we use an index of expropriation in Section 4.4 to drop countries that have very low risk. Several LDCs also restrict the percentage of equity that can be owned by foreigners for reasons of sovereign control, which also necessitates local funding. For our purposes, all we really need is that part of the funds be raised locally. However, it is simpler to assume that all equity is raised locally.[13]

The price of the blueprint P_N would be bid down by potential intermediate-good firms till there is no pure rent in a present-value sense. That is,

$$\int_t^{\infty} e^{-\int_t^z r(s)\,ds} \pi(z)\,dz \leq P_N(t) = FL(t), \tag{5}$$

which holds with equality if a positive number of blueprints are adapted. If the left-hand side is lower, the discounted present value of profits is not high enough to cover the fixed costs of adoption and therefore no blueprint is adapted. Given Assumption 2, it is r, the local interest rate, and not r_w, that is used to discount profits.

We give a simple example of such a production chain. An adoption firm in the LDC undertakes costly translation of computer manuals, written in a developed

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country, into the local language. The intermediate-good firm that buys these "blueprints," imports computer equipment (general capital) and uses the two to produce software services. These services form one of the intermediate goods in the final production process.

2.2. Education and the Household's Problem

The economy is populated by a continuum (of measure one) of identical infinitely lived households.[14] Each household consists of an infinite stream of continuously overlapping generations. Each individual lives for T units of time. We refer to this quantity as the life expectancy of an individual. Since each generation (or cohort) is the same size (one), the size (T) and the demographic composition of the population are constant over time. Consumption and time allocation decisions are made by the household, whose preferences over infinite consumption streams for *each* individual alive are given by the standard isoelastic intertemporal utility function $\int_0^\infty e^{-\rho t}\frac{c(t)^{1-\sigma}}{1-\sigma}\,dt$, where $c(t)$ is the per-capita consumption, and $\sigma > 0$; $\sigma = 1$, is interpreted as $\int_0^\infty e^{-\rho t}\log(c(t))\,dt$.

At the beginning of her life, an individual spends s units of time acquiring education (accumulating human capital), and thereafter works from age s to age T. We assume that the human capital (effective units of labor) of an individual who has acquired s units of schooling is

$$h(s) = Be^{f(s)}, \tag{6}$$

where $f : [0, T] \to \mathbf{R}_+$ satisfies $f'(s) > 0$ and $f''(s) \leq 0$.[15] The exponential form is motivated by Mincerian regressions in which the logarithm of wages, rather than their level, is better explained by schooling.

Since leisure is not valued, each household member divides her time between education and work in a way that maximizes her contribution to family income as captured by the present discounted value of her lifetime earnings. The education problem of the individual and the intertemporal consumption allocation problem of the household then separate, which is analytically convenient.

Assumption 3. Education expenditures must be financed locally.[16]

In a dynastic formulation such as this, the interpretation is that family members can borrow and lend, at least implicitly, from each other, but not from a foreign country. Given the extensive involvement of the family in financing educational expenditures, this assumption is not unreasonable.

How do we reconcile our assumption of free flow of physical capital with the above one? As noted in the introduction, our assumptions are consistent with those of Barro et al. (1995), who assume that international borrowing occurs for physical capital but not human capital. They note that such a situation " would apply if the legal system enforces loan contracts based on labor income when the creditor is domestic, but not when the creditor is foreign" (p. 113). In this case there would

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be a wedge between the local and the world interest rates. In Section 4.4, we drop countries with a very high index of creditor rights to get a more applicable sample, and find a strengthening of the relevant empirical effects.[17]

Net private capital flows in 1990 (the free flow of which was captured in Assumption 1) were essentially uncorrelated with creditor rights (lack of which motivates Assumption 3) and only slightly correlated with expropriation risk (which motivates Assumption 2).[18] Given these considerations, it seems plausible that international flows would occur for more observable and more readily collateralized capital such as physical capital, but not for intangible capital such as human capital and technology. For our purposes, it suffices that it is easier to finance at least some of the investments that accompany growth domestically, so that the connection between anticipated growth and the local interest rate in equation (13) can be made. Assumptions 1 through 3, though stark, capture the essence of the idea that problems of moral hazard and transnational enforceability are likely to be more severe for intangible capital—analyzed in greater detail in the studies cited earlier and in several others—in an operationally simple way.

Given this assumption, each member of the cohort born at time z will choose a level of education by solving

$$\max_{0\le s(z)\le T} \int_{z+s(z)}^{z+T} e^{-\int_0^t r(v)\,dv} w(t) B e^{f[s(z)]}\,dt, \tag{7}$$

where the individual takes as given the time paths for r and w.

From the household's point of view, at any time t, all cohorts $z \in [t, t-T]$ will be alive. The number of workers, $L^s(t)$, and the total human capital, $H^s(t)$, that they supply to the final-goods firm are given by

$$L^s(t) = \int_{t-T}^{t} \chi_{z+s(z)\le t}\,dz \tag{8}$$

$$H^s(t) = \int_{t-T}^{t} \chi_{z+s(z)\le t} B e^{f[s(z)]}\,dz, \tag{9}$$

where χ_A denotes the indicator function for set A. Given these, the household's income at t is $Y(t) = w(t)H^s(t) + D(t) + V(t)$, where $D(t)$ is the net dividend that the household receives from the equity held in the adoption firms and $V(t)$ is the lump-sum transfer received from the government.[19] The household takes the path for w, D, and V , as given. Therefore, the household's total discounted family income at $t = 0$ is

$$Y = \int_0^\infty e^{-\int_0^t r(v)\,dv}[w(t)H^s(t) + D(t) + V(t)]\,dt. \tag{10}$$

The household thus solves the problem

$$\max_{c(t)} \int_0^\infty e^{-\rho t}\frac{c(t)^{1-\sigma}}{1-\sigma}\,dt, \tag{11}$$

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subject to the lifetime budget constraint

$$\int_0^\infty e^{-\int_0^t r(v)\,dv} c(t)\,dt \leq y, \tag{12}$$

where $y \equiv Y/T$ is the per-capita income.

2.3. Equilibrium

DEFINITION 1. *An equilibrium, given the initial conditions* $N(0)$, $[s(z), -T < z \leq 0]$, *and* $K(0)$ *at date* 0, *is a collection of piecewise continuous functions* $p(i,t)$, $x(i,t)$, $w(t)$, $r(t)$, $L(t)$, $H(t)$, $N(t)$, $K(t)$, $\pi(t)$, $s(t)$, $c(t)$, $D(t)$, $V(t)$, $L^s(t)$, $H^s(t)$, $i \in [0, N(t)]$, $t \geq 0$, *such that*

(i) *The optimizing conditions for the production entities are satisfied. The zero present value of profits condition* (5) *is satisfied with* $L(t) = L^s(t)$ *given by* (8).
(ii) *The function* $s(t)$ *solves* (7), *and* $c(t)$ *solves the household's problem* (11), *subject to the budget constraint* (12).
(iii) *Net dividends* $D(t)$ *are given by* $N(t)\pi(t) - \dot{N}(t)P_N(t)$.[20] *Lump-sum transfers* $V(t)$ *are given by* $\tau r_w \eta N(t)x(t)$. *The total capital stock rented is given by* $K(t) = \eta N(t)x(t)$.[21]
(iv) *The human capital market clears. The firm's demand,* $H(t)$, *equals the supply,* $H^s(t)$, *given by* (9).

3. STATIONARY-EQUILIBRIUM ANALYSIS

We confine our analysis to a stationary (balanced growth) equilibrium.

3.1. Stationary Equilibrium

DEFINITION 2. *A stationary equilibrium is an equilibrium in which*

(i) *All cohorts acquire the same amount of education. That is,* $s(z) = s, \forall z \geq 0$.
(ii) *The technology level and consumption grow at the same constant rate;* $g_N \equiv \dot{N}/N = \dot{c}/c = g$.

It is easy to see from the optimality and equilibrium conditions that π, p, and x are invariant with time, and w, D, V, and per-capita capital and output grow at the rate g_N.[22] On a stationary growth path, the dynasty's consumption allocation problem becomes

$$\max_{c(t)} \int_0^\infty e^{-\rho t} \frac{c(t)^{1-\sigma}}{1-\sigma}\,dt$$

subject to the constraint

$$\int_0^\infty e^{-rt} c(t)\,dt \leq \int_0^\infty e^{-rt}\left[\left(\frac{T-s}{T}\right) w(t)h(t) + \frac{D(t)+V(t)}{T}\right] dt.$$

Given the concavity of the problem and bounded utility, a standard variational argument can be used to show that the interest rate on a stationary growth path is constant and given by the usual condition

$$r = \sigma g + \rho. \tag{13}$$

As in any growth model, this is the constant interest rate that would be compatible with the household allocating consumption across time in a way that would cause it to grow at the rate g.

This one-to-one connection between r and g (assuming invariant preference parameters) allows us to switch back and forth between these two variables. In the theoretical analysis, we focus on the real interest rate.[23] In the cross-country empirical analysis, we use the growth rate instead of the real interest rate, for which reliable data are very hard to obtain.

3.2. Analysis of the Production Sector

On a stationary growth path where there is continuous adoption of technologies, condition (5) will hold with equality. Using the facts that r, π, and L are constant on such a path, differentiation of this equality with respect to time yields the equality

$$\frac{\pi}{FL} = r. \tag{14}$$

This equality just says that technologies are adopted to the point where the dividend rate is equal to the rate at which profits are discounted.

It is convenient to normalize $\eta = A(1-\alpha)^2$. Condition (3) then implies

$$\left(\frac{x}{H}\right)^{\alpha} = \frac{1}{r_w(1+\tau)}.$$

Using this and (4) in (14), we get the basic relationship that connects human capital, the tariff rate, and the interest rate that results from the optimizing conditions of the production entities,

$$r = \hat{A}\left[\frac{1}{r_w(1+\tau)}\right]^{\frac{1-\alpha}{\alpha}} h, \tag{15}$$

where h is the average human capital of workers in the economy and $\hat{A} \equiv [A\alpha(1-\alpha)]/F$.[24] In the stationary growth path with a constant education level s, $h = H/L = Be^{f(s)}$.

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3.3. Analysis of the Education Decision

The education decision problem (7) of individuals situated in a stationary equilibrium can be written as

$$\max_{0\le s\le T}\int_s^T e^{-rt}w(t)Be^{f(s)}\,dt.$$

The first-order condition for the schooling decision is

$$e^{-rs}w(s)Be^{f(s)} \le \int_s^T e^{-rt}f'(s)w(t)Be^{f(s)}\,dt,$$

with equality if a positive amount of schooling is chosen. The left-hand side is the marginal cost at birth of an extra year of schooling while the right-hand side is the discounted benefit that comes from increased productivity during the working years.[25] From the wage expression, it is clear that the rental rate of human capital w grows at the same rate as N. Therefore, on a stationary equilibrium, $w(t)=w(s)e^{g(t-s)}$. The individuals take the interest rate and the growth rate as given. Therefore, an interior schooling decision $s(r, g)$ is implicitly defined by

$$\frac{r-g}{1-e^{-(r-g)(T-s)}} = f'(s).$$

We therefore state the following lemma.

LEMMA 1. *The function $s(r, g)$ is decreasing in r and increasing in g.*

The growth rate decreases the effective discount rate and increases schooling. An increase in the growth rate can be viewed as a wealth effect that increases schooling—one can stay longer in school to take advantage of an increased starting wage since the wage profile is steeper. An increase in the interest rate can be viewed as a substitution effect that decreases schooling—the discounted future earnings decrease, and it is optimal to shift toward current consumption instead of schooling.

However, the equilibrium implications for schooling are quite different in the present setup. Using (13), we can write the above condition as

$$\frac{R(r)}{1-e^{-[R(r)](T-s)}} = f'(s), \tag{16}$$

where $R(r)\equiv(\tilde{\sigma}r+\rho)/\sigma$ and $\tilde{\sigma}\equiv(\sigma-1)$. The left side can be viewed as an effective discount factor that depends on the effective discount rate $R(r)$. The right side is the productivity factor for schooling, and the chosen level of schooling equates the two. In the Appendix we prove Lemma 2.

LEMMA 2. *For any given $r>\rho$, a $0\le s(r)<T$ exists. If $\sigma<1$, then $s'(r)>0$. If $\sigma>1$, then $s'(r)<0$, and if $\sigma=1$ (log utility), then $s'(r)=0$.*

When $\sigma>1$ (i.e., when the intertemporal substitution, $1/\sigma$, is <1), the increase in local accumulation, caused by the increase in anticipated growth rate, causes

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an even greater increase in the equilibrium local borrowing and lending rates, and the effective discount rate $R(r)$ increases. This decreases the amount of schooling desired. In terms of the above discussion, the substitution effect dominates. The effect is opposite when $\sigma < 1$. In the log utility case, the two increases cancel out, causing no change in the desired schooling.

The growth and business-cycle literature that use intertemporal models of the present kind typically consider $\sigma \geq 1$ to be empirically plausible.[26] Assumption 4 therefore follows.

Assumption 4. $\sigma \geq 1$.

Therefore, we should expect anticipated growth to decrease schooling. For completeness, we present the following straightforward result.

LEMMA 3. *A ceteris paribus increase in life expectancy T increases the desired amount of schooling.*

An anticipated increase in life expectancy increases the horizon over which education earns returns, thereby increasing the amount of schooling. In terms of (16), the effective discount factor decreases, inducing additional schooling.[27]

3.4. Characterizing the Stationary Growth Rate

Conceptually, we envision individuals choosing a level of schooling, given an anticipated interest rate r. Condition (6) would then imply an average level of human capital $Be^{f[s(r)]}$, where $s(r)$ satisfies (16). Given this level of h, actions of the adopting firm and other production entities would imply an interest rate $\hat{r}$. The stationary interest rate is the fixed point of the mapping from r to $\hat{r}$. Given equation (13), one could equivalently think of the mapping from an anticipated growth rate to the resulting growth rate.

Operationally, the model is specified simply enough for us to analyze the simultaneous system from the production sector and the households. This will also motivate the regression system to be specified later.

For the human capital "supply" equation, we write

$$\log[h^s(r)] = \log(B) + f[s(r)], \tag{17}$$

where the equation that defines $s(r)$ implicitly is obtained by manipulating (16)[28]:

$$s(r) = T + \frac{\log\left\{1 - \frac{R(r)}{f'[s(r)]}\right\}}{R(r)}. \tag{18}$$

From Assumption 4, Lemma 2, and $f' > 0$, we have that $\log[h^s(r)]$ is nonincreasing in r.

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We can write the production condition (15) in log form as

$$\log(h) = \log(r) + \left(\frac{1-\alpha}{\alpha}\right)\log[(1+\tau)r_w] - \log\hat{A}. \tag{19}$$

It is convenient to think of this as a human capital "demand" equation as a function of the (stationary) interest rate. A higher level of human capital is needed to break even with a higher interest or tariff rate. Since $\log[h(r)]$ is strictly increasing in r, it is easy to guarantee a unique positive equilibrium growth rate by just guaranteeing that the supply curve lies above the demand curve when $r = \rho$.

Assumption 5. The given parameters satisfy

$$f(s_0) > \log(\rho) + \left(\frac{1-\alpha}{\alpha}\right)\log[(1+\tau)r_w] - \log(\hat{A}B),$$

where s_0 solves:

$$s_0 = T + \frac{1}{\rho}\log\left[1 - \frac{\rho}{f'(s_0)}\right].$$

Here, s_0 is the level of schooling that will prevail if $r = \rho$, and no growth is anticipated. If that level of schooling is enough to induce technology adoption, zero growth cannot be an equilibrium. If the above condition is not satisfied, the human capital supply equation will lie below the demand equation everywhere. For all interest rates, the human capital supplied is not high enough to warrant adoption [(14) will be an inequality] and the economy is stagnant. This situation can happen, for instance, if the life expectancy T and the education productivity parameter B are low, and the tariff rate τ and the adoption cost F are high. Stagnation could arise in Romer's (1990) model as well, when the level of human capital is not high enough. However, as Romer himself notes, since the stock of human capital is treated as a given, it cannot be a complete explanation for a trap. In the present model, the human capital level is determined endogenously and growth traps are naturally tied to low life expectancy and high tariffs, which affect the returns from education and technology adoption negatively.

When the tariff rate decreases, the human capital "demand" equation (19) shifts out. Therefore, the curves intersect at a higher r, and therefore a higher g. However, since the "supply" equation is nonincreasing, human capital and the level of schooling are nonincreasing. We therefore have the following proposition.

PROPOSITION 1. *When Assumption 5 is satisfied, there is a unique positive stationary growth path. When the tariff rate decreases (i.e., openness increases), the stationary growth rate (rate of technology adoption) increases. If $\sigma > 1$, the level of education decreases, whereas if $\sigma = 1$, there is no change in the level of education.*

When the tariff rate decreases, the incentive to adopt technologies increases. Consumption has to decrease to facilitate the increased investment in technologies.

The consumers are willing to accept a steeper consumption profile only if the interest rate increases. This increase will be high enough when $\sigma > 1$ to cause the effective discount rate $R(r)$ to increase, thereby reducing schooling. The reduced human capital level tempers the increase in growth rate arising from more rapid adoption of technologies. Therefore, the same force that causes increased accumulation of one factor (technology) causes the reduced accumulation of the other factor (human capital).[29] "Shocks" to tariff rates drive changes in growth here; in practice, any other exogenous shock to growth will have the same effect of decreasing schooling.[30]

It must be emphasized that the interest-rate channel discussed earlier is not too subtle to be of significance; to the contrary, the interest rate plays a fundamental role in endogenous growth models. In this model, the local interest rate is determined locally and endogenously, and varies with the growth process even when the world interest rate on capital is fixed. This is obviously responsible for the above result. Casual observation suggests that interest rates across countries do not move in lockstep and supports the model's view of a local interest rate. The total disconnectedness between the local and world interest rates is assumed here for simplicity; the main result should be preserved if the local interest rate depends in part on the world rate but also increases with increased local adoption. If the interest rate were completely and exogenously equal to the world interest rate, as in Bils and Klenow (2000), the effect of growth on schooling would be positive. Which one of these polar assumptions is closer to reality, and therefore whether growth decreases or increases schooling, seems to be an empirical question, to which we turn in the next section.

3.5. Theoretical Robustness

Is the above result driven by the assumption that human capital is not used in adoption? Microeconometric evidence that skilled workers have a comparative advantage in adopting new technologies, such as those presented by Bartel and Lichtenberg (1987), are mainly for developed countries such as the United States, and it is not clear whether they can be appealed to in the present context. Nevertheless, we find that using human capital as a factor in the adoption process preserves the main results of the paper, in particular, Proposition 1. For instance, suppose the human capital available (H) is divided in its use into production (H_L) and adoption (H_A), and the production function for adoption of blueprints is given by $N = B(NH_A)^{\theta} G^{1-\theta}$, where G is the amount of final goods employed and B is a constant productivity factor. After a few straightforward steps, we can derive an expression analogous to the production condition (15) presented above:

$$r = C_1 + C_2[1\sqrt{r_w(1+\tau)}]^{\frac{(1-\theta)(1-\alpha)}{\alpha}} H,$$

where C_1 and C_2 are constants. Then, in a representative-family setup such as ours with a uniform rental rate per unit of effective labor, there will be no change in the

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supply condition (17). In the above condition, when $\theta = 1$, the adoption production function is identical to the one in Romer (1990), and the openness term does not matter for asymptotic growth; H will still be present. For $0 < \theta < 1$, the openness term does not drop out. In other words, it suffices that goods be at least one of the factors used in the adoption process; it need not be the only one, as has been assumed for simplicity.

4. EMPIRICAL RESULTS

We conduct an empirical analysis in this section, closely motivated by the theory developed in the preceding section.

4.1. Regression System

On the basis of conditions (13), (18), and (15), we specify the following simultaneous equation system:

$$s_i = a_0 + a_1 g_i + a_2 T_i + \epsilon_{si} \tag{20}$$

$$g_i = b_0 + b_1 s_i + b_2 O_i + \epsilon_{gi}, \tag{21}$$

where i refers to a country and O is a proxy for openness. (All other variables are from earlier sections.) The assumption is that the use of averages for the 1960–1985 period for all the above quantities will allow us to test the stationary equilibrium implications of our model, that the coefficients a_2, b_1, and b_2 are all positive, and a_1 is negative. ϵ_{si} and ϵ_{gi} are to be viewed as averages of shocks that occurred over this period to the education and production sectors.

The two endogenous variables are s and g. Our focus in the theoretical sections was on technical change. Moreover, we did not model physical capital accumulation. Therefore, we use TFP growth rates rather than per-capita output growth rates. It is unlikely that T and O are exogenous variables. Later, we describe the instruments that we use for these two variables to minimize the endogeneity problem and help identify this simultaneous equation system to get consistent two-stage least-squares estimates.[31]

Our aim is to have a parsimonious specification tied closely to the model developed. However, there are two additional variables that merit inclusion in the above system. The level of schooling can be affected by factors other than growth or life expectancy. A leading candidate is the level of government educational expenditure, which varies widely across countries. Government subsidies and other expenditures on educational infrastructure have the effect of increasing schooling by easing the liquidity constraint modeled, especially for the poor.[32] Not controlling for this variable will cause a bias in the estimation of the coefficient a_1. In other words, the model makes a prediction on the effect of schooling on growth only when other aspects of the educational institutions are held fixed. Therefore, we present results with a government educational expenditure variable included as a control in (20), though the variables that are significant continue to be so, with expected signs, even when this control is not used.

A second variable that we consider is the initial per-capita GDP, which is included in the growth regression (21). We developed only the stationary implications of our model in the preceding section. However, the data are likely to reflect transitional effects of growth. Nearly all the empirical studies cited in the introduction include the initial per-capita GDP as a regressor, and find a significantly negative coefficient for it. Ignoring the transitional effects of growth will cause a bias in the estimation of the coefficient b_1.[33]

4.2. Description of Data

The data used in the regressions and their sources are given below. Summary statistics of the variables used are presented in Table A.1. the Appendix.

- The TFP growth rates, in percentages, between 1960 and 1985 are taken from Klenow and Rodriguez (1997). We use the logarithm of the human capital stocks that Klenow and Rodriguez (1997) construct; signs and significance of coefficients do not change if we use raw levels.[34] Since, we use their measure of TFP growth, the human capital measures they construct are likely to be most consistent with these growth rates. Theirs is also a composite measure since it accounts for experience (which is affected by the level of schooling) and the quality of education in addition to the actual level of schooling. We also present results using primary schooling attainment data from Barro and Lee (1996).
- For T, we use the average (over 1960 to 1985) of life expectancy at age 1 taken from Barro and Lee (1994).[35] Given the possibility that life expectancy is correlated with shocks to education, we instrument life expectancy using climate variables—elevation, average temperature difference between the hottest and coldest months, log of the highest monthly average, ratio of the highest monthly rainfall to average rainfall, all for the most populous urban agglomeration, and the fraction of the country's boundary that is coastal.[36] In the section on robustness, we explore the use of life expectancy at age 5 and alternative instruments.
- For the (*lack of*) openness measure O, we use the *bmpl* variable from the Barro and Lee (1994) database, which is the logarithm of one plus the black-market premium (BMP) on the exchange rate. We expect b_2 to be negative in the regressions. As we noted in the introduction, this choice is useful in limiting endogeneity. To further control for endogeneity, inspired by Lee (1995), we instrument the measure of openness by distance from trade partners, a proxy for natural barriers, and the initial BMP. The results were not sensitive to using the start-of-the-period BMP instead of the average.

  In our model, openness stimulates growth, by increasing capital imports. So, an alternative measure that we use for openness is the ratio of capital imports to GDP—the value of capital goods imports (adjusted by PPP investment prices) to GDP (in PPP prices) over 1960–1985—instrumented in the same way as the BMP.[37]
- For the government educational expenditure variable, we use the total government educational expenditure as a fraction of GDP [Barro and Lee (1994)]. When primary schooling is used, we use current educational expenditure per pupil at primary school as a ratio of real per-capita GDP [from Barro and Lee (1996)]; data are available at

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the per-pupil level in this case. The 1960 per-capita GDP was taken from the Penn World Tables (Mark 5.6).

4.3. Regression Results

The basic regression results are presented in Table 1. In the discussion that follows, we refer to (20) as the schooling regression and (21) as the growth regression. Our aim is to explore the causal nature of the openness-growth and growth-schooling relationships, which calls for a simultaneous equations approach. However, to develop this systematically, we first present simple OLS estimates of the schooling and growth regressions run separately (Regression 1).

In the schooling regression, life expectancy and the expenditure variable enter positively and significantly, with p values of 0.00 and 0.07, respectively, whereas TFP growth enters with a negative coefficient, however, is not significant. The regression is essentially in the spirit of Barro (1991). The signs of the coefficients are consistent with the empirical studies mentioned in the introduction, most of which use per-capita output growth rather than TFP growth. Schooling is positively associated with TFP growth, lack of openness is negatively correlated with growth, and there are convergence effects as evidenced by the negative coefficient on initial per-capita GDP. All variables in this regression are significant at the 5% level. Taken together, all coefficients enter with expected signs but with varying significance.

On the basis of the theory presented earlier, we can argue that positive shocks to schooling would increase growth whereas positive shocks to growth would decrease schooling. That is, we expect $\mathrm{cov}(g, \varepsilon_s) > 0$ in (20) and $\mathrm{cov}(s, \varepsilon_g) < 0$ in (21). The OLS regression would overestimate a_1 in (20) and underestimate b_1 in (21). In other words, instead of running equation-by-equation OLS, if we estimate a simultaneous-equation system with the excluded exogenous variables as instruments, we should expect a_1 to decrease and b_1 to increase. Regression 2 presents two-stage least-squares (2SLS) estimates for the simultaneous system. The coefficient on growth in the schooling regression (a_1) does decrease and becomes significant. The coefficient on schooling in the growth regression (b_1) does increase in magnitude and stays significant. All other coefficients retain the signs from the previous regression and retain their significance. Therefore, all variables have the signs predicted by the model and are significant at the 5% level or better. An increase in the TFP growth by 0.1% decreases a country's relative human capital by about 2.6%, and an extra year of life expectancy increases it by more than 12%.[38] The coefficient on life expectancy is positive and highly significant, as suggested by the theory, across all specifications, and is not discussed further. A 10% increase in a country's relative human capital increases TFP growth by slightly more than 0.1%; an increase in the BMP by 10% decreases TFP growth by 0.26%.[39]

If life expectancy and openness are not exogenous to the process of growth and development, this estimation procedure is unlikely to yield consistent estimates. The coefficients on these two variables, as well as on schooling and growth, which

TABLE 1. Simultaneous-equation regressions[a]

	Regression									
	(1) OLS		(2) g, s endog.		(3) g, s, T endog.		(4) g, s, O endog.		(5) g, s, T, O endog.	
Variable	Human capital	TFP growth	Human capital	TFP growth	Human capital	TFP growth	Human capital	TFP growth	Human capital	TFP growth
TFP growth	−0.034		−0.268		−0.160		−0.321		−0.199	
	(−0.87)		(−3.21)		(−2.66)		(−2.58)		(−2.75)	
Life expectancy	0.112		0.115		0.130		0.114		0.118	
	(16.55)		(11.82)		(12.79)		(9.44)		(9.75)	
Total govt. educ.	0.073		0.126		0.068		0.120		0.100	
expenditure/GDP	(1.85)		(2.49)		(1.31)		(1.80)		(1.57)	
Human capital		0.730		1.086		1.430		1.032		1.453
		(3.79)		(3.80)		(3.12)		(2.29)		(2.70)
log(1 + BMP)		−2.222		−2.729		−2.789		−3.300		−3.475
		(−2.22)		(−3.74)		(−3.54)		(−2.14)		(−2.68)
1960 per capita GDP		−0.0005		−0.0006		−0.0007		−0.0006		−0.0008
		(−4.68)		(−4.75)		(−3.77)		(−3.88)		(−3.76)
R^2	0.803	0.236	0.710	0.276	0.768	0.223	0.615	0.292	0.733	0.235
N	91	86	81	81	80	83	69	69	68	71

[a]In this and the following tables, the instruments used for life expectancy, wherever applicable, are (for the most populous urban agglomeration) elevation, average temperature differences between the hottest and coldest months, log of the highest monthly average, ratio of the highest monthly rainfall to average rainfall, and the fraction of the country's boundary that is coastal. The instruments used for BMP are distance from trade partners and the initial BMP. Heteroskedasticity-corrected t-statistics are given within parentheses.

are positively correlated to these measures, will be suspect. Therefore, in Regressions 3 through 5, we present 2SLS estimates when life expectancy and openness are instrumented as explained in the data subsection. In Regression 3, life expectancy alone is instrumented; in Regression 4, the BMP measure alone is instrumented; and in Regression 5, both are instrumented. When either of these variables is made endogenous, we hope not only to minimize its correlation with the error term in the regression where it a regressor but also to provide the other equation with better instruments. It would be difficult to provide qualitative arguments for the direction of movement of the various coefficients. For our purposes, it suffices to note that the magnitude of the negative coefficient on growth in the schooling regression decreases most when life expectancy alone is treated as endogenous, and the magnitude of the positive coefficient on schooling in the growth regression decreases most when the openness variable alone is treated as endogenous. The magnitude on the life-expectancy variable is not too sensitive to the endogenizing of these variables, whereas the magnitude of the lack-of-openness variable increases in all cases relative to Regression 2. All variables in these three regressions have the signs predicted by the model. Moreover, the four coefficients of interest are all significant at the 5% level or better.

In Regression 5, an increase in the TFP growth by 0.1% decreases a country's relative human capital by about 2%, and a 10% increase in a country's relative human capital increases TFP growth by close to 0.14%. An increase in the BMP by 10% now decreases TFP growth by a bit more than 0.33%. Given a mean relative human capital level of 13.7% and a mean TFP growth rate of 1%, these effects appear economically significant.[40]

4.4. Are the Modeled Mechanisms Relevant?

The above evidence is broadly consistent with the theory presented—openness and a higher level of human capital increase productivity growth by increasing the incentives to adopt technologies, and a higher productivity growth will increase the interest rate applicable to local inputs, thereby decreasing the level of education. In this subsection, we conduct further tests to explore whether the results are stronger in certain subsamples "dictated" by our theory; the aim is to provide support, even if indirect, for the mechanisms we have modeled.

As mentioned in the text, the risk of expropriation is one reason why adoption activities might have to be conducted locally. Likewise improper protection of creditor rights might result in lack of foreign credit for local human capital accumulation. We use the index of expropriation from La Porta et al. (1998), and study whether the coefficient on openness is stronger in a subsample in which countries that rank in the top 10% in this index (lowest risk) are dropped; the growth regression is the more relevant one for this exercise. We then use the creditor rights index provided by Galindo and Micco (2001), and study whether the coefficient on growth is strengthened when countries that rank in the top 10% of this index (highest rights) are dropped; the schooling regression is more relevant for this

Table 2. Results in subsamples

Variable	(6) Drop low-risk expropriation: Human capital	(6) Drop low-risk expropriation: TFP growth	(7) Drop high-credit rights: Human capital	(7) Drop high-credit rights: TFP growth	(8) Drop both: Human capital	(8) Drop both: TFP growth
TFP growth	−0.190		−0.223		−0.208	
	(−2.70)		(−3.02)		(−3.00)	
Life expectancy	0.116		0.110		0.108	
	(9.70)		(7.91)		(7.91)	
Total govt. educ. expenditure/GDP	0.098		0.146		0.147	
	(1.51)		(2.18)		(2.15)	
Human capital (prim. schooling)		1.53		1.404		1.438
		(2.56)		(2.22)		(2.01)
$\log(1 + \text{BMP})$		−3.740		−3.860		−4.065
		(−2.86)		(−3.19)		(−3.30)
1960 per-capita GDP		−0.0009		−0.0007		−0.0008
		(−3.55)		(−3.07)		(−2.76)
R^2	0.716	0.231	0.712	0.241	0.700	0.249
N	65	68	59	62	56	59

exercise.[41] We drop countries by each criterion separately as well as together. Table 2 presents the results.

From Regression 6, we can see that the coefficient on openness increases in magnitude, relative to the benchmark Regression 5, when countries with a low risk of expropriation are dropped. Coefficients of interest in the schooling regression continue to be significant. When countries with high creditor ratings are dropped in Regression 7, the coefficient on TFP growth in the schooling regression increases in magnitude. Interestingly, the coefficient on local government expenditure on education and its significance increase greatly; when foreign credit is not forthcoming, the dependence on local government expenditure seems to become more important. The coefficient on openness in the growth regression also strengthens. Finally, in Regression 7, when countries that score well on both dimensions are dropped, the coefficients on growth and government expenditure in the schooling regression and on openness in the growth regression all increase in magnitude.[42]

Therefore, the results appear stronger in subsamples in which the mechanisms of the theory are most likely to be applicable.

4.5. Robustness of Results

In this subsection, we perform a few robustness checks on the results presented above. The results, shown in Table 3, should be viewed as deviations from Regression 5 of Table 1.

Table 3. Robustness of results

	Regression							
	(9) Primary schooling		(10) Cap. imp./GDP		(11) Life expectancy at 5		(12) Alternative instr.	
Variable	Schooling	TFP growth	Human capital	TFP growth	Human capital	TFP growth	Human capital	TFP growth
TFP growth	−0.321		−0.199		−0.240		−0.239	
	(−1.65)		(−2.75)		(−2.64)		(−3.11)	
Life expectancy	0.187		0.118		0.161		0.108	
	(8.30)		(9.75)		(8.86)		(9.31)	
Total govt. educ. expenditure/GDP	0.035		0.100		0.108		0.114	
	(1.34)		(1.57)		(1.50)		(1.93)	
Human capital (prim. schooling)		0.390		1.398		1.453		1.147
		(1.62)		(2.16)		(2.70)		(2.38)
Log(1 + BMP)		−3.771				−3.475		−4.221
		(−2.67)				(−2.68)		(−3.06)
Capital imports/GDP				0.367				
				(1.95)				
1960 per cap. GDP		−0.0005		−0.0007		−0.0008		−0.0007
		(−3.22)		(−2.92)		(−3.76)		(−3.74)
R^2	0.569	0.321	0.733	0.077	0.649	0.235	0.700	0.253
N	67	70	68	71	66	71	65	68

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In Regression 9, we study the sensitivity of the results to the measure of human capital used. Instead of the Klenow and Rodriguez (1997) measure, we use the years of primary schooling attainment from Barro and Lee (1996). The effect of growth on human capital continues to be negative, and the effect of human capital on growth continues to be positive, though the significance now drops (close to a 10% level). As discussed earlier, the human capital and TFP growth measures of Klenow and Rodriguez go hand-in-glove and the empirical effects, though still present, are muted when only one of the two measures is used.

We use the ratio of capital imports to GDP as a proxy for openness in Regression 10. This measure is even less likely than the BMP to be exogenous; therefore, we continue to instrument openness as we did earlier. The coefficients in the schooling regression are identical to those in Regression 5 but are repeated for convenience. In the TFP growth regression, the coefficient on human capital is significant and its coefficient is comparable to the one in Regression 5. More importantly, the new openness variable is significant, close to the 5% level—an increase in capital imports to GDP of 1% increases TFP growth by about 0.37%.

One could argue that life expectancy calculated at a later age is a better measure for T. Regression 11 uses life expectancy at age 5 instead of age 1.[43] The coefficients on TFP growth and life expectancy in the schooling regression actually increase in magnitude relative to the ones in Regression 5; all coefficients of interest remain significant.

Thus far, we have instrumented life expectancy with climate variables in order to minimize the problem of reverse causality in the schooling regression—higher schooling could increase life expectancy through improved knowledge of health and hygiene. There is no obvious choice of instruments for life expectancy. To ensure that our particular choice of instruments is not driving the results, we use beginning-of-period (1960) life expectancy and 1960 schooling as instruments in Regression 12. The coefficients on TFP growth and the openness variable strengthen in magnitude; the coefficient on life expectancy drops slightly but stays highly significant. When these as well as the previously used climate variables are used together as instruments, the results are similar.

When the outliers in TFP growth rates are dropped, the results are very similar to those in Regression 5, except for a drop in the magnitude of growth in the schooling regression. Our model is most applicable to an economy that adopts technology developed elsewhere. To ensure that technology production—a highly human-capital-intensive process—is not driving the positive association between technical change and human capital, we drop those countries that had a per-worker income of 80% or more than that of the United States in 1985 or an average annual R&D expenditure of greater than 2% of GDP. Again, the results are very similar; in particular, the significant positive coefficient on human capital in the growth regression remains.[44]

In summary, deviations from the specification in Regression 5 all yield very similar results: The coefficient on growth in the schooling regression is always negative, that on human capital in the growth regression is always positive, and greater openness is always associated with higher TFP growth.

5. CONCLUSIONS

The evidence suggests that openness and the level of education have a positive effect on technical change and growth has a negative effect on schooling. This is broadly consistent with the model developed in this paper, where capital can be imported at a given world rate but is subject to tariffs, while the complementary activities of human capital accumulation and technology adoption are subject to liquidity constraints. The necessity for local accumulation of these inputs causes the local interest rate to respond to anticipated growth, causing schooling to respond negatively to growth.

We thus find little evidence of a "reverse" channel between growth and schooling as found by Bils and Klenow (2000).[45] In their model, there is no interaction between anticipated growth and the local interest rate. A given world interest rate is the discount rate that applies to local human capital accumulation, and any increase in growth rate decreases the discount factor; the effect of growth on schooling can only be positive.

As mentioned in the introduction, the *level* of schooling, rather than growth in schooling, matters for productivity growth in our model. Bils and Klenow focus primarily on the connection between *growth* in schooling and TFP growth. Their study is novel in its use of evidence from the labor literature to carefully construct stocks of human capital, and calibration to study the effect of schooling on growth and the effect of growth on schooling *separately*. The empirical strategy in our paper is conventional, though attention is paid to causality in a regression system that closely mirrors a fully specified model in which the above two channels operate *simultaneously*. Given these differences in modeling and empirical strategies, in addition to their focus on output growth rather than productivity growth, it is best to view our study as complementary to that of Bils and Klenow.

Modeling the local interest rate to be either purely endogenous or purely exogenous is unrealistic. One should expect both external and internal forces to play a role in the determination of the local interest rate. The model here can be extended to model this interdependence carefully. In the present model, different skill (human capital) levels of labor are viewed as perfect substitutes. If imperfect substitutability across heterogeneous skill levels is modeled, one could study the issue of relative gains to opening up a closed economy. Such a model could also shed light on the political pressures that the government of a closed economy faces to liberalize. This leads to the question of why some countries are more open than others. An investigation of openness would presumably involve modeling the feedback between the political process of policymaking and economic development, and might provide insights into why some economies continue to remain closed in the face of evidence that such a stance harms economic growth and development.[46]

NOTES

1. Benhabib and Spiegel (1994) offer suggestive evidence that there is an *interactive* effect between technology gap and human capital, and Borensztein et al. (1998) argue that there is an interactive effect

between openness and human capital. Such evidence bolsters the case for an integrated framework that features human capital, technological change, and openness.

2. Caucutt et al. (in press) construct a heterogeneous-agent endogenous growth model to explore the relative rates of return of skilled and unskilled labor to anticipated growth. However, the representative-agent framework is more readily amenable to cross-country data.

3. See Autor et al. (1998) and Murnane et al. (1995) and the references cited therein.

4. Although it is preferable to use human-capital-stock data instead of volatile flow data, the choice of which measure to use is not obvious. Luckily, most estimates are highly correlated, and we study robustness using an alternative measure.

5. Lee (1993) describes an economy, which seems an accurate depiction of several LDCs, in which "the domestic price of imports reflects the black market premium: imported inputs, obtained at the official exchange rate, are resold to the producers of export goods with the premium accruing to the importers" (p. 317). It also has the advantage of much broader coverage across countries and over time. Levine and Renelt (1992) argue in favor of the BMP as a proxy for external sector distortions.

6. In light of our simultaneous-equation framework driven by theory, their strategy of using single-equation regressions to critique existing empirical studies could itself be questioned.

7. The firm raises this amount by issuing shares to the households in the economy.

8. It is assumed that the economic agents in the less developed economy cannot accumulate or export physical capital. A less restrictive assumption used by Lee (1995), that domestic and imported investment are imperfect substitutes in the production of a composite investment good, would yield results similar to ours. A discussion of this case with domestic capital accumulation is provided in the Appendix.

9. As will be seen later, an increase in the tariff rate negatively affects the growth rate. Why would a benevolent government choose to harm its citizens by imposing import duties on capital goods? This is an effective way to raise government revenues in an environment where collection of income taxes is difficult. See, for instance, Figs. 3 and 4 in Easterly and Rebelo (1993), which show that the share of customs taxes in government revenue is high for low-income countries. The presumption that all LDC governments are benevolent and follow enlightened policies seems unreasonable. A more complete answer will require the modeling of politicoeconomic considerations mentioned in the introduction. Here, for simplicity, we just assume that the tariff revenues are returned, lump sum, to the households.

10. Evidently, this model is isomorphic to a closed-economy model with taxation of capital. However, the motivation of the study and its empirical implementation lead one to identify τ with measures of openness.

11. If at least part of the costs of adoption is training workers who would not have had knowledge about this new technology embodied in school, the per-worker nature of the cost assumption is reasonable. Relaxing the per-worker assumption would not alter the results central to this paper.

12. Also see Lessard (1986), who notes, "In the case of risks involving an element of choice $\cdots$ comparative advantage lies with the party most able to mitigate the risks in question. ... [G]iven the degree of choice involved in national economic policies, national governments have a clear comparative advantage in bearing these risks ..." (p. 167).

13. One possible objection to this assumption is that it contradicts the previous assumption, since some of the capital flows can occur through foreign direct investment (FDI). Although this might be true, in practice it is not clear that FDI plays a greater role than direct capital imports in growth. For instance, the IMF's 1999 *World Economic Outlook* reports that FDI was 0.4% of GDP as late as the 1980s for developing countries. In contrast, for the poorer half of the countries that we use for empirical analysis, capital imports were 1.7% of GDP. Japan and Korea, for example, actually tended to discourage FDI [see Krueger (1995)]. Moreover, as Hausmann and Fernandez-Arias (2000) argue, FDI does not constitute physical assets of a firm, which are more relevant for our purposes, but only one way by which it finances itself.

14. The formulation in this section is motivated by the setup in Stokey (1991).

15. The mapping of schooling to human capital is inspired by the specification in Bils and Klenow (2000). Their specification is $h(s) = \bar{h}^{\phi} e^{f(s)+g(a-s)}$, where g captures on-the-job learning, $\bar{h}$ is the human capital of a prior generation ("teachers"), and $0 \le \phi \le 1$ is an externality parameter. For simplicity, we have omitted on-the-job learning; adding it would not significantly alter our conclusions. Moreover, it will be empirically accounted for, given our use of the human capital data in Klenow and Rodriguez (1997). More importantly, we set $\phi = 0$; externality is not needed here to get growth. It is only necessary for our analysis that $\phi < 1$, and setting ϕ to zero is only a simplification. The Bils–Klenow formulation lacks endogenous technological change; to generate growth there endogenously, one would require the externality parameter ϕ to be 1.

16. In this setup where there is only foregone earnings, this assumption is equivalent to the statement that households cannot borrow from abroad to finance consumption. This assumption is even less controversial than Assumption 2. Incompleteness in the human capital market, on account of the moral hazard inherent in the process of accumulation, is a widely accepted assumption. See, for example, the discussion in Becker (1993, pp. 247–248).

17. The ideal index, based on the point noted by Barro et al. (1995), would be the creditor rights for foreign investors alone. However, data on this are not available, and the hope is that the aggregate index used is correlated with the protection provided to foreigners.

18. The correlation coefficients are -0.03 and 0.24, respectively. A higher value for the expropriation index signifies lower risk.

19. All rental income is paid to foreigners.

20. A mutual fund collects all profits from the intermediate-goods firms, invests in the shares issued by the new firms, and pays the net amount as dividends.

21. There are only two aggregate state variables—the index of technology, N, and the average level of human capital, h.

22. For utility to be bounded, a sufficient condition is $\rho > (1-\sigma)g_T$, where

$$g_T \equiv \frac{1}{\sigma}\left[\frac{A\alpha(1-\alpha)}{F}\left(\frac{1}{r_w}\right)^{\frac{1-\alpha}{\alpha}} e^{f(T)} - \rho\right] > 0.$$

The inequality is satisfied trivially for $\sigma \ge 1$, and g_T is the maximum growth rate that can be obtained in the economy and corresponds to an education level of T and a tariff rate of zero.

23. This is done, for instance, by Stokey and Rebelo (1995), who are "primarily interested in how tax policy affects the interest rate, since the change in the growth rate is proportional to it $\cdots$" (p. 524).

24. The assumption that the fixed cost F is incurred on a per-worker basis causes the *average* human capital rather than the aggregate level to enter this condition.

25. We assume a sufficient condition for the education problem to be concave: $f'(s) > (\sigma-1)g_T + \rho$ in $[0, T]$. The maximum possible growth rate, g_T, is defined in note 22.

26. See, for instance, Cooley (1995) and Stokey (1996).

27. See Ehrlich and Lui (1991) where a similar result obtains in an alternative context—an increase in young-age longevity triggers a demographic transition and an increase in human capital investment.

28. Note that $R(r) < f'(s)$ is required for the second-order condition to be satisfied, and the second term is negative. In the special case where $f'(s)$ is a constant, equation (18) explicitly defines $s(r)$.

29. It is easy to see that when σ or ρ increases, the effective discount rate $R(r)$ increases, and s and h^s decrease. That is, the human capital supply curve shifts leftward, the demand curve is unchanged, and the equilibrium interest and growth rate decrease, as is the case in any growth model.

30. A simple numerical example illustrates Proposition 1. Set $(1-\alpha) = 1/3$ (capital share), $\sigma = 2$, $\rho = 0.04$, $T = 60$, and $r_w = 0.08$. For parameters specific to the present model, set $\theta = 0.05$, and the ratio of adoption costs to the product of education and manufacturing productivity, F/AB, to 25. Using (17) through (19), we compute the stationary values when $\tau = 0.2$ as $g = 0.0045$, $r = 0.0488$, and $s = 10.65$ years, and when $\tau = 0$ as $g = 0.0049$, $r = 0.0498$, and $s = 9.2$ years (g is to be interpreted as the TFP growth rate). With low life expectancy and a high tariff rate—for example, $T = 48$ years and $\tau = 0.5$—a growth trap results.

31. It is possible that increased life expectancy could directly feed into growth, but when such a process is unmodeled, it is not clear whether it should appear as an explanatory variable in the growth regression. Likewise, the testing of whether increased openness preferentially increases the return to skilled labor (i.e., whether openness should be in the schooling regression), is more appropriately done in the context of heterogeneous agent growth models such as the one in Caucutt et al. (in press).

32. See, for instance, the model developed by Caucutt and Kumar (in press), where the strength of educational participation by the poor in response to subsidies is studied.

33. Initial per-capita GDP is used in lieu of the initial level of technology because more reliable estimates are likely to be available for the former; the two are highly correlated in any case [see, e.g., Fig. 1 in Hall and Jones (1999)].

34. The average measure of human capital is constructed from their 1985 per-worker human capital data and growth rate in this quantity from 1960 to 1985, using the formula $\bar{h} = (h_{1985}/25g_h)(1-e^{-25g_h})$.

As Bils and Klenow (2000) note, this combination of productivity growth and human capital is consistent with a situation in which "introduction of technology is based on the amount of human capital in the country as a whole (e.g., when there is a fixed component to transferring technology)" (p. 1163). This is precisely the case in our model.

35. Life expectancy at age 0 (*lifee*0) is used in conjunction with the under-1 mortality rate to get life expectancy at age 1.

36. The data were assembled from these internet sources: worldclimate.com, un.org/Depts/unsd/demog, and odci.gov/cia/publications/factbook.

37. I thank Jong-Wha Lee for supplying me with these data.

38. The relevant calculations are $[1 - \exp(-0.268 * 0.1)] * 100$ and $[\exp(0.115) - 1] * 100$.

39. The relevant calculations are $1.086 * \ln(1.1)\%$ and $-2.729 * \ln(1.1)\%$.

40. For sake of completeness, we present the regression results for life expectancy and openness when they are both treated as endogenous (Regression 5): Life exp., 3.674 HC -0.0005 height -12.52 hitempl $+0.056$ tempdiff $+$ 4.815 coast $-$ 2.104 hiavrain ($R^2 = 0.84$); BMP; -0.084 HC -0.03 TFP growth $+$ 0.007 distance $+$ 0.508 *bmpl*60 ($R^2 = 0.51$).

41. Galindo and Micco (2001) extend the data set on creditor rights provided by La Porta et al. (1997). As mentioned earlier, ideally we would like the creditor rights for foreign investors alone; in the absence of such data, we use the aggregate index. Also, both indices are available for the end rather than the beginning of our sample period; this should not be a serious problem, given their slow-moving nature. Countries with risk index ≥ 9.9 (max is 10) and those with creditor rights $= 1$ (max is 1) are dropped.

42. Countries with missing data for these two indices are not dropped under the operative assumption that countries with the lowest risk and highest creditor rights are likely to have data readily available. Dropping such countries hugely reduces an already small sample. (In general, there is a trade-off between having a relevant enough subsample and having enough observations.) However, if a country is dropped when its risk rating is not available, the coefficient on openness increases in magnitude by more than what has been presented in Table 2.

43. The under-5 mortality rate from the *World Development Indicators 2001* (for the year 1970, which is in the middle of the sample period) is used to get life expectancy at age 5.

44. These two results have not been presented in detail here for sake of brevity.

45. However, our finding is consistent with that of Stokey (1991), who argues that an open economy that is sufficiently backward or advanced relative to the rest of the world would invest less in human capital than it would under autarky.

46. The model in Parente and Prescott (1999), for instance, could be extended to model lack of openness as another barriers to riches.

REFERENCES

Acemoglu, D. (1998) Why do new technologies complement skills? Directed technical change and wage inequality. *Quarterly Journal of Economics* 113, 1055–1089.

Autor, D.H., L.F. Katz, & A.B. Krueger (1998) Computing inequality: Have computers changed the labor market? *Quarterly Journal of Economics* 113, 1169–1213.

Barro, R.J. (1991) Economic growth in a cross section of countries. *Quarterly Journal of Economics* 106, 407–444.

Barro, R.J. & J.-W. Lee (1994) Data Set for a Panel of 138 Countries. Mimeograph.

Barro, R.J. & J.-W. Lee (1996) International measures of schooling years and schooling quality. *American Economic Review Papers and Proceedings* 86, 218–223.

Barro, R.J., N.G. Mankiw, & X. Sala-i-Martin (1995) Capital mobility in neoclassical models of growth. *American Economic Review* 85, 103–115.

Bartel, A. & F. Lichtenberg (1987) The comparative advantage of educated workers in implementing new technology. *Review of Economics and Statistics* 69, 1–11.

Becker, G.S. (1993) *A Treatise on the Family*. Cambridge, MA: Harvard University Press.

Benhabib, J. & M.M. Spiegel (1994) The role of human capital in economic development: Evidence from aggregate cross-country data. *Journal of Monetary Economics* 34, 143–173.

Bils, M. & P.J. Klenow (2000) Does schooling cause growth? *American Economic Review* 90, 1160–1183.

Borensztein, E., J. De Gregorio, & J.-W. Lee (1998) How does foreign direct investment affect economic growth? *Journal of International Economics* 45, 115–135.

Caucutt, E.M. & K.B. Kumar (in press) Higher education subsidies and heterogeneity: A dynamic analysis. *Journal of Economic Dynamics & Control.*

Caucutt, E.M., S. Imrohoroğlu, & K.B. Kumar (in press) Growth and welfare analysis of tax progressivity in a heterogeneous-agent model. *Review of Economic Dynamics.*

Cooley, T.F. (ed.) (1995) *Frontiers of Business Cycle Research*. Princeton, NJ: Princeton University Press.

Easterly, W. & S. Rebelo (1993) Fiscal policy and economic growth. *Journal of Monetary Economics* 32, 417–458.

Edwards, S. (1998) Openness, productivity and growth: What do we really know? *Economic Journal* 108, 383–398.

Ehrlich, I. & F.T. Lui (1991) Intergenerational trade, longevity, and economic growth. *Journal of Political Economy* 99, 1029–1059.

Eicher, T.S. (1996) Interaction between endogenous human capital and technological change. *Review of Economic Studies* 63, 127–144.

Galindo, A. & A. Micco (2001) Creditor Protection and Financial Cycles. Working paper 443, Inter-American Development Bank.

Grossman, G.M. & E. Helpman (1992) *Innovation and Growth: Technological Competition in the Global Economy*. Cambridge, MA: MIT Press.

Hall, R.E. & C.I. Jones (1999) Why do some countries produce so much more output per worker than others? *Quarterly Journal of Economics* 114, 83–116.

Harrison, A. (1996) Openness and growth: A time-series, cross-country analysis for developing countries. *Journal of Development Economics* 48, 419–447.

Hausmann, R. & E. Fernandez-Arias (2000) Foreign Direct Investment: Good Cholesterol? Working paper 417, Inter-American Development Bank.

Klenow, P.J. & A. Rodriguez (1997) The neoclassical revival in growth economics: Has it gone too far? In B.S. Bernanke & J. J. Rotemberg (eds.), *NBER Macroeconomics Annual 1997*, pp. 73–103. Cambridge, MA: MIT Press.

Krueger, A.O. (1995) East Asian experience and endogenous growth theory. In T. Ito & A. O. Krueger (eds.), *Growth Theories in Light of the East Asian Experience*. Chicago: University of Chicago Press.

La Porta, R., F. Lopez-de-Silanes, A. Shleifer, & R.W. Vishny (1997) Legal determinants of external finance. *Journal of Finance* 52, 1131–1150.

La Porta, R., F. Lopez-de-Silanes, A. Shleifer, & R.W. Vishny (1998) Law and finance. *Journal of Political Economy* 106, 1113–1155.

Lee, J.-W. (1993) International trade, distortions, and long-run economic growth. *IMF Staff Papers* 40, 299–328.

Lee, J.-W. (1995) Capital goods imports and long-run growth. *Journal of Development Economics* 48, 91–110.
Lessard, D.R. (1986) The supply of external finance: Comments. In C. Lancaster & J. Williamson (eds.), *African Debt and Financing*. Washington, DC: Institute for International Economics.
Levine, R. & D. Renelt (1992) A sensitivity analysis of cross-country growth regressions. *American Economic Review* 82, 942–963.
Lucas, R.E., Jr. (1988) On the mechanics of economic development. *Journal of Monetary Economics* 22, 3–42.
Mankiw, G.N., D. Romer, & D.N. Weil (1992) A contribution to the empirics of economic growth. *Quarterly Journal of Economics* 107, 407–437.
Murnane, R.J., J.B. Willet, & F. Levy (1995) The growing importance of cognitive skills in wage determination. *Review of Economics and Statistics* 77, 251–266.
Parente, S.L. & E.C. Prescott (1999) Monopoly rights: A barrier to riches. *American Economic Review* 89, 1216–1233.
Rodriguez, F. & D. Rodrick (1999) Trade Policy and Economic Growth: A Skeptic's Guide to the Cross-National Evidence. NBER working paper 7081.
Romer, P.M. (1990) Endogenous technological change. *Journal of Political Economy* 98, S71–S102.
Romer, P.M. (1994) New goods, old theory, and the welfare cost of trade restrictions. *Journal of Development Economics* 43, 5–38.
Sachs, J. & A. Warner (1995) Economic reform and the process of global integration. *Brookings Papers on Economic Activity* 1, 1–118.
Stokey, N.L. (1991) Human capital, product quality, and growth. *Quarterly Journal of Economics* 106, 587–616.
Stokey, N.L. (1996) Free trade, factor returns, and factor accumulation. *Journal of Economic Growth* 1, 421–447.
Stokey, N.L. & S. Rebelo (1995) Growth effects of flat-rate taxes. *Journal of Political Economy* 103, 519–550.
Tamura, R. (1992) Efficient equilibrium convergence: Heterogeneity and growth. *Journal of Economic Theory* 58, 355–376.
Tamura, R. (1996) Regional economies and market integration. *Journal of Economic Dynamics & Control* 20, 825–845.
Tamura, R. (2001) Teachers, growth, and convergence. *Journal of Political Economy* 109, 1021–1059.
Telesio, P. (1979) *Technology Licensing and Multinational Enterprises*. New York: Praeger.

APPENDIX

A.1. PROOF OF LEMMA 2

From result 1, it is clear that the equilibrium growth rate can be used instead of the equilibrium interest rate in deriving the subsequent results. In this and the following results, we work in terms of the growth rate g.

Write (16) in its log form as

$$s = T + \frac{\log\left[1 - \frac{\tilde{\sigma}g+\rho}{f'(s)}\right]}{\tilde{\sigma}g + \rho}.$$

Fix a $0 < g < \infty$. If we plot the two sides of this equation as a function of s, then the left side of this equality is a 45-degree line. Given $f'' \leq 0$, the right side is nonincreasing in s. The right side is $< T$ on $(0, T]$, given that $R(g) \equiv \tilde{\sigma} g + \rho < f'(s)$, for the second-order condition to be satisfied. Therefore, if the two curves intersect, they have to do so at a value less than T. (The effective discount factor in (16) tends to infinity when $s = T$, and so, this is to be expected.) Now, if an Inada condition held for f [i.e., $\lim_{s \to 0} f'(s) = \infty$], the value of the right side when $s = 0$ is always T, and a $0 < s < T$ exists. In the absence of an Inada condition, it is likely for certain growth rates that

$$T + \frac{\log\left[1 - \frac{\tilde{\sigma} g + \rho}{f'(0)}\right]}{\tilde{\sigma} g + \rho} \leq 0,$$

in which case, $s = 0$ is the solution. This situation can arise, for instance, when the life expectancy is very low. The returns from schooling are lower than the cost of foregone earnings, and no education is acquired. Therefore, in general, $0 \leq s < T$.

To see what happens when g changes, differentiate both sides with respect to g to get

$$s' \left[1 - \frac{f_{ss}}{f_s\,(f_s - R)}\right] = -\frac{\tilde{\sigma}}{\tilde{\sigma} g + \rho} \left[\frac{1}{f_s - R} + \frac{\log(1 - R/f_s)}{R}\right].$$

The left side is positive. The term in square brackets on the right side is positive if

$$\frac{R/f_s}{1 - R/f_s} > -\log(1 - R/f_s).$$

For any $0 < x < 1$, it is true that $x > -(1-x)\log(1-x)$, and given that $R < f_s$, the above term is always positive. Given that $R > 0$ (which follows from Assumption 4), the sign of s' depends entirely on the sign of $\tilde{\sigma}$. Noting that $\tilde{\sigma} = \sigma - 1$, the result that $s'(g) > (<)0$, when $\sigma < (>)1$ follows. ■

A.2. DOMESTIC CAPITAL ACCUMULATION

We investigate whether the thrust of Proposition 1 is preserved when agents in the economy accumulate capital domestically, in addition to importing it. The main factors that drive the result in Lemma 2, and thus Proposition 1, are the endogeneity of the domestic discount rate, r, and its connection to the growth rate, g, via (13).

In the main text, it is assumed that an intermediate good is produced from general imported capital according to $x = k/\eta$, and the total amount of capital rented is $K = \eta N x$. Instead, similar to an assumption by Lee (1995), we now assume that domestic and foreign capital are used in the production of x. We specify

$$x = \frac{k_d^{\gamma} k_f^{1-\gamma}}{\eta}, \tag{A.1}$$

where k_d denotes domestic capital and k_f denotes foreign capital. The case in the text obtains when $\gamma = 0$.

The intermediate-good firm's problem now becomes $\max_{k_d, k_f, x} A(1-\alpha)x^{1-\alpha}H^{\alpha} - (1 + \tau)r_w k_f - r k_d$, subject to (22). The final-good sector condition $(x/H)^{\alpha} = [A(1-\alpha)]/p$

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continues to hold. Use this, (A.1), and the FOCs of the above problem, to get

$$p = \frac{\eta}{\gamma(1-\alpha)}\left[\frac{\gamma}{1-\gamma}\right]^{1-\gamma}[(1+\tau)r_w]^{1-\gamma}\,r^{\gamma}. \qquad \textbf{(A.2)}$$

The domestic interest rate is now a factor that determines the price of the intermediate good. Profits are still given by (4), and condition (14) still holds in a stationary equilibrium. These two conditions imply $[\alpha A(1-\alpha)]/F(x/H)^{1-\alpha}h = r$, as before. In this, use the final-good condition mentioned above and (A.2) to get the analogue of (15), the production condition for a stationary equilibrium:

$$r = \left[\frac{A\alpha(1-\alpha)}{F}\right]^{\frac{\alpha}{\alpha+\gamma(1-\alpha)}}\left[\frac{1}{r_w(1+\tau)}\right]^{\frac{(1-\alpha)(1-\gamma)}{\alpha+\gamma(1-\alpha)}} h^{\frac{\alpha}{\alpha+\gamma(1-\alpha)}}, \qquad \textbf{(A.3)}$$

where η is normalized to $A(1-\alpha)^2\gamma^{\gamma}(1-\gamma)^{(1-\gamma)}$.

Condition (A.3) reduces to (15) when $\gamma = 0$. Equation (A.3) can be written in log form to get a human capital "demand" equation, which differs from (19) only in the coefficients:

$$\log(h) = \left[\frac{\alpha+\gamma(1-\alpha)}{\alpha}\right]\log(r) + \left[\frac{(1-\alpha)(1-\gamma)}{\alpha}\right]\log[(1+\tau)r_w] + \log\left[\frac{F}{A\alpha(1-\alpha)}\right]. \qquad \textbf{(A.4)}$$

The elasticity of h with respect to r is greater now than the elasticity in (19), and with respect to r_w is lower.

Since the human capital "demand" equation is upward sloping, all that is needed to establish Proposition 1 in this modified setup is to verify that the human capital "supply" equation is nonincreasing in r when $\sigma \geq 1$ and (13) still continues to hold. Note that the main change in the household's problem is the accumulation of (domestic) physical capital. If the household can borrow abroad at the rate r_w to finance domestic capital accumulation using its capital as collateral (i.e., trade in international bonds subject to the constraint $B \geq -K$), the household will do so, as long as $r_w < r$. The distinction between domestic and foreign capital then becomes vacuous and the situation is identical to the one in the text. Instead, we assume that the household cannot borrow to finance domestic capital accumulation.

In the original model, the individual's schooling problem (7) and the household's intertemporal problem (11) were treated as separable; the individual and household were in perfect agreement. When there is investment in physical capital, the household solves

$$\max_{c(t),i(t)} \int_0^{\infty} e^{-\rho t}\,T\,\frac{c(t)^{1-\sigma}}{1-\sigma}\,dt$$

subject to the following constraints [instead of (12)]:

$$Tc(t) + i(t) \leq w(t)H^s(t) + r(t)K_d(t) + D(t) + V(t)$$
$$\dot{K}_d(t) = i(t);\ i(t) \geq 0.$$

Depreciation of domestic capital has been omitted for simplicity (and to make the modified model comparable to the one in the main text). The nonnegativity constraint on investment

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in domestic capital prevents us from writing the budget constraint in the present-value form, similar to (12). Provided the household takes $H^s(t)$ as given, the above problem can be formulated as a Hamiltonian with costate λ on the capital accumulation condition to get the necessary conditions, $c^{-\sigma} = \lambda$, and $\dot{\lambda}/\lambda = -(r - \rho)$. On a stationary equilibrium (BGP) where c grows at the rate g, these conditions imply (13).

However, in general, it will not be optimal for the household to take H^s as given. When the stock of domestic physical capital is low relative to the other stocks, h and N, the household will want to decrease earnings foregone due to the schooling choice of its members and invest more in physical capital. The path of $w(t)H^s(t)$ would matter to the household and it would choose to make schooling decisions different from the one given by the individual's problem (7). This lack of separability is essentially an off-stationary equilibrium phenomenon. We instead implicitly assume that the ratio K_d/N is at its steady-state value to begin with and study only the stationary equilibrium. Therefore, the household and schooling problems are unchanged: The human capital supply curve is nonincreasing and Lemma 2 and Proposition 1 obtain. Using the above conditions, one can readily obtain the stationary values of r, h, s, x, and K_d/N.

A.3. SUMMARY STATISTICS FOR REGRESSION VARIABLES

Table A.1 presents summary statistics for the main variables.

TABLE A.1. Summary statistics

Variable	N	Mean	S.D.	Min.	Max.
Primary schooling (yr)	97	3.16	1.83	0.31	7.98
Klenow and Rodriguez (1997) human capital	98	0.137	0.143	0.007	0.738
TFP growth (%)	98	1.03	1.66	−3.26	5.16
Life expectancy at age 1 (yr)	94	63.49	8.85	43.90	75.78
Life expectancy at age 5 (yr)	84	66.74	6.62	52.51	76.45
log (1 + BMP)	86	0.19	0.26	0	1.32
Capital imports to GDP (%)	96	2.67	2.15	0.23	14.7
Per-pupil primary exp./per-capita GDP (%)	95	13.01	7.43	3.99	48.10
Total govt. education exp./GDP (%)	95	3.85	1.42	1.17	7.23
1960 per-capita GDP (1985 intl. $)	98	2,467	2,277	313	9,895