Interaction between knowledge and technology: a contribution to the theory of development

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Interaction between knowledge and technology: a contribution to the theory of development

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Abstract

This article attempts to explain the large and persistent disparities in levels of output per worker across countries. It is argued that an explanation for these disparities requires an understanding of the relationship between knowledge and technology. The model that is constructed can be summarized as an open economy version of the Solow-Swan growth model; in which technological change is investment-specific, and knowledge about new technologies is embodied in labour. In the model, income differences arise because poor countries lack the knowledge to implement foreign technologies productively. Furthermore, these disparities persist when countries differ in their ability to learn. JEL classification: F43, O11

1 Introduction

In 1960 average GDP per worker among the countries in the top 10 percent of the world income distribution was 25 times larger than the countries in the bottom 10 percent of the distribution. By 2000 the income gap between these two groups of countries fell, but only to a factor of 21. The poor were catching up to the rich, but at an annual rate of only 0.1 percent.[1] A major task facing economists, and the primary objective of this article, is to explain the large and persistent disparities in income levels that we observe across countries. It will be argued that an explanation for these disparities requires an understanding of the relationship between knowledge and technology. To preview the model, income differences arise because poor countries do not have the knowledge to implement foreign technologies productively. Furthermore, these disparities persist when countries differ in their ability to learn. A country that is able to learn about an advancement in technology quickly, will converge to the technology frontier quickly; otherwise convergence can be quite slow. It will be demonstrated that large and persistent income disparities can arise out of plausible convergence rates.

The neoclassical growth model of Solow (1956) and Swan (1956) relies on differences in total factor productivity (TFP) to explain the large differences observed in output per worker across countries. This explanation has received support from a number of studies that have found significant differences in TFP across countries.[2] However, despite the support that the standard Solow-Swan model has received, the explanation that it provides is unsatisfactory, and this is because it fails to answer a number of important questions. For example, why are poor countries so much less productive than wealthy countries? Why do TFP differences across countries persist? Do poor countries employ inferior technology? Is their workforce less skilled?

If technological knowledge was disembodied, as it is assumed to be in the standard Solow-Swan model, then we may expect so see persistent differences in TFP across countries. However, in fact much of the technology used by less developed countries (LDCs) is embodied in physical capital imported from abroad. For example, Eaton and Kortum (2001) have studied the pattern of trade in capital goods, and have documented the following: First, world R&D and world production of capital are highly concentrated in a small number of countries. Second, the most R&D intensive countries are also the ones that are the most specialized in equipment production.[3] Third, LDCs import most of their equipment.[4] These observations suggest that while only a few countries may conduct R&D, the benefits may be spread around the world through exports of capital goods. As such, a central issue in understanding cross-country income and productivity differences is to understand the flow of capital (or lack of it) from rich to poor countries.

Lucas (1990) suggested that physical capital embodying advanced technologies will not flow to poor countries, because of their relatively poor endowments of complementary human capital. The model constructed in the current paper takes Lucas' suggestion seriously. In particular, in this paper a model is created where productivity and income differences between countries arises because a knowledgeable workforce has an advantage in technology adoption. If we assume that technological change is investment-specific, that is, new technologies are embodied in physical capital; then a knowledge advantage in technology adoption implies a temporary productivity loss following a capital investment, but this productivity loss can be alleviated by accumulating more knowledge (or human capital). Empirical support for these assumptions are provided by Flug and Hercowitz (2000), who found that equipment investment levels have a positive effect on the relative wages and employment of skilled labour; by Benhabib and Spiegel (1994), who found that TFP depends positively on a nation's human capital stock, and that human capital levels play an important role in attracting physical capital; and by Bartel and Lichtenberg (1987), who found that the relative demand for educated workers declines as the age of capital increases, especially in R&D-intensive industries.

In the model, the interaction between knowledge and technology will not only affect productivity in the production of goods, but also in the production of new knowledge. Productivity in human capital production is assumed to depend on the availability of learning opportunities, which are a function of the distance worker knowledge is from the technology frontier. If learning opportunities are plentiful, as one may expect in a poor country, then productivity in learning will be high, ceteris paribus. It is this feature of the model that will lead to convergence in human capital levels, TFP and output per worker. Since the model predicts convergence, then it must rely on something else to explain the observed income disparities. In this paper, it is argued that these disparities exist because of differences in the speed at which countries converge to the technology frontier. It will be demonstrated that when human capital accumulation depends on the state of technology, the rate of convergence of output and TFP can be quite slow; and will depend on the elasticity of human capital accumulation with respect to technology, that is, a country's ability to learn.

Do countries really differ in their ability to learn? Evidence provided by Lee and Barro (2001) indicates that they do. Lee and Barro used data on internationally comparable test scores, repetition rates and dropout rates; to show that differences in school quality across countries are substantial. One result they found was that schoolchildren from higher-income countries tend to achieve higher test scores, holding fixed other factors that influence school achievement. In other words, a given amount of time spent learning may not yield equal outcomes across countries.

In that the rate of human capital accumulation depends on the state of technology the theory resembles works by Erosa, Koreshkova and Restuccia (2006) and Lloyd-Ellis and Roberts (2002). In the Erosa et al. paper, resources devoted to schooling are endogenous, whereas in the current paper time spent accumulating knowledge is exogenous. However, in their paper TFP is exogenous; and therefore, unlike the current paper, they cannot account for international differences in TFP. In the Lloyd-Ellis and Roberts paper, technological change, TFP and human capital investment decisions are all endogenous; however, they only characterize the balanced growth path.[5] Although their paper may be richer along some dimensions, the current paper has the advantage that it allows for an analysis of transitional dynamics. Therefore, the current paper may be better suited for studying growth in poor countries.

In that this paper models barriers to technology transfer/adoption the theory resembles the works of Parente and Prescott (1994), Easterly et al. (1994), Lloyd-Ellis (1999), and Acemoglu and Zilibotti (2001). Parente and Prescott (1994) suggested that barriers to technology adoption take many forms; such as, regulatory and legal constraints, bribes that must be paid, violence or the threat of violence, sabotage, and/or worker strikes. However, unlike the current paper, they do not specifically model human capital as a barrier to technology adoption. Although Easterly et al. (1994), Lloyd-Ellis (1999), and Acemoglu and Zilibotti (2001) have also studied the effects that human capital has on the rate of technology adoption, they all assumed that human capital production does not depend on the state of technology. Although this assumption may be appropriate for studying the current performance of LDCs, which employ technologies that are sufficiently far from the technology frontier; it is inappropriate for studying the entire transitional growth paths of developing countries, which are in the process of catching up to the technology frontier. At some point additional learning will only be possible if the frontier expands, that is, if technology improves.

The two papers that most closely resemble the current paper are

Greenwood and Jovanovic (2004) and Kosempel (2004). In those papers, and this one, technological progress is investment-specific, and before a new technology can be implemented productively an investment in learning must be undertaken. However, in those papers the model economies are closed to international trade. A closed economy model will not be desirable if the objective is to explain economic development, and this is because technological change is important to the development and growth process, and new technologies can be imported. Therefore, in order to improve our understanding of the process of economic development, we require a model that permits international trade.

The model developed in this paper presents a framework with which to analyze development and long-run growth in a small open economy. The foundation of the analysis is the neoclassical growth model of Solow (1956) and Swan (1956), but it is extended to allow for international capital flows and trade. This is not the first paper to extend the Solow-Swan model along this dimension (see, for example, Grossman and Helpman, 1991; Barro, Mankiw and Sala-i-Martin, 1995; Milbourne, 1997; Ventura, 1997; Escot and Galindo, 2000; and Benge and Wells, 2002). However, in all of the previous work technological change was modelled as being disembodied; whereas in the current paper technological change is investment-specific, and knowledge is embodied in labour. Restricting technological change to be embodied within capital and labour will be necessary in order for the properties of the neoclassical growth model to be consistent with the recent evidence on technological change and the sources of productivity growth.

The remainder of the paper is organized as follows. A set of facts that describe the process of development and long-run growth are identified in Section 2. The model is constructed in Section 3. The model's predictions for economic development and long-run growth are discussed in Section 4. Concluding remarks are provided in Section 5.

2 The facts

It will be demonstrated that the predictions of the model coincide with key facts that characterize the process of growth and development; whereas the properties of the standard Solow-Swan model will be shown to be inconsistent with some of these facts. The first six facts listed below are for the U.S. economy, but describe the general characteristics of most economies in the long-run; whereas the remaining two facts are based on cross-country data, and reveal important characteristics about the process of economic development.

(F1) The average growth rate of output per capita (Y/L) has been positive and more or less constant over time.

(F2) Consumption (C) and investment expenditures (PQI) have been growing at more or less the same rate as aggregate expenditures (Y). Here P denotes the price of new capital relative to the price of consumption goods, and Q is an index that denotes the level of technology embodied in new capital goods.

(F3) The capital stock (K) has been growing at a more or less constant rate greater than the growth rate of the labour input (L).

(F4) The rate of return to capital displays no trend.

These four facts describe an economy on a balanced growth path. The properties of the standard Solow-Swan model have been shown to be consistent with all of these facts, and therefore it provides an excellent framework with which to build on for the current analysis.[6]

(F5) The price of new capital goods relative to the price of consumption goods displays a downward trend (Gordon, 1990).

(F6) The investment-to-output ratio (QI/Y) displays a positive trend.

Greenwood, Hercowitz and Krusell (1997, 2000) and Gort, Greenwood and Rupert (1999) interpret the negative co-movement between the price and quantity of new capital (F5 and F6) as evidence that there has been significant technological progress in the production of capital goods. In fact, Greenwood et al. (1997) have found that in order to sustain growth in the long-run the U.S. economy has relied on investment-specific technological change. In comparison, TFP growth (which they call residual-neutral technological change) had virtually no impact on the long-run performance of the U.S. economy, at least not since the mid-1970s. Carlaw and Kosempel (2004) found similar results for Canada.

One problem with the standard Solow-Swan model is that, in the model, neither the relative price of capital nor the investment-to-output ratio show any trend. In order to make the model's properties consistent with (F5) and (F6), it will be necessary to follow Greenwood et al.; that is, it will be assumed that new technologies are investment-specific. As such, benefiting from a new technology will require a capital investment. Following Greenwood et al., new technologies are assumed to reduce unit production costs, and this will be modelled as a fall in the relative price of capital.

(F7) International data does not support the theory of absolute income convergence (see De Long, 1988; or Barro and Sala-i-Martin, 2004, Chpt. 12). This implies that income disparities between rich and poor countries may persist, or even widen.

(F8) The empirical evidence supports conditional convergence, which suggests that countries with similar preferences and technologies will converge to the same level and growth rate of per capita income (see Barro and Sala-i-Martin, 1991, 1992, 2004; and Mankiw, Romer and Weil, 1992).

Fact (F8) defines the concept of development as the process by which a poor country catches up to a wealthy country in terms of its per capita income level. Barro et al. (1995) show that introducing an international credit market into the standard neoclassical growth model causes the model to predict rates of convergence that are counterfactually high. Since the neoclassical growth model assumes diminishing returns to accumulative factors, physical capital should flow to capital poor countries, ceteris paribus. These international capital flows will add to domestic savings and lead the model to predict an extremely rapid rate of development. In the current model, on the other hand, a poor country may also be deficient in a complementary factor, like human capital; and therefore the rate of return to physical capital may not actually be that high in the poor country. In the current model, convergence can be slow, and will depend on the rate at which workers can acquire new knowledge.

3 The model

The model outlined in this section can be summarized as an open economy version of the Solow-Swan growth model, in which technological change is embodied within the factors of production. The model is set in continuous time. Upper case letters are used to denote aggregate variables, whereas lower case letters denote per capita variables.

3.1 Production

Final output, $Y(t)$, at time t is produced using inputs of physical capital, $K(t)$, and effective labour units, $E(t)\mu L(t)$. Here $L(t)$ denotes the size of the labour force; μ is a constant denoting the fraction of time devoted to the production of output; and $E(t)^{1-\alpha}$ is TFP, and is interpreted as a measure of the effectiveness of labour at operating high-technology capital goods. The production function takes the Cobb-Douglas form,

$$Y(t) = [E(t)\mu L(t)]^{1-\alpha} K(t)^{\alpha}, \quad 0 < \alpha < 1. \tag{1}$$

This production function satisfies the neoclassical properties: constant returns to scale in K and μL; positive but diminishing marginal products for K and μL; and the Inada conditions,

$$\lim_{K\to\infty}\left(\frac{\partial Y}{\partial K}\right)=\lim_{\mu L\to\infty}\left(\frac{\partial Y}{\partial \mu L}\right)=0 \text{ and } \lim_{K\to 0}\left(\frac{\partial Y}{\partial K}\right)=\lim_{\mu L\to 0}\left(\frac{\partial Y}{\partial \mu L}\right)=\infty.$$

3.2 Evolution of the inputs

The labour force is assumed to grow at a constant and exogenous rate n, and therefore

$$L(t)=L(0)\,e^{nt}. \tag{2}$$

Here $L(0)=1$ is assumed to be the value of L at time 0.

The law of motion for physical capital is given by

$$\dot{K}(t)=Q(t)\,I(t)-\delta K(t), \tag{3}$$

where δ denotes the rate of capital depreciation, and a dot $(\cdot)$ over a variable is used throughout the paper to indicate a time derivative. The most important feature of equation (3) is the variable $Q(t)$, which measures the current state of technology for producing capital goods. This variable will be permitted to grow over time, and therefore newer capital will embody better technology. The rate of investment-specific technological change (g) is assumed to be constant and exogenous,[7] and therefore

$$Q(t)=Q(0)\,e^{gt}. \tag{4}$$

Here $Q(0)=1$ is assumed to be the value of Q at time 0.

Following Nelson and Phelps (1966), it is assumed that TFP depends positively on the average stock of human capital and negatively on the sophistication of existing technology,

$$E(t) = \left[\frac{h(t)}{Q(t)}\right]^{\theta}, \quad \theta > 0. \tag{5}$$

Here $h(t) = H(t)/L(t)$ is the average stock of human capital, and $H(t)$ is the aggregate stock. This specification implies that new technologies will not be operated productively until an investment in learning is undertaken. However, labour can augment their productivity by devoting time to learning.

The law of motion for an individual's human capital is given by

$$\dot{h}(t) = (1-\mu)\, Q(t)^{\varepsilon}\, h(t)^{1-\varepsilon} - (\delta + n)h(t), \quad 0 < \varepsilon < 1, \tag{6}$$

where $1-\mu$ denotes time allocated to learning. This specification of the human capital production function exhibits diminishing returns to the existing stock of human capital. As a result, human capital will accumulate in the long-run only if there is technological progress. The technology term is incorporated into the function to capture the idea that new technologies create new learning opportunities, and therefore offset the tendency for diminishing returns to set in.[8]

3.3 Consumption, savings and aggregate demand

Aggregate demand for goods is set equal output. This condition can be written as

$$Y(t) = C(t) + P(t)\, Q(t)\, I(t) + NX(t), \tag{7}$$

where $C(t)$ and $P(t)\,Q(t)\,I(t)$ denote consumption and investment expenditures, respectively; $P(t)$ is the price of new capital relative to the price of consumption goods; and $NX(t)$ is net exports.

Advances in capital good technology will act to reduce the cost of producing an efficiency unit of capital. Following Greenwood, Hercowitz and Krusell (1997), these cost reductions are assumed to be passed on to consumers through lower prices,

$$P(t) = 1/Q(t)\,. \tag{8}$$

Note that a declining price series for physical capital is consistent with property (F5) of the data.[9]

One important open economy feature to consider is the difference between output (GDP or $Y(t)$) and income (GNP or $Z(t)$). The relationship between these two variables is given by

$$Z(t) = Y(t) + rA(t)\,, \tag{9}$$

where r is the exogenous world real interest rate, and $A(t)$ is net foreign assets. Like the standard Solow-Swan model, the current model incorporates a constant and exogenous savings rate, s.[10] As such, consumption and national savings, $S(t)$, satisfy the following equations:

$$C(t) = (1-s)Z(t)\,, \tag{10}$$

$$S(t) = P(t)\,Q(t)\,I(t) + \dot{A}(t) = sZ(t)\,. \tag{11}$$

The law of motion for net foreign asset holdings is derived from equations

(7)-(11), and is given by

$$\dot{A}(t) = NX(t) + rA(t). \tag{12}$$

A second important open economy feature to consider is that there can be no arbitrage opportunities between physical capital and the foreign asset. This restriction requires that the rates of return to these assets be equalized,[11]

$$\frac{\alpha \left[E(t+1)\, \mu L(t+1)\right]^{1-\alpha} K(t+1)^{\alpha-1}}{P(t)} - \delta = r. \tag{13}$$

Since the world real interest rate is constant, the rate of return to physical capital will also be constant. This property of the model is consistent with feature (F4) of the data.

Although each country has access to the same technology for converting investment into capital, the no-arbitrage condition (13) reveals that LDCs may not borrow a lot of capital initially. In particular, the no-arbitrage condition reveals that the rate of return to physical capital depends in part on the ratio of physical capital to labour (K/L), and in part on the productivity variable E. Therefore, this condition can be satisfied with a low K/L value, if E also has a low value. In this case, convergence will require productivity growth, and because of (6) if ε is low then convergence will be slow.

4 Economic development and long-run growth

This section outlines the model's predictions for the time path of a developing economy.

4.1 The balanced growth path

In the long-run the aggregate state of technology and the stock of human capital must grow at the same rate, g. This feature of the model is readily apparent by examining the human capital production function (6). If technology grows faster than human capital, then the Q/h ratio rises. This implies that more learning opportunities are becoming available, and therefore the marginal product of time devoted to learning is increasing, which in turn increases the rate of human capital accumulation. Eventually, the rate of human capital accumulation will catch up to the rate of technological change. The exact opposite happens if human capital initially grows faster than technology.

Since the Q/h ratio is constant in the steady-state, the efficiency parameter (E) will also be constant in the steady-state. This restriction and equations (4), (8) and (13) can be used to reveal the steady-state growth rate of the aggregate capital stock (g_K^*),

$$g_K^* = -\frac{\dot{P}/P}{1-\alpha} + \frac{\dot{L}}{L} = \frac{g}{1-\alpha} + n. \tag{14}$$

A star (*) superscript is used here and throughout the paper to denote a steady-state value. Equation (14) reveals that in the long-run the aggregate capital stock grows at a constant rate greater than the growth rate of the labour input. This property of the model is consistent with feature (F3) of the data.

Since the growth rate of the aggregate capital stock is constant in the long-run, the investment-to-capital ratio (QI/K) must also be constant (see equation 3); and therefore in the long-run

$$g_{QI}^{*} = g_{K}^{*}. \tag{15}$$

However, since the relative price of capital declines over time, investment expenditures (PQI) will not be growing as fast as the actual quantity of capital investment (QI). That is,

$$g_{PQI}^{*} = \dot{P}/P + g_{QI}^{*} = \frac{\alpha g}{1-\alpha} + n. \tag{16}$$

The growth rate of aggregate output at date t is given by

$$\frac{\dot{Y}(t)}{Y(t)} \approx (1-\alpha)\left(\frac{\dot{E}(t)}{E(t)} + \frac{\dot{L}(t)}{L(t)}\right) + \alpha\frac{\dot{K}(t)}{K(t)}. \tag{17}$$

Imposing the steady-state restrictions that $\dot{E}(t)/E(t) = 0$ and $\dot{K}(t)/K(t) = g_{K}^{*}$, gives the long-run growth rate of aggregate output as a function of the rate of technological change and rate of population growth,

$$g_{Y}^{*} \approx \frac{\alpha g}{1-\alpha} + n. \tag{18}$$

Equations (15), (16) and (18) reveal that the long-run properties of the model are consistent with features (F2) and (F6) of the data; that is, $g_{QI}^{*} > g_{PQI}^{*} = g_{Y}^{*}$. Note also that the model's predictions regarding the sources of long-run growth are consistent with the observations of Greenwood et al. (1997).[12] Specifically, equation (18) indicates that investment-specific technological change is required to sustain long-run growth in output per person. In the model, TFP does not represent a source of long-run growth, and this is true despite the fact that human capital accumulates indefinitely. In the steady-state the rate of human capital accumulation is just sufficient to keep pace with the state of technology, and therefore TFP is not improving.

The analysis above demonstrated that the long-run properties of the model coincide with properties (F1)-(F6) of the data. The remainder of this section will present an analysis of the transitional growth paths in the model, and the discussion will focus on the properties (F7) and (F8) of the data.

4.2 The transitional growth paths

To analyze the transitional dynamics of the model economy, it will be convenient to rewrite the system in terms of variables that will remain constant in the steady-state. A transformation that will facilitate our dynamic analysis involves the ratios:

$$\begin{aligned}
\hat{c}(t) &= \frac{C(t)}{L(t)\,Q(t)^{\frac{\alpha}{1-\alpha}}},\ \hat{\imath}(t) = \frac{I(t)}{L(t)\,Q(t)^{\frac{\alpha}{1-\alpha}}},\ \widehat{nx}(t) = \frac{NX(t)}{L(t)\,Q(t)^{\frac{\alpha}{1-\alpha}}},\\
\hat{a}(t) &= \frac{A(t)}{L(t)\,Q(t)^{\frac{\alpha}{1-\alpha}}},\ \hat{y}(t) = \frac{Y(t)}{L(t)\,Q(t)^{\frac{\alpha}{1-\alpha}}},\ \hat{z}(t) = \frac{Z(t)}{L(t)\,Q(t)^{\frac{\alpha}{1-\alpha}}},\\
\hat{k}(t) &= \frac{K(t)}{L(t)\,Q(t)^{\frac{1}{1-\alpha}}},\\
\hat{h}(t) &= \frac{H(t)}{L(t)\,Q(t)}.
\end{aligned}$$

The transformed system is given by the following equations:

$$\hat{y}(t) = \mu^{1-\alpha}\hat{h}(t)^{(1-\alpha)\theta}\,\hat{k}(t)^{\alpha}, \tag{19}$$

$$\hat{y}(t) = \hat{c}(t) + \hat{\imath}(t) + \widehat{nx}(t), \tag{20}$$

$$\hat{z}(t) = \hat{y}(t) + r\hat{a}(t), \tag{21}$$

$$\hat{c}(t) = (1-s)\hat{z}(t), \tag{22}$$

$$r = e^{-g}\alpha\mu^{1-\alpha}\hat{h}(t)^{(1-\alpha)\theta}\hat{k}(t)^{\alpha-1} - \delta, \tag{23}$$

$$\dot{\hat{k}}(t) = \hat{\imath}(t) - \left(\delta + n + \frac{g}{1-\alpha}\right)\hat{k}(t), \tag{24}$$

$$\dot{\hat{a}}(t) = \widehat{nx}(t) - \left(n + \frac{\alpha g}{1-\alpha} - r\right)\hat{a}(t), \tag{25}$$

$$\dot{\hat{h}}(t) = (1-\mu)\hat{h}(t)^{1-\varepsilon} - (\delta + n + g)\hat{h}(t). \tag{26}$$

It is assumed that the no-arbitrage condition (23) holds in every period, including period 0; and therefore $K(0) = [\alpha/(e^{g}(r+\delta))]^{1/(1-\alpha)}\mu h(0)^{\theta}$. The initial endowment $h(0)$ and $A(0)$ will be taken as given. Therefore, in the model, period 0 may have actually followed some initial period of international borrowing and lending.

Let $\hat{w}(t) = \hat{k}(t) + \hat{a}(t)$ denote nonhuman wealth. Summing (24) and (25) and using the information in (19)-(23) gives

$$\dot{\hat{w}}(t) = \chi_1 h(t)^{\theta} - \chi_2\hat{w}(t), \tag{27}$$

where

$$\chi_1 = \left[\frac{(e^{g}-\alpha)sr}{\alpha} + \frac{(se^{g}-\alpha)\delta}{\alpha} - g\right]\left[\frac{\alpha}{(r+\delta)e^{g}}\right]^{\frac{1}{1-\alpha}}\mu, \tag{28}$$

$$\chi_2 = n + \frac{\alpha g}{1-\alpha} - sr > 0. \tag{29}$$

It is assumed that $sr < n + \frac{\alpha g}{1-\alpha}$. This condition will enable us to avoid the possibility of setting in motion a process of an ever increasing rate of net foreign asset accumulation, or ever increasing rate of net foreign borrowing.

Equations (26) and (27) represent a system of two differential equations and two unknowns: $\hat{h}(t)$ and $\hat{w}(t)$. A solution to this system involves finding functions that relate these variables to the initial endowments $\left(\hat{h}(0), \hat{a}(0)\right)$, the parameters of the model, and time. As is often the case with non-linear dynamic systems a solution cannot be derived analytically, however, an approximate solution can be obtained. The steps are as follows: First, the variables in equations (26) and (27) will be converted into logarithmic form. Second, a first-order Taylor approximation will be performed around the steady-state of the log-formed system. This procedure will transform the equations into approximations, which will be linear functions in the deviations of the variables from their steady-state values. Third, the transformed system will be solved. Finally, the solutions derived for $\ln \hat{w}(t)$ and $\ln \hat{h}(t)$ will be substituted back into the equations of the model to reveal the dynamic behavior of the other variables.

The log-formed version of equations (26) and (27) are examined in detail in the Appendix. The analysis in the Appendix reveals that the steady-state is a stable node. Functions that describe the time paths for $\ln \hat{h}(t)$ and $\ln \hat{w}(t)$, and for some of the model's other variables, were also calculated algebraically in the Appendix. The results of these calculations were used below in two capacities. First, they were used to derive expressions for the average growth rates of several of the model's variables over an interval of length T:

$$\frac{\ln\left[h(T)/h(0)\right]}{T} = g + \left[\frac{1-e^{-\varepsilon(\delta+n+g)T}}{T}\right] \ln\left[\hat{h}^{*}/\hat{h}(0)\right], \tag{30}$$

$$\begin{aligned}\frac{\ln\left[k(T)/k(0)\right]}{T} &= \left(\frac{1}{1-\alpha}\right) g + \left[\frac{1-e^{-\varepsilon(\delta+n+g)T}}{T}\right] \ln\left[\hat{k}^{*}/\hat{k}(0)\right] \\ &= \left(\frac{1}{1-\alpha}\right) g + \theta\left[\frac{\ln\left[h(T)/h(0)\right]}{T} - g\right],\end{aligned} \tag{31}$$

$$\begin{aligned}\frac{\ln\left[y\left(T\right)/y\left(0\right)\right]}{T} &= \left(\frac{\alpha}{1-\alpha}\right)g+\left[\frac{1-e^{-\varepsilon(\delta+n+g)T}}{T}\right]\ln\left[\hat{y}^{*}/\hat{y}\left(0\right)\right] \\ &= \left(\frac{\alpha}{1-\alpha}\right)g+\theta\left[\frac{\ln\left[h\left(T\right)/h\left(0\right)\right]}{T}-g\right]. \qquad (32)\end{aligned}$$

Second, they were used to simulate the time paths of the model's key variables. These simulations and equations (30)-(32) will be used shortly to describe the model's transitional dynamics.

4.3 The quantitative behavior of the model

Before the time paths of the model's variables could be simulated and graphed on a computer it was necessary to calibrate the model. All values are based on annual data, and are set to coincide approximately with the long-run behavior of the U.S. economy. The U.S. economy is useful for the calibration exercise because its average behavior corresponds roughly to steady-state growth. Physical capital's share of income, α, is set equal to 1/3; the rate of capital depreciation, δ, is set to 5%; the population growth rate, n, is set to 1%; the rate of return to physical capital is set to 7%;[13] and the long-run growth rate of income per capita, $\alpha g/(1-\alpha)$, is set to 2%. The rate of convergence for output per worker, $\beta \equiv \varepsilon(\delta+n+g)$, is set to 2%, and matches evidence provided by Barro and Sala-i-Martin (1991; 1992; 2004, Chpt. 11). It is assumed that net exports are zero in the steady-state; and this implies that in the steady-state GNP ($\hat{z}^{*}$) equals GDP ($\hat{y}^{*}$), and net foreign asset holdings ($\hat{a}^{*}$) equal zero. Finally, the steady-state level of human capital $\left(\hat{h}^{*}\right)$ is normalized to one. There are now enough restrictions to determine the steady-state values for all remaining variables, and the values of the following parameters: $g = 4\%$, $\varepsilon = 0.2$, $\mu = 90\%$, and $s = 32\%$. By setting $\mu = 90\%$ the average human capital level will grow in the long-run at a rate of 4%, which also corresponds to the rate of technological change A savings rate of 32% coincides with the fraction of GDP spent on durable goods in the U.S. economy.

There is one remaining parameter to set, θ. This is the parameter that determines how sensitive TFP is to deviations of h from Q. Given an initial value of h, the size of θ will also determine the initial disparity in the level of output per worker predicted by the model. In order to circumvent the lack of micro evidence for θ, its value is inferred indirectly, and is based on the following: First, in 1960 LDCs had achieved only 20 percent of the steady-state human capital level.[14] Second, according to the growth accounting study of Hall and Jones (1999), in 1988 differences in the production function residual (E) explained approximately a factor of 18 difference in output per worker between the 5 wealthiest and 5 poorest countries. They attribute the remainder of the output gap (a factor of only 1.8) to differences in physical capital intensity. In the current paper, the no-arbitrage condition (13) guarantees that capital-output ratios are equalized in the model, and therefore in the model all differences in output per worker are explained by differences in TFP. The calibration procedure will be to set θ to match the importance of TFP in explaining the output disparity, not to match the actual disparity. Therefore, the model will account for most, but not all, of the observed disparity in output per worker across countries. It will be demonstrated later (in Figure 2) that when θ is set to a value of 1.85, the model will predict a factor of 18 difference in output per worker between the wealthiest countries $\left(\hat{h}\,(29) = \hat{h}^*\right)$ and the poorest countries in period 29 (which corresponds to 1988).

The simulated time paths of the model's key variables are displayed in Figure 1. The simulation assumes that initially the level of human capital is low relative to its steady-state level, $\hat{h}\,(0) = \hat{h}^*/5$; and that the economy starts with no net foreign debt, $\hat{a}\,(0) = 0$.

{insert Figure 1 here}

Consider first the transitional dynamics of the human capital stock. Figure 1 and Equation (30) indicate that if $\hat{h}^* > \hat{h}_0$, then h rises monotonically from its starting value to its steady-state value. However, the average growth rate of h falls as the length of the interval, T, rises. This is because the opportunities for learning diminish as the human capital to technology ratio approaches its steady-state from below. The speed at which h converges to its steady-state equals $\varepsilon(\delta + n + g)$. Once the steady-state is attained, the average stock of human capital grows at its long-run rate, g.

Now consider the transitional dynamics of the physical capital stock. Holding fixed the rate of technological change, g, and the averaging interval, T; equation (31) indicates that the average rate of physical capital accumulation depends positively on the difference between the growth rates of human capital and technology. If human capital growth exceeds the rate of technological change, then TFP will be rising, and leads to an increase in the rate of return to physical capital. But this would violate the no-arbitrage condition (23). If the rate of return to capital exceeded the interest rate, then the economy would borrow from abroad to finance additional physical capital investments, and this explains the initial accumulation of foreign debt in Figure 1. However, since capital has a diminishing marginal product, a higher physical capital stock would lower its rate of return. Therefore, during the process of economic development we should expect to see increases in TFP, and a high rate of physical capital accumulation. However, growth in these variables will have exacting offsetting effects on the rate of return to physical capital, and therefore the no-arbitrage condition will always hold.

We can see in Figure 1 that the rates of convergence for physical capital and output are not instantaneous, and this is true despite the fact that the domestic economy can borrow in international markets. Poor countries will not import high-technology capital goods if they do not have the know-how to employ these goods productively. Equations (31) and (32) reveal that the rates of convergences for physical capital and output both equal $\varepsilon(\delta + n + g)$, and therefore depend on the speed at with human capital converges to its steady-state.

Figure 1 and equations (31) and (32) reveal that the growth rates of $\hat{k}\,(t)$ and $\hat{y}\,(t)$ decline monotonically as the model economy transits towards the balanced growth path. Therefore, like the standard Solow-Swan model, the current model predicts conditional convergence. In other words, the model predicts that countries with similar parameter values will converge to the same balanced growth path. All countries on the balanced growth path will have the same level and growth rate of per capita income. This property of the model is consistent with feature (F8) of the data.

4.4 A quantitative experiment

The one remaining property of the data to discuss is (F7), which states that income differences between rich and poor countries are sometimes persistent. In order to explain this feature of the data, the standard Solow-Swan model relies on differences in the level or growth rate of technology. In the Solow-Swan model, international differences in the behavior of technology will cause countries to converge on separate balanced growth paths. In comparison, in the current model even poor countries are assumed to have access to advanced technologies, and therefore it predicts that all countries converge to a more or less common balanced growth path.[15] In order to explain persistent differences in income levels between countries, the current model relies on differences in the speed of convergence to the balanced growth path. A numerical example is provided below, which will demonstrate that international differences in the speed of convergence can allow a rich country to growth faster than a poor country, and will create income disparities that may persist for a long period of time.

Figure 2 provides a numerical demonstration of how income differences could arise and be sustained in the model. This figure shows the steady-state level of output ($\hat{y}^* = 1.47$) and the transitional growth paths of output ($\hat{y}(t)$) for four different sets of economies. These economies differ only with respect to the parameter ε. In the model, ε determines the relative importance of technology in the production function for human capital (see equation 6), and it is the most important parameter for determining the rate of convergence to the balanced growth path (β). The range of values for ε was not selected arbitrarily. The highest ε-value produces a convergence speed of 2 percent per year, and this matches evidence for the U.S. economy. In comparison, the lowest ε-value produces a convergence rate of 0.1 percent per year, and this enables the model to match the persistence of the cross-country income disparities that we observe in the data.

{insert Figure 2 here}

The four sets of economies in Figure 2 are assumed to start with the same initial endowment of human capital ($\hat{h}(0) = \hat{h}^*/5$) and no foreign debt ($\hat{a}(0) = 0$). The predicted gap between the steady-state output level and the initial level is a factor of 20, and therefore the model can produce a sizeable disparity. Recall that in 1960 output per worker between the wealthiest 10 percent and poorest 10 percent of countries differed by a factor 25. In order to produce an income disparity this large in the model, the no-arbitrage condition would have to be relaxed. This would allow the model economies to differ in their capital intensities. Under the current set of restrictions, the model economies differ only in their level of TFP. After 40 years the gap between the steady-state and the existing output level narrows to a factor of 4 for the set of economies that have the highest ε-value, but only to a factor of 17 for the countries with the lowest ε-value. After 200 years the economies with the highest ε-values have approximately achieved the steady-state output level, whereas output in the poorest economies still differs from the steady-state level by over a factor of 11. After 300 years the poor are within a factor of 9 of the wealthy, and after 500 years the gap closes to a factor of 6. In other words, in the model, income disparities may persist over a long time period - just like we observe in the data.

In the analysis above the speed of convergence for poor countries was set to generate the required amount of persistence. However, the empirical evidence on the speed of convergence indicates that the values applied above are plausible. There have been many empirical papers that have studied the patterns of convergence within and between countries. For example, Barro and Sala-i-Martin (1991; 1992; 2004, Chpt. 11), Coulombe and Lee (1995), and Persson (1997) have studied convergence within or between relatively wealthy regions and countries; such as Canada, the United States, Japan and Europe. These studies all reveal that, for the regions/countries in their samples, the income gap between a typical poor and rich economy diminishes at roughly 2 percent per year. However, studies of convergence within or between LDCs reveal slower convergence rates. For example, Zind (1999) studied income convergence (or the lack of it) within and between 89 LDCs. Zind's results reveal that only a small subsample of 30 displayed a tendency to converge, and that convergence works well only when the political and economic institutions in poor countries are supportive of inward flows of foreign capital and technology. Murthy and Ukpolo (1999) discovered a relatively low speed of convergence among African countries. Like Zind, they attributed this feature to structural factors including the prevailing political and economic institutions. Hossain (2000) studied convergence within the regions of Bangladesh, and found evidence of income convergence before 1991, but not after. Finally, there are a small number of papers that have studied convergence rates using an unrestricted sample of countries, that is, a sample that includes both wealthy and poor countries (see, Evans, 1997; Lee, Pesaran, and Smith, 1998; Rappaport, 2000; and Barro and Sala-i-Martin, 2004, Chpt. 12). The evidence provided in these papers reveals that rates of convergence are increasing with per capita income. For example, Evans (1997) estimated convergence rates well above 2 percent per year for countries in the richest third and middle third of the world income distribution, but a speed of convergence of only 0.5 percent for the poorest third of countries.

Although the empirical literature has established that there are differences across countries in the speed of convergence, it is not entirely clear why these differences exist. Very little empirical work has been performed to identify and quantify the factors that affect the speed of convergence, although there is some theoretical work. For example, in the relevant theoretical literature, Barro et al. (1995) showed that the speed of convergence would slow if a constraint was imposed on international credit. If poor countries cannot acquire financing for their capital investments, then they will not be able to acquire foreign capital and technology. Furthermore, Parente and Prescott (1994) identified a number of non-human capital related barriers to technology adoption, and showed that these also slow convergence.

Like Parente and Prescott, in the current paper convergence requires that LDCs adopt foreign technologies. However, in the current paper, the speed of convergence depends on the elasticity of human capital with respect to technology, ε; because this is the parameter that determines the rate at which workers can acquire knowledge about new foreign technologies. Differences in the value of ε could arise because of differences in the speed at which the educational institutions in the various economies implement new technologies into their curriculum. This could be due to differences in the funding level of the educational system, or perhaps the quality of the teachers.[16] This is not the first paper to argue that educational quality could have important economic effects. For example, Rosenberg (2000, Chpt. 3) argues that the post-war growth success of the U.S. relative to other countries was related in part to the responsiveness of its universities in achieving a rapid rate of diffusion of potentially useful new knowledge. Rosenberg claims that U.S. universities differ from those of other countries in that they are quicker to respond to changing economic circumstances.

5 Conclusion

The neoclassical growth model of Solow-Swan studied the process of economic growth for a closed economy and modelled technological change as being disembodied. Although these modelling assumptions may have been useful as a first approach to determine the factors affecting growth, they are inconsistent with the features of real economies and recent evidence on technological change. Creating a growth model that permits international trade is important because of the recent process of economic integration and globalization, and the fact that the majority of the world's economies must reasonably be considered small and open. In both the Solow-Swan model and the current model, technological progress is required to sustain a positive growth rate of output per capita in the long-run. However, the Solow-Swan model relied heavily on differences in technology to explain international differences in income levels and growth rates, whereas the current model does not. This is a problem for the Solow-Swan model, because the recent evidence suggests that advanced technologies can be acquired by importing capital, and therefore even poor countries should have access to these technologies. If new technologies can be imported, then why are some countries poor and others rich?

The current model relied on skill differences between the workers in various countries to explain international differences in output per worker, rates of convergence to the balanced growth path, and international capital flows. The model suggests that poor countries do not import capital goods that embody advanced technologies, despite their accessibility; and this is because the workers in these countries do not have the skills/know-how required to use these goods productively. Although the model has identified the human capital convergence coefficient $\varepsilon(\delta + n + g)$ as a possible explanation for the low growth rates and levels of income that have been sustain by LDCs; in order to make specific policy recommendations to help these economies, empirical research into the factors that affect the speed of convergence is required. However, the model does provide us with some general policy recommendations. For example, the model reveals that policy makers in poor countries should focus their efforts on improving transitional growth rates, rather than targeting policies to improve the long-run growth path. In other words, for poor countries policies to improve the rate of technology adoption, such as an investment directed at improving human capital accumulation technology; will be more effective than policies to improve the rate of technology creation, such as an investment in R&D.

A Appendix: transitional growth paths

Equations (26) and (27) can be converted into logarithmic form as follows:

$$\frac{d\left[\ln \hat{h}(t)\right]}{dt} = (1-\mu)\, e^{-\varepsilon \ln \hat{h}(t)} - (\delta + n + g), \tag{A1}$$

$$\frac{d\left[\ln \hat{w}(t)\right]}{dt} = \chi_1 e^{\theta \ln \hat{h}(t) - \ln \hat{w}(t)} - \chi_2. \tag{A2}$$

Performing a first-order Taylor approximation around the steady-state of this system and converting to matrix notation gives:

$$\begin{bmatrix} d\left[\ln \hat{h}(t)\right]/dt \\ d\left[\ln \hat{w}(t)\right]/dt \end{bmatrix} = \begin{bmatrix} -\chi_2 & \theta\chi_2 \\ 0 & -\varepsilon(\delta+n+g) \end{bmatrix} \begin{bmatrix} \ln \hat{h}(t) - \ln \hat{h}^* \\ \ln \hat{w}(t) - \ln \hat{w}^* \end{bmatrix}, \tag{A3}$$

where the steady-state values, $\hat{h}^*$ and $\hat{w}^*$, are:

$$\hat{h}^* = \left[\frac{(1-\mu)}{\delta+n+g}\right]^{\frac{1}{\varepsilon}}, \tag{A4}$$

$$\hat{w}^* = \chi_1 \hat{h}^{*\theta}/\chi_2. \tag{A5}$$

The characteristic roots of the simultaneous differential equation system (A3) are $-\chi_2$ and $-\varepsilon(\delta+n+g)$. Since both roots are negative, the steady-state is a stable node. The general solutions for the time paths of the human capital stock and total wealth are given by:

$$\ln \hat{h}(t) = \ln \hat{h}^* - \ln\left(\frac{\hat{h}^*}{\hat{h}(0)}\right) e^{-\varepsilon(\delta+n+g)t} \tag{A6}$$

$$\ln \hat{w}(t) = \ln \hat{w}^* - e^{-\chi_2 t} \ln\left(\frac{\hat{w}^*}{\hat{w}(0)}\right) + \tag{A7}$$

$$+ \frac{\theta\chi_2}{\chi_2 - \varepsilon(\delta+n+g)} \left[e^{-\varepsilon(\delta+n+g)t} - e^{-\chi_2 t}\right] \ln\left(\frac{\hat{h}^*}{\hat{h}(0)}\right).$$

Solutions for all other variables are easily obtainable by substituting (A6) and (A7) into equations (19)-(25). The solution functions for physical capital and output are given by:

$$\begin{aligned}\ln \hat{k}\,(t) &= \ln \hat{k}^{*} - \theta \ln \left(\frac{\hat{h}^{*}}{\hat{h}\,(0)}\right) e^{-\varepsilon(\delta+n+g)t} \\ &= \ln \hat{k}^{*} - \ln \left(\frac{\hat{k}^{*}}{\hat{k}\,(0)}\right) e^{-\varepsilon(\delta+n+g)t}, A8 \end{aligned} \tag{35}$$

$$\begin{aligned}\ln \hat{y}_{t} &= \ln \hat{y}^{*} - \theta \ln \left(\frac{\hat{h}^{*}}{\hat{h}\,(0)}\right) e^{-\varepsilon(\delta+n+g)t} \\ &= \ln \hat{y}^{*} - \ln \left(\frac{\hat{y}^{*}}{\hat{y}\,(0)}\right) e^{-\varepsilon(\delta+n+g)t}, A9 \end{aligned} \tag{36}$$

where

$$\hat{k}^{*} = \left[\frac{\alpha}{(r+\delta)e^{g}}\right]^{1/(1-\alpha)} \mu \hat{h}^{*\theta}, \tag{A10}$$

$$\hat{y}^{*} = \mu^{1-\alpha} \hat{h}^{*(1-\alpha)\theta} \hat{k}^{*\alpha}. \tag{A11}$$

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Notes

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[1]Author's calculations based on the Heston, Summers and Aten (2002) data set.

[2]See, for example, Hall and Jones (1999). Or, for a review of this literature, see Acemoglu and Zilibotti (2001).

[3]According to Gordon (1990) the technologies in new equipment have increased dramatically in the United States.

[4]For example, the Eaton and Kortum study displays trade data for 7 African countries. Within this group 74 percent of their capital investment demand was satisfied by imports, most of which (72 percent) came from 7 large capital producing countries: France, Germany, Japan, Italy, Sweden, United Kingdom, and United States.

[5]In the Roberts and LLoyd-Ellis paper, rapid accumulation of one type of knowledge stimulates the accumulation of the other via the distribution of wages.

[6]For a detailed description of facts (F1)-(F4) and a discussion of the standard

Solow-Swan model see Barro and Sala-i-Martin (2004, Chpt. 1).

[7]Since technological change is investment-specific, and capital goods can be imported; even LDCs will have access to advanced technologies, despite the fact that they may not actually be undertaking their own R&D. Therefore, restricting technological change to be exogenous is appropriate in a growth model of a small open economy.

[8]The human capital production function adopted by Uzawa (1965) and Lucas (1988) can be considered a special case of (6), in which $\varepsilon = 0$. Setting $\varepsilon = 0$ is, however, somewhat unrealistic. It implies that a given percentage increase in human capital requires the same amount of learning-time, no matter what level of $h(t)$ has already been attained. One would think, however, that if technology were to remain constant then eventually the opportunities for further learning would completely vanish.

[9]The computer market provides an excellent example of the type of price-quantity movement predicted by the model. Computer processing speeds have been increasing rapidly; despite the fact that new computers are manufactured in about the same way, are constructed from just about the same assortment of metals, plastics and other raw materials and are sold for about the same price as older models. Although the price of a physical unit of capital (PQ) has remained roughly constant, the price per efficiency unit (P) has been falling, and as a result computers show rapid growth.

[10]In an open economy model capital accumulation can be financed by

borrowing from abroad. If there are no borrowing constrains, then the savings rate will not impose a constraint on the level of capital accumulation. Under these conditions, capital and output levels will be invariant to the savings rate, and this would be true even if the savings rate was endogenous. Since endogenizing the savings rate will not have a significant effect on the results, the Solow-Swan framework is preferable.

[11]The marginal cost of acquiring a unit of new capital is $P(t)$, and the marginal benefit is $\alpha\left[E(t+1)\mu L(t+1)\right]^{1-\alpha} K(t+1)^{\alpha-1}+(1-\delta)P(t)$. Therefore, the net rate of return to physical capital is given by the left hand side of (13).

[12]Refer to Section 2.

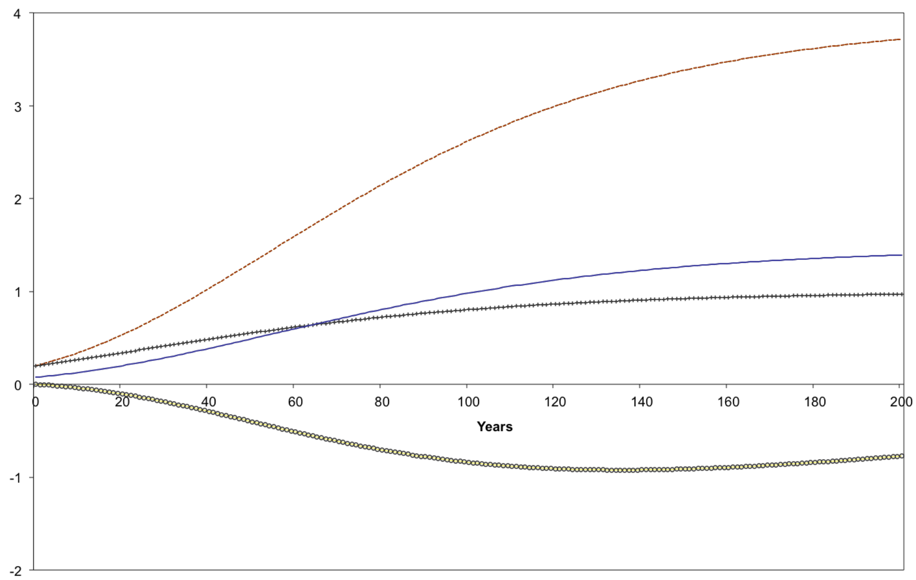
[13]A 7% rate of return corresponds to the average real annual return on equity estimated by Mehra and Prescott (1985) for the U.S. economy.

[14]In 1960 developing countries had an educational attainment that was 1/5 the level achieved in advanced countries in 2000. Source: Lee and Barro, Table 4, 2001.

[15]Like the standard Solow-Swan model, in the current model international differences in the savings rate or the rate of population growth will also affect the position of the balanced growth paths of some variables. Therefore, the current model does not predict absolute convergence.

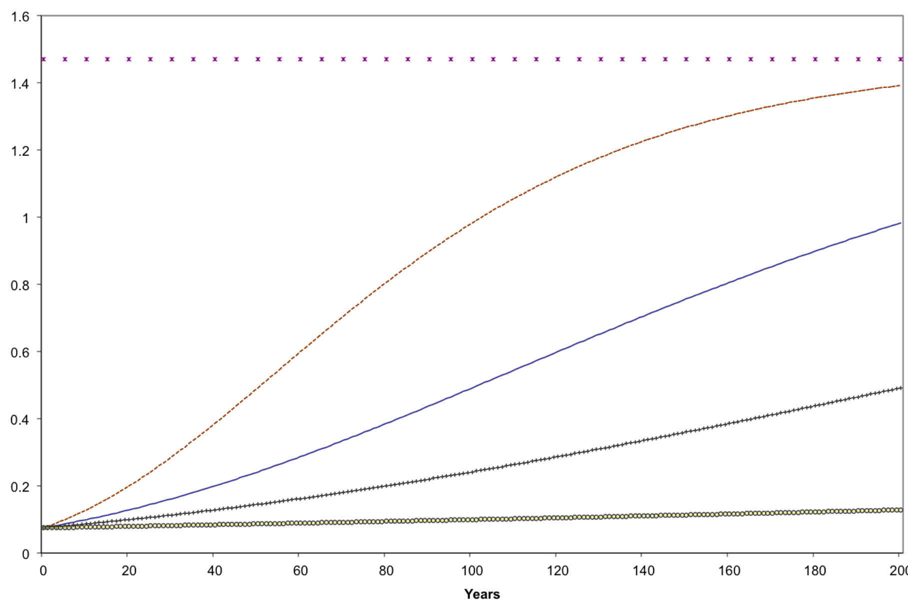
[16]Lee and Barro (2001) found that the quality of schooing varies substantially

across countries, and that family inputs and school resourses are closely related to school outcomes.



$- - -\ \hat{k}\,(t)$ $\qquad$ $———\ \hat{y}\,(t)$ $\qquad$ $+++\ \hat{h}\,(t)$ $\qquad$ $\circ\circ\circ\ \hat{a}\,(t)$

Figure 1: Transitional growth paths



$$
\begin{aligned}
-- \ \varepsilon &= 0.20, \ \beta = 2.0\%; \\
\text{——} \ \varepsilon &= 0.10, \ \beta = 1.0\%; \\
+{+}+ \ \varepsilon &= 0.05, \ \beta = 0.5\%; \\
\circ\circ\circ \ \varepsilon &= 0.01, \ \beta = 0.1\%
\end{aligned}
$$

Figure 2: Sensitivity analysis for the transition path of (transformed) GDP $\hat{y}(t)$