CYCLICAL TECHNOLOGY EVOLUTION AND COMPARATIVE ECONOMIC GROWTH

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ABSTRACT

A two-country model of growth is developed with exogenous fluctuations in the rate of technological progress. Technological growth in the leading country follows a random walk, while in the lagging country the rate of advance depends on the technological distance between the two countries and the efficiency of imitation. In the absence of cyclical technological change or lags in technology transfer, there is monotonic convergence in income levels. If the two countries share initially identical technologies, their standards of living never diverge. In the presence of cyclical technological change and lags in imitation, a rich pattern of relative growth emerges: the model generates convergence, divergence and leapfrogging along balanced growth equilibria, and also demonstrates why observed convergence rates may be substantially slower than those predicted by the standard neoclassical model.

SINTESIS

Se desarrolla un modelo de crecimiento para dos países con fluctuaciones exógenas en la tasa de progreso tecnológico. El crecimiento tecnológico en el país líder sigue un camino aleatorio, en tanto que en el país rezagado la tasa de progreso depende de la distancia tecnológica entre ambos países y de la eficiencia en la imitación. En ausencia de un cambio tecnológico cíclico o de rezagos en la transferencia tecnológica, hay una convergencia monotónica en los niveles de ingreso. Si los dos países inicialmente comparten tecnologías idénticas, sus niveles de vida nunca divergen. En presencia de un cambio tecnológico cíclico y de rezagos en la imitación, emerge un rico esquema de crecimiento relativo: el modelo genera convergencia, divergencia y desarrollo acelerado a lo largo de equilibrios de crecimiento balanceado, y también demuestra porque las tasas de convergencia observadas podrían ser sustancialmente más lentas que aquellas previstas por el modelo neoclásico tradicional.

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1. INTRODUCTION

The study of comparative economic growth is experiencing something of a revival. Motivated, at least in part, by the availability of a new dataset [Summers and Heston (1991)] and in part by the development of advanced theoretical tools (the emergence of endogenous growth theory), recent empirical studies of growth have raised a number of fundamental issues: What are the determinants of growth across countries and over time? Why do growth rates differ across countries? Is there a tendency for incomes *per capita* to converge over time? What is the nature of policies (if any) which influence the pace of economic growth?

It would not be and exaggeration to suggest that, in the case of comparative economic growth, measurement is running slightly ahead of theory. Recent empirical studies have established that, contrary to predictions from the Solow-Swan [Solow (1956), Swan (1956)] neoclassical growth model, the standards of living in countries with different income levels immediately after World War Two clearly were not converging, even over a long period of time [Barro (1992)]. In addition, the observed impact on growth of changes in the savings rate is too large [Romer (1987)], and population growth is too small [Lucas (1988)], to lend support to the Solow model. Moreover, independently of its ability to fit the data, the neoclassical model cannot provide an endogenous link between policy instruments and long-run growth.

Recent endogenous growth theories have proposed alternative mechanisms of growth based on learning-by-doing [Krugman (1987), Stokey (1988), Young (1991)], technological externalities which generate increasing returns [Romer (1986, 1990)], human capital accumulation [Lucas (1988)] and Schumpeterian growth consisting of quality improvements [Aghion and Howitt (1992), Grossman

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and Helpman (1991), Segerström, Anant and Dinopoulos (1990), Thompson and Waldo (1994)]. In contrast with the standard neoclassical model, the endogenous growth literature allows for sustained differences in growth rates and income levels, and in particular provides a link between policy and growth. To date, however, there have been relatively few empirical tests of these models.[1]

Several recent case studies have attempted to analyze the connection between national policies and long-run. For example, Lucas 81993) compares the performance of the Philippines and South Korea; Young (1992) compares Hong Kong and Singapore; Romer (1993) draws a comparison between Mauritius and Sri Lanka; while Page (1994) compares the growth performance among the eight "East Asia miracle" countries. Yet, while these case studies have provided some insights into the determinants of growth, they cannot constitute a general analytical framework for the study of comparative economic growth.

Comparative growth studies using the neoclassical framework have continued to rely on cross-sectional regressions. In a celebrated paper, Mankiw, Romer and Weil (1992) [hereafter M-R-W] use cross-sectional regressions to address two major concerns with the textbook Solow-Swan model.[2] First, they explicity allow for variations in population growth and savings rates across countries, and show that the convergence prediction finds reasonable support from the data when each country's steady state is conditioned on these variables. Put another way, variations in population growth and savings behavior can explain a significant proportion of cross-country differences in income per capita.[3]

Second, M-R-W find that the predicted rate of (conditional) convergence is about double the observed rate. Equivalently, capita's observed share of GDP (about one-third) is only half the share implied by M-R-W's regression estimates.[4] These issues are addressed with the inclusion of human capital in the regressions. M-R-W argue that the resulting share estimates (approximately one-third each for physical capital, human capital, and labor) are plausible,[5] and conclude that

> "Overall, the findings ... cast doubt on the recent trend among economists to dismiss the Solow growth model in favor of endogenous-growth models that assume constant or increasing returns to scale in capital. One can explain much of the cross-country variation in income while maintaining the assumption of decreasing returns" (p. 409).

[1] Some recent exceptions include Arroyo, Dinopoulos and Donald (1994), Backus, Kehoe and Kehoe (1992), Caballero and Jaffe (1994), and Thompson (1995).

[2] See also Barro (1991), Barro and Lee (1993), Barro and Sala-i-Martin (1992), and Elias (1994).

[3] M-R-W obtain an adjusted R^2 ranging, across samples, from 0.06 to 0.59

[4] Barro and Sala-i-Martin (1992) also obtain this result for convergence regressions on state GDP in the United States.

[5] Human capital also increases the adjusted R^2 to a range of 0.26 to 0.78.

We remain skeptical that the substantive questions regarding comparative economic growth have been resolved. Questions have been raised elsewhere regarding the reliability of M-R-W's results,[6] and we will not discuss them here. We ought to comment, however, that their results for human capital are entirely consistent with a treatment of education as a consumption good which has no bearing on productivity, and thus the case for human capital as a major determinant of the standard of living is much weaker than it may appear.

Two features of the international post-war growth experience, which do not seem amenable to analysis with the textbook Solow-Swan model, merit particular mention:

(i) Although there is considerable evidence of long-run convergence, *on average*, this has been neither universal, nor monotonic. In M-R-W, all countries are assumed to have identical technologies, and thus deviations from the convergence predictions of the neoclassical model, and variations in growth rates, are *by construction* the result of transitory deviations from a common steady-state growth path. As is well known, the transition path to the steady-state in the textbook model is monotonic, and thus many growth experiences cannot be explained by imposing a common technology on all countries.[7]

(ii) The textbook model excludes by construction the potential role of international technology transfer through imitation. Technological followers would be fools not to imitate the leaders: it is likely to be cheaper and quicker. In fact, many of the major success stories in post-war growth can readily be explained by turning to examples of particularly rapid imitation of advanced countries' technologies.

The differences in long-run growth rates obtained in the endogenous growth models do not seem adequate these phenomena. In a two-country framework, balanced growth equilibria cannot generate plausible differences in long-run growth rates across countries.[8] The country with the lower steady-state growth disappears! On the other hand, out-of-steady-state analysis of the Solow-Swan model, extended to at least two state variables to allow for non-monotonic convergence paths, has proved to be analytically complicated.

In this paper, we introduce stochastic cycles which generalize the steady-state to allow for fluctuating growth regimes. Long-run fluctuations in growth

[6] See for example, Grossman and Helpman (1994) and Keller (1994).

[7] Non-monotonic convergence paths may be sufficient to explain the many instances of leapfrogging in GDP rankings among the large set of technological followers.

[8] Using the neo-Schumpeterian approach to growth, Dinopoulos and Syropoulos (1994) have generated steady-state differences in total factor productivity growth acriss countries. However, the growth rate of consumption per capita is identical across countries in the long run.

can be generated through shifts in technological opportunities.[9] Few would argue with the claim that technological innovations are not all equally valuable, and that innovation and imitation are not equally easy at all period in time. Some inventions and innovations have clearly had a major impact on the way we do business and, indeed, on who does business. Steam power and, later, electricity, revolutionized the textile industry; railroads opened America's mid-west; the internal combustion engine revolutionized transport. There are innumerable instances in which major changes in industries and trading patterns have been facilitated by specific innovations. The decline of the British textile industry is one case in point: power sources other than water enabled India and Japan, among others, to break Britain's domination of trade in textile. Another example is offered by Rosenberg (1982, p. 270), who credits the emergence of the Belgian and German steel industries to a British innovation in blast furnace design.

It must be emphasized that our approach differs from the real business cycle approach to economic fluctuations. The latter relies on stochastic fluctuations in the *level* of technology, whereas our approach assumes that the *rate* of technological change is subject to exogenous and stochastic fluctuations. We do not, therefore, subscribe to Schumpeter's (1939) characterization of technological waves as regular cycles. Nor are we persuaded by the evidence supplied by Mensch (1979), among others, purporting to show secular clustering in time of major innovations. Indeed, the credibility of long wave theories has suffered from the many uncritical adoptions of the early characterizations of long waves as regular cycles with predictable amplitudes and a stable periodicity. Nonetheless, there is a growing consensus that, at least, Western economic growth over the last 200 years or so has exhibited a number of distinct phases. We concur with the conclusion recently drawn by Angus Maddison (1991, p. 108):

> "The existence of *regular* long-term rhythmic movements in economic activity is not proven ... Nevertheless, it is clear that major changes in growth momentum have occurred since 1820,and some explanation is needed. In my view it can be sought not in systematic long waves, but in specific disturbances of and *ad hoc* character."

As a result of these disturbances, recent economic history can be described by phases of distinct *technological paradigms* which, as Carlota Perez (1985) has cogently argued, guides the investment and technological decisions of managers and the design of the organizations in which they operate.

[9] See Cheng and Dinopoulos (1993) and Dinopoulos and Thompson (1994) for closed-economy models with cyclical growth caused by shifts in technological opportunities.

Unequal technological opportunities and cyclical technological progress are not sufficient to generate cross-country differences in growth rates. The role of international technology transfer needs to be addressed as well. This is important, because countries which are technological laggards innovate primarily by *imitation*. Even if patent protection were perfect (which it clearly is not), imitators could exploit the "blueprints" of more advanced economies, thereby facilitating rapid growth through imitative innovation.[10] But just as innovation has been concentrated in a relatively small number of countries, so has imitation. Explaining this concentration of imitation is tantamount to explaining many of the growth miracles of the post-War period. We argue that the initial technological "distance" between laggards and leaders is a major determinant of the ease with which the laggards can imitate. Absent government intervention, initial conditions will therefore be the major determinant of the rate of growth.

One might expect that imitation and differences in initial technology levels will merely give added impetus to a process of convergence. Perhaps surprisingly, however, we can illustrate how rich patterns of comparative growth and technological evolution can be obtained in the presence of fluctuations in the rate of technical change. In Section 2, we describe our extension to the standard model, and show through simulation analysis how changes in the efficiency of imitation can generate a rich pattern of relative technology levels. It is shown that (i) monotonic convergence is a natural result if either technological fluctuations or imitation lags are absent from the model; (ii) fluctuations in the rate of technological advance slow down the rate of convergence below that predicted by the standard textbook model, without requiring a reinterpretation of the aggregate production function; (iii) relative technologies need not follow a monotonic path in the presence of lags and fluctuations, although we establish that convergence is guaranteed in an expectational sense. It follows that cross-sectional regressions of the sort carried out by M-R-W will always yield convergence results if the time-period is long enough, and the sample size large enough, even though no country converges monotonically. Furthermore, we need not be concerned by the fact that the textbook model predicts faster convergence than has been typically observed.

Section 3 concludes. To recapitulate, the main message of the present paper is to identify three independent features of the growth process which must be modeled simultaneously, if one wishes to explain the rich pattern of cross-country growth rates: cyclical technological evolution, a two-country framework, and an imitation lag in the acquisition of technology. We argue that the inclusion of technological lags and fluctuations in the Solow-Swan model accords well with the post-War diversity of growth experiences. However, it is our view that the

[10] Mansfield, Schwartz and Wagner (1981), who studied the imitation process of 48 product innovations in the chemical, drug, electronics and machinery industries, found that half of these innovations were imitated within four years after the introduction of new products.

study of comparative economic growth is unlikely to be much advanced by further empirical work within the standard neoclassical framework.

2. TECHNOLOGICAL FLUCTUATIONS AND TECHNOLOGY LAGS

Consider a two-country world with the home country being the advanced one. Using a discrete time notation, assume that aggregate output at time t is given by

$$Y_t = A_t N \tag{1}$$

$$Y_t^* = A_t^* N^* \tag{2}$$

where asterisks denote foreign fluctuations and variables. Equation (1) describes the aggregate production function of the home country, where Y_t is aggregate output, A_t is the level of technology,and N is population. Equation (2) states the aggregate production function in the foreign country. In order to emphasize the role of technology, we abstract from population growth and capital accumulation considerations. Our results are robust to the incorporation of these features into the model.

Growth per capita in the home country is determined by the evolution of technology. The rate of technological change in the home country, $\mu_t = (A_t - A_{t-1})/A_t$, is exogenous and follows a random walk with reflecting barriers at $\mu = 0$ and $\mu = \bar{\mu}$. The formalization of this assumption is somewhat awkward, but lends itself readily to the simulation we carry out below:

$$\mu_t = (-1)^{INT(z_t/\bar{\mu})}\left[z_t - 2\bar{\mu} \cdot INT\left(\frac{z_t + \bar{\mu}}{2\bar{\mu}}\right)\right] \tag{3}$$

$$z_t = |z_{t-1} + \varepsilon_t|, \quad E(\varepsilon_t) = 0, \quad E(\varepsilon_t \varepsilon_s) = \begin{cases} 0, & s \neq t \\ \sigma^2, & s = t \end{cases} \tag{4}$$

where $INT(\bullet)$ is the integer function, and z_t is a random walk. The continuous mapping $z_t \rightarrow \mu_t$ in (1) induces an upper reflecting barrier at $\mu_t = \bar{\mu}$, so that $\mu \in [0, \bar{\mu}]$, for all t.

Initially, the level of technology in the foreign country is lower. Technology is transferred from the home country to the foreign country through an exogenous imitation rate. Here, we follow a simplified version of Wan (1993) and assume that the rate of technical change in the backward country is related to the lagged rate of technological change in the leading country:

$$A*_{t+1} - A*_t = A_{t+1-L} - A_{t-L} \tag{5}$$

where L is a parameter denoting the technological distance between the two countries. If $L = 0$, imitation is immediate, while if $L > 0$, the foreign country is the technological follower. It is convenient, therefore, to assume that L is a linear function of the proportional difference in the two countries' technological levels:

$$L_t = INT\left(\gamma\left(\frac{A_t - A*_t}{A_t}\right)\right) \tag{6}$$

where the integer function here ensures compatibility with the discrete-time notation used.

The parameter γ captures a variety of forces determining the rate of technology transfer across countries (e.g. trade, multinationals, skilled labor migration, licensing, technological externalities, and government industrial policies). If γ increases, the foreign country is said to become less efficient at imitation; it is, in essence, imitating and adapting older technologies.

Equations (1) through (6) highlight the principal forces which determine relative income levels: the rate at which the frontier moves over time, and the efficiency with which the lagging country imitates. In order to focus on the role of technology, we assume that both countries instantaneously adjust to their steady state level of output. Because we are restricting analysis at this stage to steady-state equilibria and we do not consider difference sin savings rates or population growth, we are indifferent between analyzing GDP and technology levels, and choose to focus on the latter.

Two immediate conclusion can be drawn from equation (6). First, in the absence of fluctuations in the rate of technical change (i.e. if $\sigma^2 = 0$), long-run growth rates are equal in both countries. This conclusion holds, even in the presence of technological lags: the lagging country grows faster than the lead country, so that convergence in income levels is guaranteed. In other words, in the absence of fluctuations in the pace of technological change, the convergence result of the textbook neoclassical model is preserved. The second conclusion is that when $\gamma = 0$, then $\Delta A^*_t/A^*_t \rightarrow \Delta A_t/A_t$ monotonically. The absence of a technological lag implies convergence in growth rates, and in income levels, despite fluctuations in the long-run rate of growth.

In the general case, in which $\sigma^2 \neq 0$ and $\gamma \neq 0$, the model generates rich patterns of comparative economic growth. There may be, in this case, periods in which growth in the lead country exceeds that in the lagging country, while in other periods the reverse is true. These cases depend upon the current rate of advance of the technological frontier, compared with the rate of advance of the technologies that the lagging country is currently attempting to imitate. We show below, however, that over a sufficiently long period of time the lagging country will manage to catch up with the leader, although the path of relative technologies is clearly not monotonic. This prediction is consistent with the widely accepted empirical evidence that growth and income levels *per capita* are not highly correlated.

Figure 1 though 4 show the rich variety of growth patterns that can emerge in this model. Each figure reports the results of a simulation exercise conducted over 200 time periods. In each period, a random draw for ϵ_t was taken from a uniform distribution. The corresponding evolution of the rate of advance of the technological frontier was calculated according to equations (3) and (4), while technological change in the foreign country was calculated using (5) and (6). There are four panels in Figures 1 through 4. Panel (a) shows the log of technology levels, A_t and A^*_t ; panel (b) shows the growth rates of A_t and A^*_t ; panel (c) plots the relative technology ratio A^*_t/A_t ; and panel (d) plots the distance, L, that the foreign country lags behind the technology frontier.

In general the levels of technology grow relatively smoothly over time, with significant changes in the balanced-path rate of growth as each economy moves from high-growth regimes to low-growth regimes. Despite that fact that individual growth rates appear to be well behaved, the combined effect of technology lags and fluctuating growth regimes on *relative* technology levels can be rather dramatic. We consider four distinct cases, three of which are illustrated in at least one of the figures.

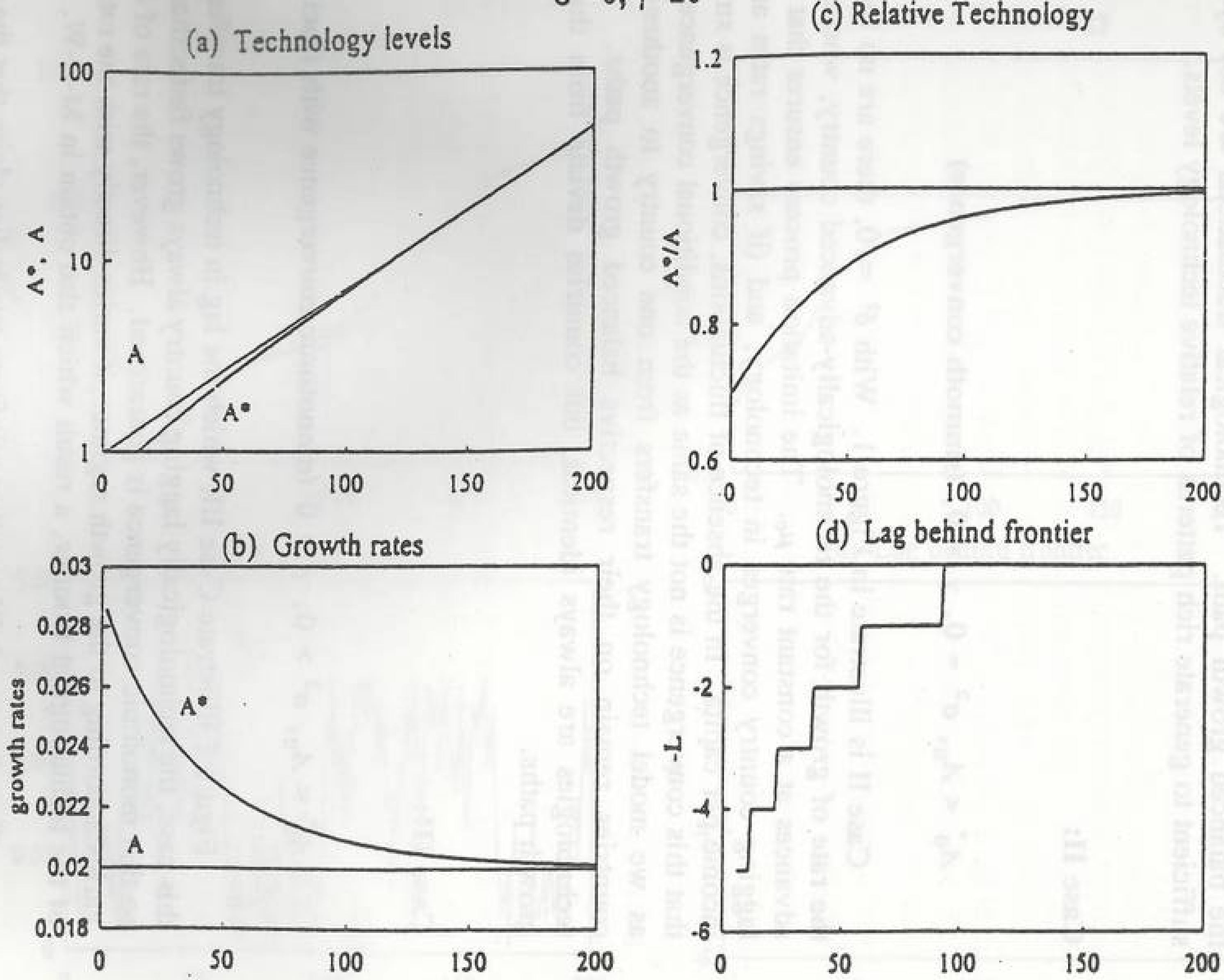
Case I:

$$A_0^* = A_0,\ \sigma^2 > 0,\ \gamma = 0,\ \text{(identical economies)}$$

FIGURE 1

NO FLUCTUATIONS

$\sigma = 0, \gamma = 20$



In case I, both economies have identical technologies at time $T = 0$. Although there are fluctuations in the rate of technological changes, the growth paths of these two economies *never* diverge. This is the M-R-W approach to comparative growth. When GDP figures differ between countries, it is necessarily the case that savings rates differ, or that at least one economy is off the balanced growth path. Technological fluctuations are not by themselves sufficient to generate rich patterns of relative technology levels.

Case II:

$A_0^* < A_0$, $\sigma^2 = 0$, $\gamma > 0$, **(smmoth convergence)**

Case II is illustrate in Figure 1. With $\delta^2 = 0$, there are no fluctuations in the rate of growth for the technologically-advanced country, whose technology advances at a constant rate μ_0. The imitation process ensures that the initially lagging country converges in technology, and (if savings rates are equal) in income per capita. In the absence of fluctuations, convergence is smooth. Note that this convergence is not the same as the conditional convergence of M-R-W, as we model technology transfers from one country to another while both countries remain on their respective balanced growth paths. In M-R-W, technologies are always identical, but countries deviate from their balanced growth paths.

Case III:

$A_0^* < A_0$, $\sigma^2 > 0$, $\gamma = 0$ **(monotonic convergence with fluctuations)**

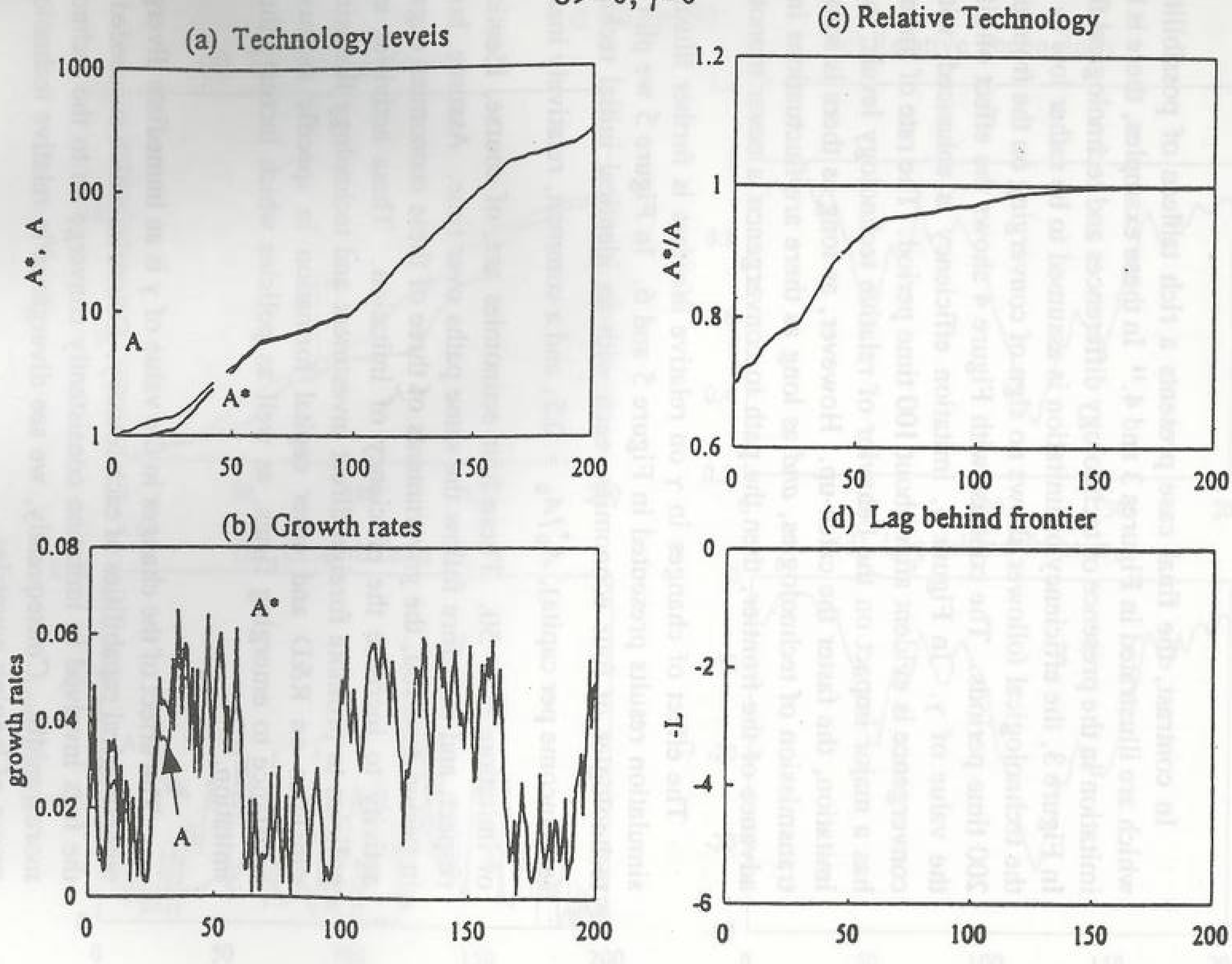
Figure 2 illustrate Case III, which the lag in technology transfer is zero. In this case, the technologically lagging country always grows faster than the leader, so that monotonic convergence is guaranteed. However, the rate of convergence varies according to the growth regime: it varies directly with the rate of advance of the technological frontier, a result which also obtain in M-R-W.

Cases I through III together reinforce our earlier claim that the rich tapestry of comparative growth experiences cannot be understood without both technological fluctuations *and* technological lags. If either characteristic is missing, then convergence is guaranteed.

FIGURE 2

NO LAG IN TECHNOLOGY TRANSFER

$\sigma >= 0, \gamma = 0$



Case IV:

$A_0^* < A_0$, $\sigma^2 > 0$, $\gamma > 0$, **(non-monotonic convergence)**

In contrast, the final case presents a rich tableau of possibilities, two of which are illustrated in Figures 3 and 4.[11] In these examples, there is both lagged imitation in the presence of technology differences and technological fluctuations. In Figure 3, the efficiency of imitation is assumed to be rather low ($\gamma = 50$), and the technological follower shows no sign of converging on the frontier even after 200 time periods. The contrast with Figure 4 shows the effect of differences in the value of γ. In Figure 4, imitation efficiency is enhanced, with $\gamma = 20$; convergence is evident after about 100 time period. The rate of imitation clearly has a major impact on the behavior of relative technology levels; the better the imitation, the faster the catch-up. However, as long as there is some lag in the transmission of technologies, *and* as long as there are fluctuations in the rate of advance of the frontier, then the path to convergence is never monotonic.

The effect of changes in γ on relative incomes is further illustrated by the simulation results presented in Figure 5 and 6. In Figure 5 we plot the relative technologies of four economies, each with an identical initial technology level (and income per capita), $A_0^*/A_0 = 0.5$, and a common, relatively inefficient, rate of imitation, $\gamma = 50$. These four economies are, of course, identical in every respect, and therefore follow the same paths over time. Assume, however, that in period $t = 100$, the governments of three of these economies engage in some activity to increase the efficiency of imitation. These activities may include policies to promote foreign direct investment and technology licensing, targeted subsidies on R&D and other capital formation in specific sectors, technical assistance to emerging firms, as well as policies which increase the returns to imitation.[12]

The effect of the changes in the value of γ is an immediate divergence of the technological capabilities of each country. Countries which succeeded in reducing the lags involved in imitation consistently converge on to the technology leader more rapidly. Consequently, we see divergence in relative technologies of this group of lagging countries.

[11] The examples in Figures 3 and 4 are based on the same draw of random numbers, ϵ.

[12] For example, the Chinese government's refusal to acknowledge international copyright laws has stimulated domestic production of compact discs and computer software.

FIGURE 3

LONG LAGS IN TECHNOLOGY TRANSFER

$\sigma > 0, \gamma = 50$

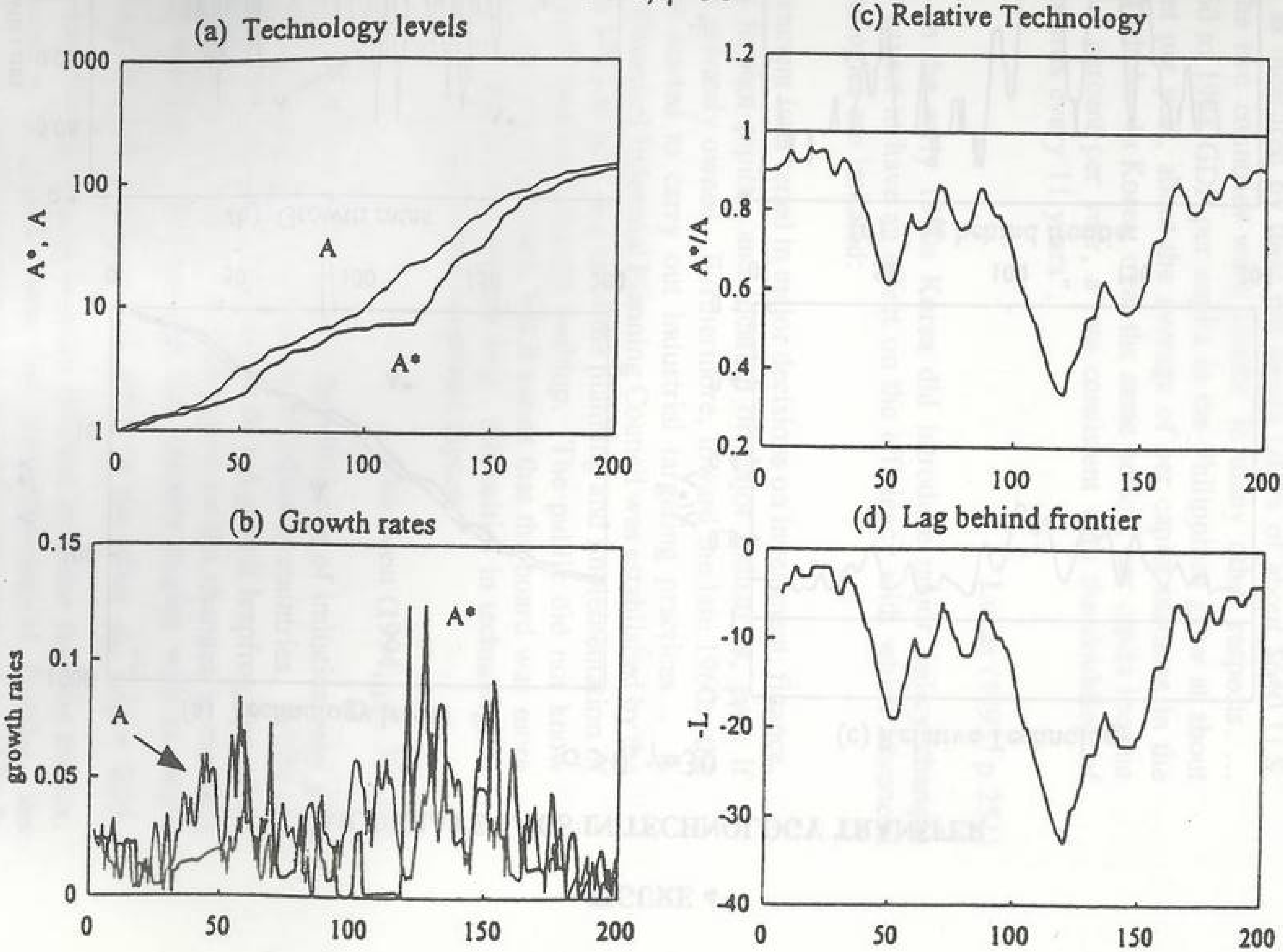
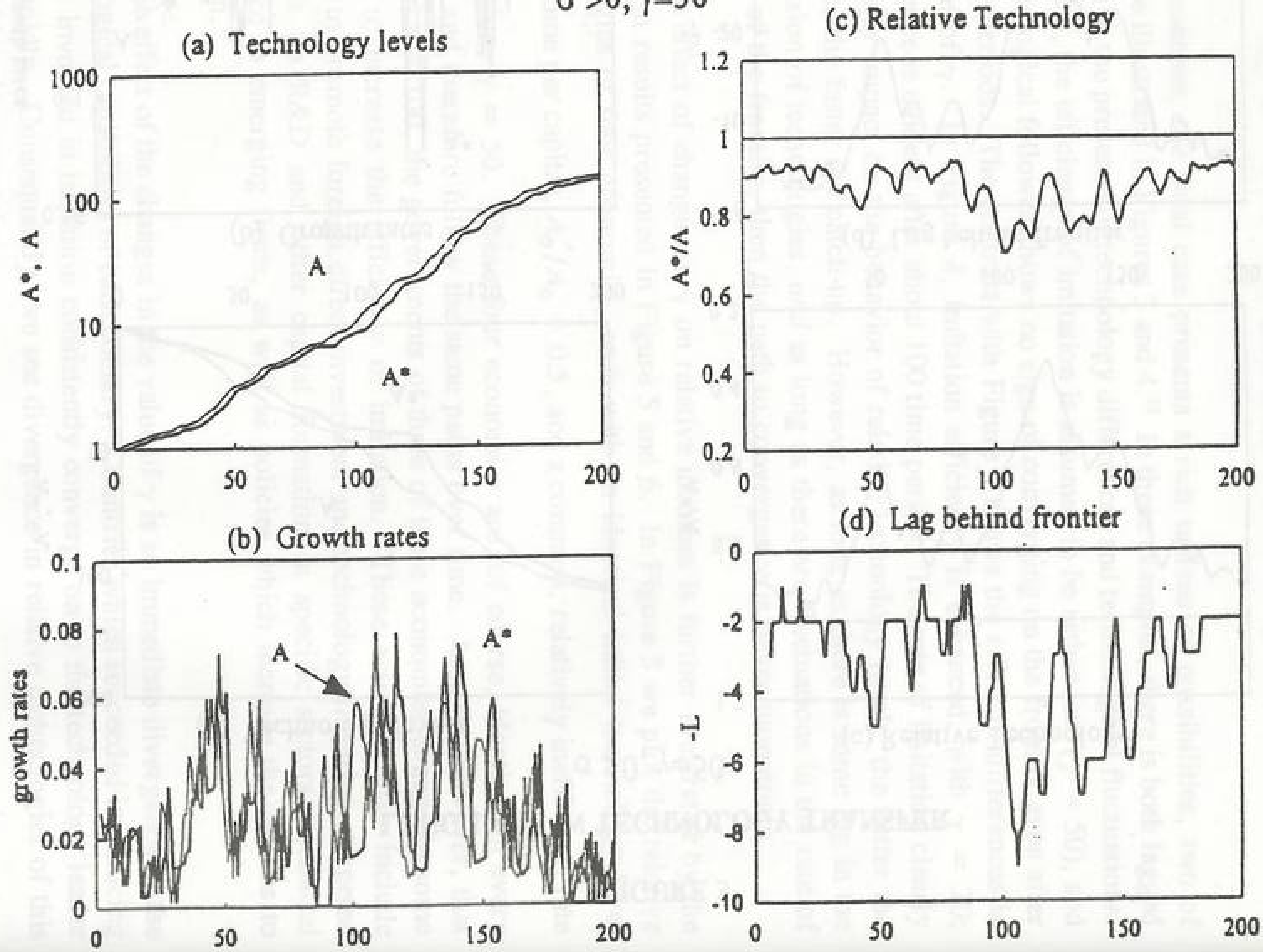


FIGURE 4

MODERATE LAGS IN TECHNOLOGY TRANSFER

$\sigma > 0, \gamma = 30$



Changes in the efficiency of imitation may be the answer to a puzzle to which Lucas 81993) recently drew our attention

> "In 1960, the Philippines and South Korea had about the same standard of living, as measured by their per capita GDPs of about $640 U.S. 1975. The two countries were similar in many other respects. ... From 1960 to 1988 GDP per capita in the Philippines grew at about 1.8 percent per year, about the average of per capita incomes in the world as a whole. In Korea, over the same period, per capita income grew at 6.2 percent per year, a rate consistent with the doubling of living standards every 11 years".

Lucas (1993, p.251)

Certainly, in the early 1960s Korea did introduce major policy changes which one may expect to have an effect on the efficiency with which advanced countries' technologies are imitated:

> "The government intervened in major decisions on investment, finance, imports of foreign capital, and location of major industries, even if firms were privately owned. Furthermore, toward the late 1960s, the government started to carry out industrial targeting practices... A Heavy and Chemical Industrial Planning Council was established by the president in 1973 to take charge of the planning and implementation of the heavy and chemical industry buildup. The public did not know exactly how the board operated, but it seems that the board was more concerned with engineering aspects (e.g., difficulties in technological developments or locations) than economic aspects."

Cho Soon (1994, pp. 33, 41)

Figure 6 illustrates how differences in the efficiency of imitation may give rise to instance of leapfrogging in the ranking of follower countries. While our assumptions about the evolution of technology do not permit leapfrogging of the technology leader there are *few a priori* restrictions on the changes in rankings of the remaining countries. In Figure 6, one country begins with as initial relative technology level of $A_0^*/A_0 = 0{,}5$, while in the other $A_0^{**}/A_0 = 0.25$. However, the latter country engages in more efficient imitation than the former. Given the realization of growth rates for the technological frontier, the technologically inferior country converges on the leader monotonically, while in the other, convergence is non-monotonic. The lagging country soon leapfrogs the lead country. As the simulation shows, however, there may be more than one crossing of relative technology levels, but eventually, the effect of the greater efficiency of imitation dominates the initial conditions.

FIGURE 5
CHANGES IN THE EFFICIENCY OF IMITATION

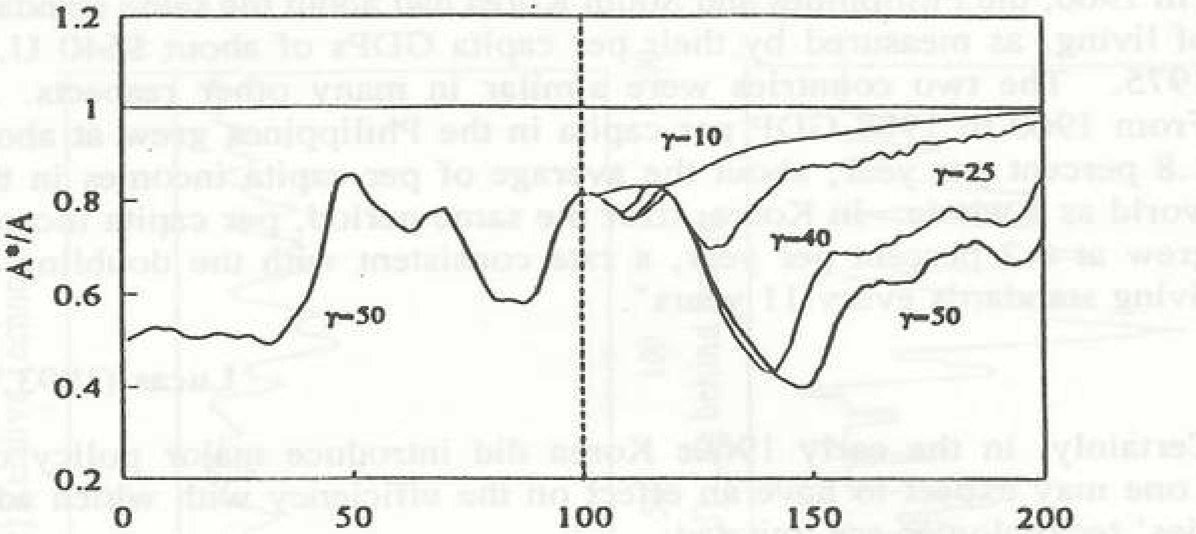
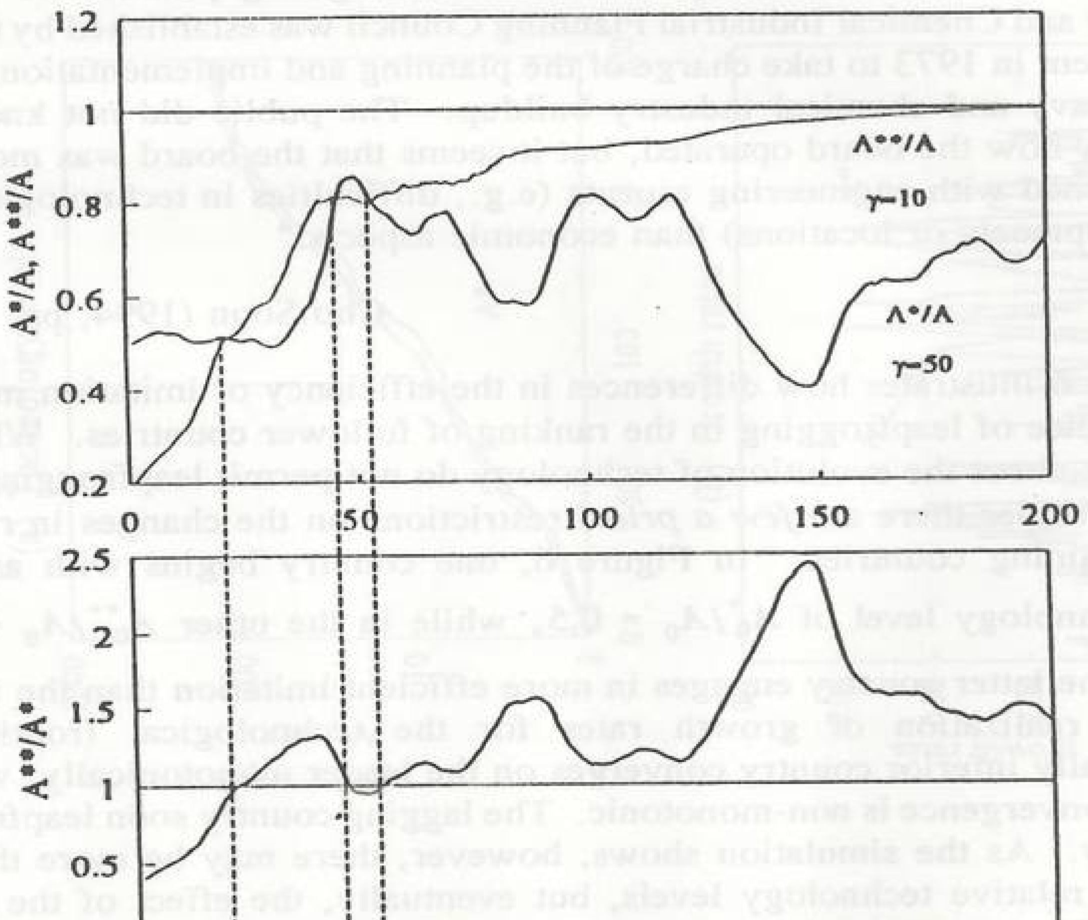


FIGURE 6
THE EFFICIENCY OF IMITATION AND LEAPFROGGING



It is easy to establish that these simulation results are not atypical. Let $\Lambda_t = A_t^*/A_t$. Then,

$$\Lambda_{t+1} = \frac{A_t^* \ (1 + \mu_{t+1-L}/\Lambda_t)}{A_t \ (1 + \mu_{t+1})} \quad (7)$$

and it is easy to show that

$$\Delta_{t+1} = \frac{\Lambda_{t+1} - \Lambda_t}{\Lambda_t} = \left(\frac{1}{1 + \mu{-t+1}}\right)\left(\frac{\mu_{t+1-L}}{\Lambda_t} \ \mu_{t+1}\right) \tag{8}$$

In the absence of fluctuations in growth, $\mu_{1+1-L} = \mu_{t+1} = \mu_0$, and

$$\Delta_{t+1} = \frac{\mu_0}{1 + \mu_0}\left(\frac{1}{\Lambda_t} - 1\right) \tag{9}$$

from which we can establish that (i) Δ_{t+1} is an increasing function of the growth rate, μ_0; (ii) Δ_{t+1} is a decreasing function of the level of relative technology, Λ_t, and, (iii) $\lim_{\Lambda \to 1} \Delta_{t+1} = 0$. These are, of course, results which obtain in the standard model.

Turning now to the case in which there are fluctuations but not lags in technology transfer, we need to take conditional expectations of (8), after setting μ_{t+1-L} equal to μ_{t+1}:

$$E_t\Delta_{t+1} = E_t\left[\frac{\mu_t + 1}{1 + \mu_{t+1}}\right]\left(\frac{1}{\Lambda_t} - 1\right) \tag{10}$$

As $\mu/(1+\mu)$ is an increasing concave function of μ, we can readily establish that the expected rate of convergence, $E_t\Delta_{t+1}$, is (i) an increasing function of the average rate of growth, $E_t(\mu_{t+1})$; (ii) a decreasing function of the conditional variance of growth, σ^2, and; (iii) a decreasing function of Λ_t. Thus, as in the case of no fluctuations, relative technology converges to unity at a rate which varies directly with the expected growth rate. However, the expected rate of convergence varies inversely with the variance of growth,and hence fluctuations are sufficient to lower the average rate of convergence below that predicted by the standard model. It follows, that even withhout the inclusion of human capital, we should not expect to see convergence rates as high as those predicted by the standard neoclassical model.

Finally, we consider the general case of imitation lags and fluctuations. In this case, taking expectations of (8) yields:

$$E_t\Delta_{t+1} = \frac{\mu_{t+1-L}}{\Lambda_t} E_t\left(\frac{1}{1+\mu_{t+1}}\right) - E_t\left(\frac{\mu_{t+1}}{1+\mu_t+1}\right)$$

$$\geq \frac{\mu_{t+1-L}}{\Lambda_t}\left(\frac{1}{1+E_t(\mu_{t+1})}\right) - \frac{E_t(\mu_{t+1}}{1+E_t(\mu_{t+1})}$$

$$= \frac{1}{1+E_t(\mu_{t+1})}\left[\frac{\mu_{t+1-L}}{\Lambda_t} - E_t(\mu_t)\right] \tag{11}$$

where the second line was obtained by means of Jensen's inequality. Because μ has reflecting barriers at 0 and $\bar{\mu}$, $E_t[\mu_{t+1} | \mu_t] > (<) \; 0$ as $\mu_t < (>) \bar{\mu}/2$. Hence, (11) is ambiguous in sign. For μ_{t+1-L} sufficiently small, $E[\mu_{t+1}]$ may exceed μ_{t+1-L}/Λ_t. Fortunately, we can exploit the symmetry of conditional expectations for values of μ_{t+1-L} around $\bar{\mu}/2$: Let $x_t \in [0, \bar{\mu}/2]$. Then,

$$E_t\,[\mu_{t+l} | \mu_t = \bar{\mu}/2 + x_t] - \bar{\mu}/2 = \bar{\mu}/2 - E_t[\mu_{t+1} | \mu_t = \bar{\mu}/2 - x_t] \tag{12}$$

and integrating (11) over all possible values for μ_{t+1-L}, we obtain:

$$\int_0^{\bar{\mu}} E_t\Delta_{t+1}\, dF(\mu) \geq \int_0^{\bar{\mu}} \left(\frac{\mu}{(}\Lambda_t\; E(\mu_t | \mu\right)\left(\frac{1}{1+E(\mu_t | \mu)}\right) dF(\mu)$$

$$= \frac{1}{\Lambda_t} \int_0^{\bar{\mu}} \left[\frac{\mu}{1 + E(\mu_t | \mu)} \right] dF(\mu) - \int_0^{\bar{\mu}} \left[\frac{E(\mu_t | \mu}{1 + E(\mu_t | \mu)} \right] dF(\mu)$$

$$\geq \frac{1}{\Lambda_t} \int_0^{\bar{\mu}} \left[\frac{E(\mu_t | \mu)}{1 + E(\mu_t | \mu)} \right] dF(\mu) - \int_0^{\bar{\mu}} \left[\frac{E(\mu_t | \mu)}{1 + E(\mu_t | \mu)} \right] dF(\mu)$$

$$= \left(\frac{1}{\Lambda_t} - 1 \right) \int_0^{\bar{\mu}} \left[\frac{E(\mu_t | \mu)}{1 + E(\mu_t | \mu)} \right] dF(\mu)$$

$$\geq 0 \tag{13}$$

where there third line exploits (12) and the concavity of $\mu/(1 + \mu)$.

Thus, if we take a long-enough time period, we would expect to see convergence in the sense that there is, on average, faster growth in countries whose technologies are initially lagging. This is not the same as saying that we would expect to see convergence in the short-run at any given point in time.

3. CONCLUSIONS

One of the major challenges of comparative economic growth is to explain how rich patterns of relative growth can arise within the framework of a single model. We argue that the standard neoclassical model of growth, in which all countries have access to the same technology and in which the rate of technological change is constant over time, is ill-equipped to address this issue. Mankiw, Romer and Weil (1992) test the standard model under just these assumptions. They find that, although the convergence property of the Solow model is supported by the data, the actual rate of convergence is too slow. Their solution is to introduce human capital as a third factor of production, which lower the share of labor in GDP, and consequently slows down the predicted rate of convergence.

In this paper we take an alternative route which does not rely on the introduction of new factors of production into the aggregate production function. We argue that fluctuations in the rate of technological advance are an observable feature of the data, and the they have important implications for the expected rate of convergence. We show that when the rate of technological advance fluctuates, the rate of convergence predicted by the textbook neoclassical model represents an upper bound to the rate which we should observe.

However, even with fluctuations, convergence is still monotonic. We further extend the standard model to allow for differences in the efficiency with which technological followers imitate technologies being developed at the frontier. Lags in technology transfer by themselves have no impact on the convergence properties of the model, but when combined with fluctuations a rich pattern of relative growth experiences can emerge. We provide simulated examples of non-monotonic convergence paths, divergence and leapfrogging. Our simulations concentrate on technology levels or –equivalently– steady-state growth paths in which all countries have identical saving rates and population growth rates. It should be apparent that even richer possibilities for relative growth can emerge when differences in steady-states are considered.

M-R-W note that despite their positive conclusion on the Solow-Swan model, it

> "does not imply that the Solow model is a complete theory of growth: one would like also to understand the determinants of saving, population growth and worldwide technological change, all of which the Solow model treats as exogenous. Nor does it imply that endogenous growth models are not important, for they may provide the right explanation of worldwide technological change".
>
> Mankiw, Romer and Weil (1992, p. 409).

Similarly, ours is not a complete model of growth. In particular, we would like to understand the causes of technological fluctuations and differences in the efficiency of imitation.[13] We believe that neither of these can be understood withhout a serious analysis of the determinants of innovation and imitation. We believe that innovation and imitation are not independent of the market structure and government policy. We consequently believe that the answers to these questions require further advance in the theory of endogenous growth.

[13] In Lucas' (1993) model of learning by doing, growth miracles can occur when a country engages in some policy to concentrate its labor force more heavily in industries which lie closer to the technological frontier.

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