R&D, Implementation and Stagnation: A Schumpeterian Theory of Convergence Clubs*

By Peter Howitt† and David Mayer-Foulkes‡

August 2, 2004

We provide a theoretical explanation, based on Schumpeterian growth theory, for the divergence in per-capita income that has taken place between countries since the mid 19th Century, as well as for the convergence that took place between the richest countries during the second half of the 20th Century. The argument is based on the premise that technological change underwent a fundamental transformation in the 19th Century, associated with new scientific ideas and the increasingly scientific content of new technologies. We model this transformation as the introduction of a new method for producing innovations, which we call "modern R&D". In order to use this method a country's entrepreneurs must have at least some minimum level of skills, which depends on the technological frontier. Countries not fulfilling this requirement can only create new technologies through an older method, which we call "implementation". A multi-country Schumpeterian growth model incorporating these ideas implies that countries will sort themselves into three groups. Those in the highest group will converge to an "R&D steady state", while those in the intermediate group converge to an "implementation steady state". Countries in both of these groups will grow at the same rate in the long run, as a result of technology transfer, but inequality of per-capita income between the two groups will increase during the transition to the steady state. Countries in the lowest group will grow at a slower rate, with relative incomes that fall asymptotically to zero. Which group a country belongs to in the long run will depend on initial conditions as well as on fundamentals. More specifically, once modern R&D has been introduced, a country may have only a finite window of opportunity in which to raise its skill levels to those required for R&D, failing which the country will remain trapped in implementation or stagnation even if it adopts the same policies and institutions as the world's technology leaders.

*The authors wish to thank Philippe Aghion, Jess Benhabib, Oded Galor and Steve Redding for helpful comments and conversations. Useful comments were received from an anonymous referee and from seminar participants at the 2001 NBER Summer Institute, Boston University, Brown University, North Carolina State University, the University of Quebec at Montreal, the University of Western Ontario, the Canadian Institute for Advanced Research, the Minerva Center for Macroeconomics and Growth, and the Ohio State University.

†Corresponding author. E-mail: peter_howitt@brown.edu. Address: Department of Economics, Box B, Brown University, Providence, RI 02906.

‡División de Economía, Centro de Investigación y Docencia Económicas, Mexico. E-mail: david.mayer@cide.edu

"The greatest invention of the 19th Century was the invention of the method of invention." Alfred North Whitehead (1931, p. 98)

"Countries that are technologically backward have a potentiality for generating growth more rapid than that of more advanced countries, provided their social capabilities are sufficiently developed to permit successful exploitation of technologies already employed by the technological leaders." Moses Abramovitz (1986, p.225)

"Lack of investment in an area of expertise early on may foreclose the future development of a technical capability in that area." Wesley Cohen and Daniel Levinthal (1990, p.128)

1 Introduction

The history of cross-country income differences exhibits mixed patterns of convergence and divergence. The most striking pattern over the long run is the "great divergence" - the dramatic widening of the distribution that has taken place since the early 19th Century. Pritchett (1997) estimates that the proportional gap in living standards between the richest and poorest countries grew more than five-fold from 1870 to 1990, and according to the tables in Maddison (2001) the proportional gap between the richest group of countries and the poorest[1] grew from 3 in 1820 to 19 in 1998. But over the second half of the twentieth century this widening seems to have stopped, at least among a large group of nations. In particular, the results of Barro and Sala-i-Martin (1992), Mankiw, Romer and Weil (1992) and Evans (1996) seem to imply that most countries are converging to parallel growth paths.[2]

However, this recent pattern of convergence is not universal. In particular, the gap between the leading countries as a whole and the very poorest countries as a whole has continued to widen. The proportional gap in per-capita income between Mayer-Foulkes's (2002) richest and poorest convergence groups grew by a factor of 2.6 between 1960 and 1995, and the proportional gap between Maddison's richest and poorest groups grew by a factor of 1.75 between 1950 and 1998. Thus as various authors[3] have observed, the history of income differences since the mid 20th Century has been one of club-convergence.

According to a large number of empirical studies, cross-country differences in per-capita GDP growth rates are mainly attributable to different rates of productivity growth, rather than to the differences in schooling and capital accumulation invoked by neoclassical growth theory. Easterly and Levine (2001) attribute about 60% of the cross-country variation in per-capita GDP growth rates to differences in productivity growth,

[1] The richest group was Western Europe in 1820 and the "Euopean Offshoots" (Australia, Canada, New Zealand and the United States) in 1998. The poorest group was Africa in both years.

[2] In what follows "convergence" is defined in this sense, to mean convergence in growth rates. Although the neoclassical growth model with instantaneous technology transfer exhibits convergence in growth rates, nevertheless the concept is not the same as the more familiar "conditional convergence," which means (Galor, 1996) that countries with the same characteristics converge to the same growth path. For example, in the case of multiple steady states of the sort illustrated in Figure 3 below, countries with the same characteristics but different initial conditions could converge to different growth paths but with the same growth rate. Conversely, in a model of conditional convergence, countries with one set of characteristics could all converge to a growth path that was not parallel to the common asymptotic path of countries with a different set of characteristics.

[3] Baumol (1986), Durlauf and Johnson (1995), Quah (1993, 1997) and Mayer-Foulkes (2002, 2003).

while Klenow and Rodríguez-Clare (1997) attribute about 90% of it to differences in productivity growth. In light of these studies[4], any explanation of the great divergence and recent club-convergence needs to focus on the main driving force of long-run productivity growth, namely technological progress.

There is a problem however with any technological explanation of divergence, namely that technology transfer should act as a force for convergence, because of the "advantage of backwardness" (Gerschenkron, 1952) that it confers on technological laggards. This is why almost every existing theory of international income differences that takes technology transfer into account implies that all countries share the same long-run growth rate, including those in which technologies developed on the frontier are not "appropriate" for poorer countries (Basu and Weil, 1998; Acemoglu and Zilibotti, 2001), those in which technology transfer can be blocked by local special interests (Parente and Prescott, 1994, 1999) and those in which a country adopts institutions that do not permit full advantage to be taken of technology transfer (Acemoglu, Aghion and Zilibotti, 2002). None of them can therefore explain how a country's growth rate could remain significantly below that of the rest of the world for almost two centuries.

So what force was opposing technology transfer so as to produce the technological divergence that took place over the longer period from the early 19th Century, and which to some extent still remains? And why did that force stop working for a large group of countries during the second half of the 20th Century, but not for the poorest countries?[5] The purpose of this paper is to address these questions using modern innovation-based growth theory.

We take a variant of the Aghion-Howitt (1992, 1998) model of growth, in which international technology transfer takes place in just the same way as cross-industry technology spillovers, and show that in this model technology transfer is not always strong enough to keep all countries growing at the same rate in the long run. In particular, countries in which parameter values are sufficiently favorable to innovation will all converge to the same frontier growth rate (which is endogenously determined in the model) but others will grow at a strictly lower rate that depends on local parameter values. We go on to show that this model provides an account of the great divergence and recent club-convergence.

There are three key components to our argument. The first is that technology transfer is a difficult, skill-intensive process. The receiving country cannot just take foreign technologies off the shelf and implement them costlessly. Instead, the country must make technology investments of its own to master foreign technologies and adapt them to the local environment, because technological knowledge is often tacit and circumstantially specific.[6] Although in some countries these investments may not involve scientists and high

[4] See also Knight, Loayza and Villanueva (1993), Islam (1995), Caselli, Esquivel and Lefort (1996), Prescott (1998), Hall and Jones (1999) and Feyrer (2001).

[5] Except for a small number of formerly poor "miracle" countries such as Botswana, China, Mauritius and the East Asian NICs.

[6] See Arrow (1969) or Evenson and Westphal (1995).

tech labs, and hence would not fit the conventional definition of R&D, nevertheless they play much the same role as R&D in an innovation-based growth model. That is, they generate new technological possibilities in the country where they are conducted, building on knowledge that was created previously elsewhere. As Cohen and Levinthal (1989) and Griffith, Redding and Van Reenen (2001) have argued, each act of technology transfer requires an innovation on the part of the receiving country, and thus R&D or more generally technology investment is a necessary input to the process of technology transfer.

By integrating technology transfer into an innovation-based growth model where the innovation process is skill-intensive we are building a theory of what Nelson and Phelps (1966) called "absorptive capacity." In the original Nelson-Phelps model, absorptive capacity was assumed to be a function of human capital. Our theory represents an attempt to open the black box of that function by linking it to the broader theory of innovation-based growth.[7]

The second key component is the assumption that a country's stock of "effective skills" that can be used in innovation depends on its level of development, relative to the global technological frontier from which it draws new ideas. There are two parts to this component. The first is a human-capital externality of the sort now familiar in growth theory. That is, a given time input into schooling/training will produce fewer effective skills in a country that is technologically backward, because learning takes place in an environment where modern technology is relatively unfamiliar, teachers are not as well versed in modern techniques, classrooms and labs are less up-to-date, and so forth. The second part is an effect of increasing complexity and "fishing out." That is, as the global technology frontier advances and becomes more complex a country needs to keep increasing its skill levels just in order to keep pace with the frontier. Because of the combination of the human capital externality and the fishing-out effect, a country that does not keep pace with the frontier will find it increasingly difficult to catch up, because its absorptive capacity will erode. This erosion of absorptive capacity in technological laggards is a central part of our explanation of long-term divergence.

The third key component is a hypothesis that the main driving force behind both the great divergence and the recent club-convergence was the growth of a new set of scientific ideas and attitudes associated with the scientific revolution, what Crosby (1997) calls a quantitative, analytical "mentalité". The rise of modern economic growth starting with the first Industrial Revolution was closely associated with these ideas and attitudes.[8] A new perspective of nature founded on scientific achievements, sustaining ever deeper advances of knowledge, brought about a new era of technological change. This movement culminated in the late 19th Century with the introduction of the modern R&D lab, which exploited the growing interconnections

[7] See Foster and Rosenzweig (1996) and Griffith, Redding and Van Reenen (2001) for evidence that skills are an important determinant of a country's absorptive capacity. Benhabib and Spiegel (2002) also find that convergence-club membership is well explained by differences in human capital.

[8] See Jacob (1997) and Mokyr (2002).

between science and technology, and the rise of various institutions such as government research labs and agencies, scientific academies, universities with close ties to industry and commerce, and so forth.[9] But it started much earlier, well before the modern R&D lab became an important force.

In order to integrate this force into our analysis we model it as the introduction of a new method for technological change, which we call "modern R&D", or for short just "R&D". For simplicity we suppose that instead of diffusing gradually the new method was introduced discontinuously at a single point in time. Before this, we assume that all technological change took the form of a pragmatic creativity that we call "implementation." R&D is what goes on in the most technologically advanced countries, while implementation is the process of assimilation and adaptation that still takes place in less advanced countries. We suppose that both kinds of technology investment are costly and skill intensive, and both draw on the world's technology frontier, but R&D draws more heavily on scientific knowledge, and thus requires higher skill levels than implementation. In particular, graduating from implementation to R&D requires surpassing a threshold skill level that increases with the demands of new, ever advancing, leading technologies.

First we lay out our model and solve it for the dynamics of productivity differences and of the world growth rate, showing the conditions needed for a country to converge to the growth rate of the global technology frontier. We then show how the model can replicate the great divergence and the recent club-convergence as a response to a single event, namely the introduction of modern R&D at some time t_0. In the model this event leads to a trifurcation of countries, creating three distinct convergence groups. A sketch of our argument goes as follows.

Suppose that before t_0 all countries were on parallel growth paths, with some level-differences attributable to differences in country-specific parameters. Figure 1 depicts the evolution of productivity in three countries, one in each convergence group. Country A has the "best" parameter values (i.e. those most favorable to innovation) and country C the worst. After t_0 only those countries whose productivity level exceeds some critical value will have a skilled enough labor force to begin using modern R&D immediately. (In Figure 1 this is only country A.) Those that do will start growing faster as a result of using the more productive (R&D) method of technology investment. All others will continue using implementation, and will start to fall further behind country A.

[9] Edison's research lab in Menlo Park, generally considered the first modern "invention factory," opened in 1876. Rosenberg and Birdzell (1986, ch.8) provide a brief account of the rise of the modern R&D lab and the increasing interconnectedness between science and technology, which they argue began around 1875. Mowery and Rosenberg (1998, ch.2) and Wright (1999) argue that a network of linkages between universities, government agencies and commercial enterprises played a key role in establishing America's technological leadership in many fields.

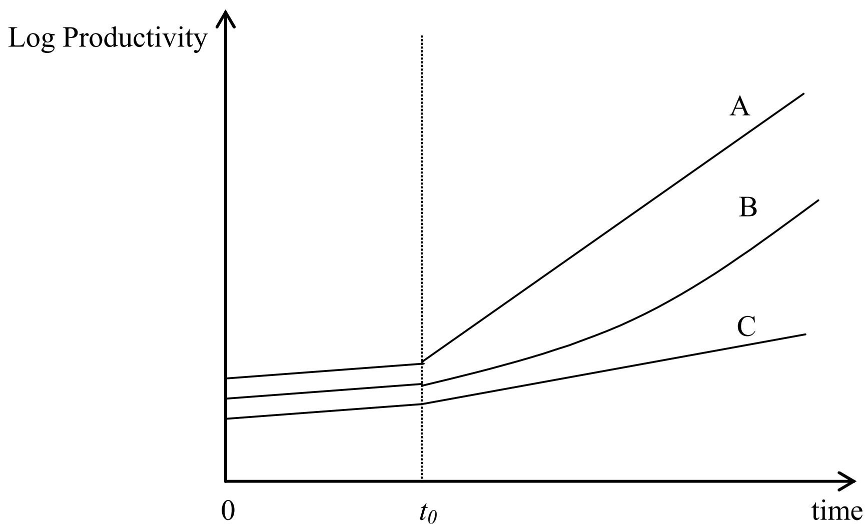

Figure 1

As the other countries fall further behind, technology transfer will start to pull their growth rates up, but until their growth rates have caught up with the growth rate of the frontier, the erosion of absorptive capacity engendered by their increasing technological backwardness will tend to weaken the force of technology transfer. In countries that are not too far behind to start with, absorptive capacity will remain strong enough to eventually put them on growth paths parallel to that of country A, but with a permanently bigger gap in productivity levels, as in the case of country B; the initial gap that was due to different parameter values is now amplified by the fact that country A has adopted modern R&D while country B has not. But if the country starts too far behind (as with country C) then the erosion of absorptive capacity will weaken the force of technology transfer to such an extent that, although the country will continue to grow forever, its asymptotic growth rate will be strictly less than the common long-run growth rate of countries A and B.

As in the historical record, the dominant long-run pattern in Figure 1 is a great divergence - - a widening in the distribution of the cross-country distribution of productivity - - but the dominant pattern in the most recent era is club-convergence, with countries like A and B all growing at some common rate and the poorest countries like C growing more slowly.

The model we use is somewhat similar to the multi-country growth model of Howitt (2000), which also generates a form of club-convergence. The difference is that the earlier model did not represent innovation as being skill-intensive, and did not allow for different methods of technology investment (implementation and R&D).[10] The earlier model could only create a limited form of club-convergence, in which one group

[10] Only a small handful of rich countries perform leading-edge R&D. In 1996, for example, 5 countries accounted for over 80 percent of the world's formal R&D expenditures, and 11 countries accounted for over 95 percent.

of countries grows at the same rate as the global technology frontier while others (who are in a corner solution doing no R&D) do not grow at all.[11] Moreover in the earlier model the introduction of modern R&D could not create divergence if there was none to begin with. This is because the crucial effect by which an acceleration of the global technology frontier erodes the absorptive capacity of a laggard depends on the assumption that innovation is skill intensive, which assumption is missing from the earlier model.[12]

A very different approach to understanding the broad facts of divergence and convergence is to see convergence as the only possibility in the long run. Thus for example Lucas (2000) believes that the great divergence is a transitory phenomenon, arising from the fact that different countries have made the transition to modern economic growth at different points in time. Those who made the transition earliest pulled ahead of the others, but one by one the others are joining the growth club. Eventually when all countries have made the transition they will all be once more on parallel growth paths. According to this view, joining the growth club is just a matter of adopting the kinds of policies and institutions that would make a country able to benefit from technology transfer and thus eligible to join the modern growth club.

This viewpoint, which we suspect is held by many macroeconomists, contrasts with ours on several points. First, it is not based on an explicit model of technology transfer that can explain what kind of "transition" is needed and why a country's long-run growth rate must be less than that of the world's technology leaders before the transition occurs despite the convergence-inducing effect of technology transfer, whereas we build our account on an explicit model of endogenous technology transfer. Second, we find it more persuasive to characterize the last two centuries of history as the long run rather than "transitory". Third, our account is more parsimonious, in the sense that it depends on a single global event, to which different countries responded differently, depending on their parameters and initial conditions and depending on each other's reactions, rather than relying on a sequence of independent shocks, each initiating a "transition" of a different country.[13]

The fourth point of contrast is that our account implies a path-dependency that is missing from the "transitory divergence" viewpoint. In our account there is nothing automatic about technology transfer that would ensure convergence if some institutional or policy barrier were simply removed. On the contrary, whether or not a country converges will depend not only on its policies and institutions but also on historically predetermined initial conditions. That is, the dynamics of productivity growth in any given country may

[11] Absolute stagnation by the lagards is also counterfactual, because not even those countries at the bottom of the distribution have been completely stagnant technologically. According to Maddison's (2001) tables, per-capita income in the poorest group of countries (Africa) grew by 60 percent from 1950 to 1998.

[12] The recent model of Aghion, Howitt and Mayer-Foulkes (2004) provides a similar analysis of convergence clubs based on financial constraints rather than skill levels.

[13] An alternative unified theory of divergence and the origins of modern growth is presented by Galor and Mountford (2003), in which the interdependencies between nations are channeled through the terms of international trade rather than through technology tansfer.

exhibit multiple steady states. We illustrate this below by showing that a country that is not in the highest convergence club, doing modern R&D, may have only a finite window of opportunity in which to join that club by changing its policies and/or institutions, after which it will be too late to join even if it mimics the policies and institutions of countries that are already in the club.

Our account is consistent with the dynamical features observed by Feyrer (2001) who notes that Quah's (1993, 1997) finding of "twin peaks" emerging in the distribution of world income is mainly attributable to diverging total factor productivity rather than diverging capital accumulation or education. (We abstract completely from capital accumulation, and time spent in education is assumed constant in each country.) As Feyrer notes, models constructing development traps based on multiple equilibria in physical or human capital accumulation (such as Becker and Barro, 1989; Murphy, Shleifer and Vishny, 1989; Azariadis and Drazen, 1990; Becker, Murphy and Tamura, 1990; Tsiddon, 1992; Galor and Zeira, 1993; Durlauf, 1993, 1996; Zilibotti, 1995; Galor and Weil, 1996; Bénabou, 1996 and Galor and Tsiddon, 1997) are inconsistent with this observation.

Section 2 below lays out our basic model, under the assumption that there is just one method for investing in technological change. It uses this model to analyze the determinants of the world growth rate and of each country's relative productivity, both in and out of steady state, before the introduction of modern R&D. Section 3 then shows what happens if we start in the steady state and introduce modern R&D, assuming that some countries can use the new method but some lack the necessary skill levels. It shows how countries sort themselves into the three convergence groups depicted in Figure 1. Section 4 then analyzes the role of initial conditions in determining long-run group membership and creating windows of opportunity. Section 5 contains our concluding remarks.

2 The basic model

We analyze a simple multi-country innovation-based growth model, in which innovations in any country require private inputs, in the form of materials and entrepreneurial skills, and a public input in the form of the world-wide stock of technological knowledge, whose value at each date t is $\overline{A}_t$. Innovations also feed back into this stock of knowledge, making the global growth rate $g_t \equiv \frac{\overline{A}_{t+1}-\overline{A}_t}{\overline{A}_t}$ proportional to the rate of innovation in leading countries. Countries are thus connected through the shared stock of knowledge $\overline{A}_t$. For simplicity we ignore all other connections, by assuming that countries do not exchange products or factors of production with each other. We begin by analyzing an isolated country, in which there is just one method of innovation; that is, before the introduction of modern R&D. To help the reader follow the analytical derivation the following table lists the variables used, in the order that they will be introduced.

Variable	Meaning
$\overline{A}_t$	global technology frontier
g_t	growth rate of global technology frontier
β	parameter representing the incentive to save
ψ	parameter representing non-technological influences on TFP
L	population and labor supply
$x_t\,(i)$	input of intermediate good i at date t
$A_t\,(i)$	technological productivity parameter of intermediate good i
$p_t\,(i)$	price of intermediate good i
α	Cobb-Douglas exponent of intermediates in general-good production
χ	unit cost of the competitive fringe in each intermediate sector
$\pi_t\,(i)$	profit in intermediate sector i
A_t	average productivity parameter across all sectors
G_t	growth rate of A_t
S_t	skill level of entrepreneurs
μ_t	innovation rate
λ	parameter representing the efficiency of the innovation technology
z_t	material input to innovation
η	Cobb-Douglas exponent of S_t in the innovation technology
ξ	effective education time
ϕ	parameter representing the incentive to innovate
a_t	normalized productivity ($= A_t/\overline{A}_t$)
σ	spillover coefficient in the global growth process
a^c	critical value of a_t for performing R&D

2.1 Preferences and production

There is a unit mass of people. Each lives for two periods, and is endowed with two units of labor services in the first period of life and none in the second.[14] Everyone's utility function is linear in consumption: $U = c_1 + \frac{1}{1+\rho}c_2$. Saving is taxed at the rate τ, so the equilibrium rate of interest will be $\rho\,(1-\tau)$ and the discount factor applied in all present value calculations will be $\beta = \frac{1}{1+\rho(1-\tau)}$. We interpret β as reflecting the policies and institutions governing the incentive to save, including the security of contracts and property rights.

There is a single general good, produced by specialized intermediate goods, according to the production function:

$$Z_t = \psi L^{1-\alpha} \int_0^1 A_t\,(i)^{1-\alpha}\, x_t\,(i)^{\alpha}\, di, \qquad 0 < \alpha < 1 \tag{1}$$

where L is labor input, ψ is a parameter representing the effects of such non-technological factors as geography, institutions and policies that influence a country's total factor productivity, $x_t\,(i)$ is the country's input of intermediate good i and $A_t\,(i)$ is the country-specific technological productivity parameter associated with it. The general good is used for consumption, as an input to R&D, and also as an input to the production of intermediate goods.

[14] A similar overlapping-generations framework is also used by Acemoglu, Aghion and Zilibotti (2002). Our 2002 NBER working paper contains a more general continuous-time analysis with infinitely-lived people.

Producers of the general good act as perfect competitors in all markets, so the equilibrium price of each intermediate good is its marginal product in producing the general good:

$$p_t(i) = \psi\alpha\left(x_t(i)/A_t(i)\right)^{\alpha-1}. \tag{2}$$

(We use the general good as numéraire, and in equilibrium $L = 1$).

For each intermediate good i there is a large number of firms capable of producing any given amount, using as the only input χ units of general good per unit of output, where $1 < \chi < \alpha^{-1}$. In addition, as a result of the innovation process to be described in the next section, in some intermediate sectors there will be a single producer (called the "incumbent") who can produce any amount using only one unit of general good per unit of output. All intermediate producers compete in prices à la Bertrand, so the equilibrium price will equal the unit cost of the second most efficient producer:[15]

$$p_t(i) = \chi. \tag{3}$$

Solving (2) and (3) for the equilibrium quantity $x_t(i)$ we see that the profit earned by the incumbent in any intermediate sector i will be proportional to the productivity parameter in that sector:

$$\pi_t(i) = (\chi - 1)\, x_t(i) = \pi \cdot A_t(i),$$

where:

$$\pi = (\chi - 1)\left(\alpha\psi/\chi\right)^{\frac{1}{1-\alpha}}. \tag{4}$$

Substituting the equilibrium quantities $x_t(i)$ into the production function (1) shows that the equilibrium output of the general good will be proportional to the aggregate productivity parameter:

$$A_t = \int_0^1 A_t(i)\, di.$$

Therefore the growth rate of aggregate output will be the growth rate of aggregate productivity:

$$G_t \equiv \frac{A_{t+1} - A_t}{A_t}$$

Our main objective in what follows is to determine whether the country's growth rate G_t converges to the global growth rate g_t.

2.2 Entrepreneurial skills, technology transfer and innovation

In each intermediate sector there is one person born each period t who is capable of producing an innovation for the next period. This person is called the "entrepreneur" in sector i. During the first period of her life,

[15] In sectors where there is an incumbent, the assumption that $\chi < \alpha^{-1}$ ensures that in equilibrium she will choose to supply the whole market at the price χ.

she obtains a skill level S_t and carries out research to innovate. If she succeeds (innovates) then she will be the i^{th} incumbent in period $t+1$, and she will get to monopolize the market for intermediate good i with a technology parameter $A_{t+1}(i)$ that embodies the world-wide stock of knowledge. For simplicity we assume that parameter equals $\overline{A}_{t+1}$, henceforth called the "global frontier", which is the same for all sectors and all countries.

The probability that an entrepreneur innovates is given by:

$$\mu_t = \lambda S_t^{\eta} z_t^{1-\eta} / \overline{A}_{t+1} \qquad 0 < \eta < 1 \tag{5}$$

where λ is a parameter representing the productivity of the innovation technology and z_t is the quantity of general good she invests in the form of material inputs to the innovation process. We divide by the targeted technology level $\overline{A}_{t+1}$ to recognize the "fishing out" effect; the more advanced the technology the more difficult it is to innovate. This effect is crucial in what follows.

Entrepreneurial skills are produced by two inputs: time and local knowledge. We take as given the amount of time spent in education by each entrepreneur.[16] Local knowledge is a public input which we assume to be proportional to aggregate productivity A_t, reflecting a human-capital spillover of the sort that is now familiar in the growth literature. That is, time spent acquiring skills is more productive in a technologically more advanced economy where there is more to learn from others. Thus each entrepreneur attains a skill level:

$$S_t = \xi A_t \tag{6}$$

where the schooling parameter ξ is "effective education time" - the product of schooling years and quality.

In equilibrium the innovation probability μ_t will be the same in all sectors. It will be chosen so as to maximize each entrepreneur's expected net payoff:

$$\beta \mu_t \pi \overline{A}_{t+1} - (1-\phi) z_t = \lambda \beta \pi S_t^{\eta} z_t^{1-\eta} - (1-\phi) z_t \tag{7}$$

where $\phi \in (0,1)$ is the rate at which technology investment is subsidized. The parameter ϕ is a proxy for all distortions and policies that impinge directly on the incentive to innovate. It can be negative, in which case the distortions and policies favoring innovation are outweighed by those discouraging it.[17]

The resulting equilibrium innovation rate can be expressed, using (6) to substitute for entrepreneurial skills, as:

$$\mu_t = \frac{\mu \cdot a_t}{1+g_t} \tag{8}$$

[16] This time is not subtracted from the aggregate labor supply L because entrepreneurs are assumed for simplicity to constitute a zero-measure subset of all people. Endogenizing the choice of education time as we did in our 2002 NBER working paper produces no new insights.

[17] An increase in ϕ can be thought of as a reduction of the "barriers to adoption" stressed by Parente and Prescott (1994, 1999), because technology transfer and innovation are all part of the same process in this model.

where a_t is the country's "normalized productivity":

$$a_t \equiv A_t/\overline{A}_t$$

and the parameter μ is:

$$\mu = \lambda^{\frac{1}{\eta}} \left(\frac{1-\eta}{1-\phi} \beta\pi \right)^{\frac{1}{\eta}-1} \xi \tag{9}$$

To ensure that the probability of innovation is less than unity we assume parameter values are always such that $\mu < 1$.

According to (8) the country's innovation rate μ_t is proportional to its normalized productivity. This is because of the fishing-out effect in the innovation process and the human-capital externality in skill formation. Because of fishing out, the level of entrepreneurial skill required to innovate at any given rate in equilibrium is strictly proportional to the global frontier $\overline{A}_t$, but because the human-capital externality is a local one the actual level of entrepreneurial skill is only proportional to local productivity A_t. Therefore the larger is the normalized productivity $A_t/\overline{A}_t$ the greater the country's entrepreneurial skill level will be relative to the amount needed to innovate at any given rate. We refer to this positive effect of normalized productivity on a country's innovation rate as the "absorption effect" because it works by altering the country's capacity to absorb global technological knowledge.

Since a_t is an inverse measure of the country's distance to the global technology frontier, the absorption effect implies a disadvantage of backwardness. That is, the further the country is from the frontier the lower will be the frequency with any given intermediate sector catches up to the global frontier. The absorption effect is important in determining whether or not the country converges, because it acts as a counterforce to Gerschenkron's (1952) more familiar advantage of backwardness, which is that the further behind the frontier the country is, the bigger is the jump in productivity expected to take place with each innovation.

The term $1 + g_t$ in the denominator of (8) reflects the fact that local skills are proportional to local productivity *this* period whereas the skill level required to innovate at any rate depend on the global frontier *next* period. Thus any increase in the frontier growth rate g_t means a reduction in the effectiveness of a country's entrepreneurial skills, and hence in its absorptive capacity, at any given distance from the current frontier.

The parameter μ in (8) is a measure of the country's "competitiveness," in the sense that a larger value of μ means a higher rate of innovation for any given initial condition.[18] According to (9), competitiveness is enhanced by any increase in the productivity of the innovation process (λ), the incentive to innovate (ϕ), the incentive to save (β) or the quality or quantity of education (ξ). Using (4) to substitute for the profit

[18] We call this "competitiveness" to recognize the Schumpeterian viewpoint, expressed in modern terms by Porter (1990), to the effect that innovation is the main form of competition in a free-enterprise market economy.

parameter π in (9) we see that competitiveness is also greater, ceteris paribus, in countries where geography, policies and institutions would tend to make productivity higher even if they did not affect the innovation process (i.e. countries where ψ is higher).

2.3 Productivity dynamics

The productivity parameter $A_t(i)$ in each sector evolves according to:

$$A_{t+1}(i) = \left\{ \begin{array}{cc} \overline{A}_{t+1} & \text{with probability } \mu_t \\ A_t(i) & \text{with probability } 1-\mu_t \end{array} \right\}$$

The average level A_t therefore obeys:

$$A_{t+1} = \mu_t \overline{A}_{t+1} + (1-\mu_t) A_t. \tag{10}$$

Subtracting A_t from each side, we have:

$$\Delta A_t = \mu_t \cdot \left(\overline{A}_{t+1} - A_t \right) \tag{11}$$

where Δ is the forward difference operator.

Like the analogous equation (8) of Nelson and Phelps (1966), equation (11) expresses the change in productivity as the product of a technology gap $\left(\overline{A}_{t+1} - A_t\right)$ and a coefficient that we can interpret as "absorptive capacity." Nelson and Phelps assumed that absorptive capacity was a given function of human capital, whereas in our theory absorptive capacity equals the endogenous rate of innovation, which will turn out to depend on domestic skills. Equation (11) also illustrates Gerschenkron's advantage of backwardness - the larger the technology gap separating the country from the frontier the larger will be the rate of domestic productivity growth, *given the degree of absorptive capacity.* As we shall see, the fact that absorptive capacity is not given means that Gerschenkron's advantage is not always enough to guarantee convergence.

Dividing both sides of (10) by $\overline{A}_{t+1}$ we see that:

$$a_{t+1} = \mu_t + \frac{1-\mu_t}{1+g_t} a_t. \tag{12}$$

Equation (12) shows how Gerschenkron's advantage of backwardness would produce convergence in the absence of the absorption effect. For suppose that the local innovation rate was constant, with $\mu_t = \mu^* > 0$. Assume for simplicity that the frontier growth rate is also constant, with $g_t = g^* > 0$. Then according to (12) normalized productivity would converge to a unique long-run equilibrium value $a^* = \mu^* \frac{1+g^*}{\mu^*+g^*} > 0$, implying that in the long run the country's productivity (the numerator of $a_t = A_t/\overline{A}_t$) would grow at the same rate as the global frontier (the denominator of a_t).

However, the absorption effect, according to which μ_t is proportional to a_t rather than constant, creates a countervailing disadvantage of backwardness, which implies that convergence will depend on the country's competitiveness parameter μ instead of being guaranteed. To analyze the conditions under which convergence will or will not occur, we focus on the following two equations.

First, replacing the innovation rate in (12) by its equilibrium value (8) yields the law of motion for normalized productivity:

$$a_{t+1} = \frac{a_t}{1+g_t}\left[\mu + 1 - \mu\frac{a_t}{1+g_t}\right] \tag{13}$$

Next, using (13) and the fact that, by construction, $1+G_t = \frac{A_{t+1}}{A_t} = \frac{a_{t+1}}{a_t}(1+g_t)$, we see that the country's growth rate G_t depends negatively on its normalized productivity, according to an equation reminiscent of those frequently estimated in cross-country growth regressions:

$$G_t = \mu \cdot \left(1 - \frac{a_t}{1+g_t}\right) \tag{14}$$

2.3.1 A follower country

Consider first a follower country that has no influence over the frontier growth rate g_t. Suppose that g_t converges to a limiting value $g^* > 0$ in the long run. (In the next section we show that this is indeed implied by the model.) Then the long-run behavior of the country's normalized productivity will be governed by the asymptotic limit of the law of motion (13):

$$a_{t+1} = \frac{a_t}{1+g^*}\left[\mu + 1 - \mu\frac{a_t}{1+g^*}\right] \equiv \Phi(a_t) \tag{15}$$

It is easy to verify that the right-hand side of (15) is an increasing and concave function of a_t on the unit interval, equal to zero when $a_t = 0$ and less than 1 when $a_t = 1$. As shown in the two panels of Figure 2, this implies that there exists a unique long-run equilibrium value to which normalized productivity will converge from any initial position.

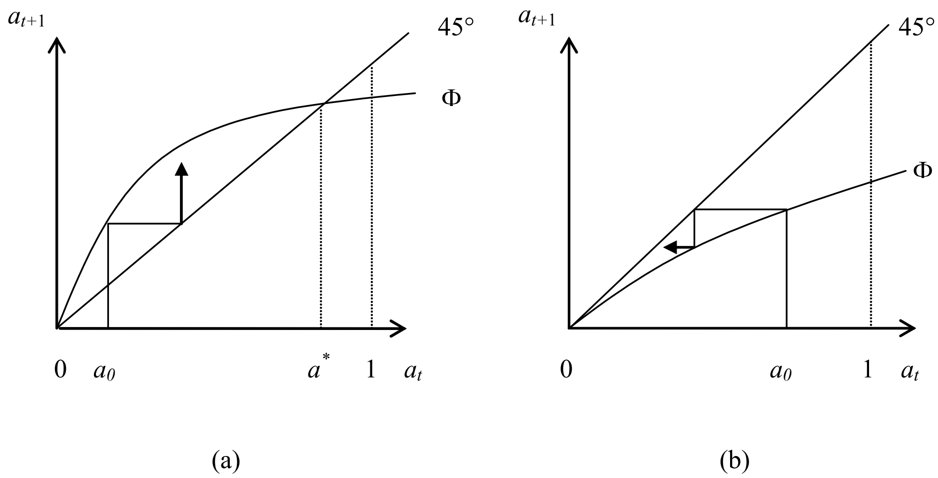

Figure 2: The dynamics of normalized productivity in a follower country

The country's long-run normalized productivity depends on the asymptotic frontier growth rate g^* and on the country's competitiveness μ. An increase in the frontier growth rate will make it harder for the country to keep up with the frontier, both because sectors that don't innovate will fall even faster relative to the growing frontier and also because, as pointed out above in the discussion surrounding equation (8), an increase in global growth will reduce the fraction μ_t of sectors that do innovate by reducing the effectiveness of entrepreneurial skills at any given current distance from the frontier. For both of these reasons the increase in g^* will shift the Φ curve down in Figure 1,[19] thereby reducing the country's long-run normalized productivity. On the other hand, an increase in the country's competitiveness will raise the innovation rate in any given situation, thus resulting in an upward shift of the Φ curve[20] and an increase in the country's

[19] Formally, we have:

$$\begin{aligned}
& \frac{\partial}{\partial g}\left\{\frac{a}{1+g}\left[\mu+1-\mu\frac{a}{1+g}\right]\right\} \\
= & -\frac{a}{(1+g)^2}\left(\mu+1-2\mu\frac{a}{1+g}\right) \\
< & -\frac{a}{(1+g)^2}(\mu+1-2\mu) \qquad \left(\text{because } 0<\frac{a}{1+g}<1\right) \\
< & \ 0 \qquad (\text{because } \mu<1).
\end{aligned}$$

[20]

$$\begin{aligned}
& \frac{\partial}{\partial \mu}\left\{\frac{a}{1+g}\left[\mu+1-\mu\frac{a}{1+g}\right]\right\} \\
= & \frac{a}{1+g}\left(1-\frac{a}{1+g}\right) \\
> & \ 0 \qquad \left(\text{because } 0<\frac{a}{1+g}<1\right).
\end{aligned}$$

long-run normalized productivity.

More specifically, if $\mu > g^*$ then the unique stable steady state of the law of motion (15) is:

$$a^* = (1 + g^*)(1 - g^*/\mu) > 0,$$

which depends negatively on g^* and positively on μ. This is the case shown in panel (a) of Figure 2. Substituting $a_t = a^*$ into the growth equation (14) above verifies that the country's productivity growth rate G_t will equal g^* in this steady state.

However, if $\mu < g^*$ then there is no positive steady-state normalized productivity. In this case, as shown in panel (b) of Figure 2, the slope of the Φ curve will be less than unity everywhere, and normalized productivity will fall asymptotically to zero. According to the growth equation (14) above the country's long-run growth rate will equal μ, the value of its competitiveness parameter.

In the borderline case where $\mu = g^*$ the only steady stage is $a^* = 0$, and the growth equation (14) implies that the country's long-run growth rate will equal the frontier growth rate g^*.

These results are formalized in the following proposition:

Proposition 1: *Long-run growth and normalized productivity in a follower country*

(a) If $\mu \geq g^*$, *then* $\lim_{t\to\infty} a_t = (1 + g^*)(1 - g^*/\mu) \geq 0$ *and* $\lim_{t\to\infty} G_t = g^*$.

(b) If $\mu < g^*$, *then* $\lim_{t\to\infty} a_t = 0$ *and* $\lim_{t\to\infty} G_t = \mu$.

2.4 The frontier growth rate

Suppose for simplicity that there is just one leading country, labeled country 1, whose innovations affect the evolution of the global stock of knowledge $\overline{A}_t$. Everything that was assumed above of a follower country is true also of country 1. Thus its rate of innovation μ_t^1 depends on its competitiveness parameter μ^1 and its normalized productivity a_t^1 according to the same equation (8) as in a follower country:

$$\mu_t^1 = \frac{\mu^1 \cdot a_t^1}{1 + g_t} \tag{16}$$

The only difference between country 1 and the others is that the global frontier depends on the rate of innovation μ_t^1 in country 1, according to:

$$g_t = \sigma \mu_t^1 \tag{17}$$

where $\sigma > 0$ is a spillover coefficient.

These last two equations solve for the frontier growth rate as a function of the leader's normalized productivity:

$$g_t = \widetilde{g}\left(a_t^1\right) = \left(\sqrt{1 + 4\sigma\mu^1 a_t^1} - 1\right)/2. \tag{18}$$

The function $\widetilde{g}$ is increasing in a_t^1. Intuitively this is because an increase in the leader's normalized productivity will increase its innovation rate, through the absorption effect analyzed above, and this increase in its innovation rate will in turn cause the frontier technology to grow more rapidly.

The function $\widetilde{g}\left(a_t^1\right)$ is also concave, the intuitive explanation for which is as follows. As the leader's normalized productivity a_t^1 rises, then because the innovation technology (5) exhibits constant returns to scale, the innovation rate μ_t^1 would rise in proportion to the rise in a_t^1 if the frontier growth rate g_t were held constant, as indicated by the reduced-form equation (16). However, this rise in the leader's innovation rate will in fact cause the frontier growth rate to increase, through the spillover equation (17). This increase in the frontier growth rate diminishes the effectiveness of the leader's entrepreneurial skills by increasing the distance between the leader's current productivity and the future productivity that its entrepreneurs are targeting, as pointed out in our discussion surrounding equation (8) above. This reduced effectiveness of entrepreneurial skills will dampen the rise in the leader's innovation rate, making it less than proportional to the increase in a_t^1. Since (17) makes the frontier growth rate proportional to the leader's innovation rate, therefore the overall increase in g_t will also be less than proportional increase to the increase in a_t^1.

Normalized productivity in country 1 obeys the same law of motion (13) as in a follower country. Substituting from (18) into this law of motion, yields the reduced-form law of motion:

$$a_{t+1}^1 = \frac{a_t^1}{1+\widetilde{g}\left(a_t^1\right)}\left[\mu^1 + 1 - \mu^1 \frac{a_t^1}{1+\widetilde{g}\left(a_t^1\right)}\right] \equiv \Lambda\left(a_t^1\right). \tag{19}$$

The function $\Lambda\left(a_t^1\right)$ on the right-hand side of (19) is increasing and concave, with $\Lambda'(0) > 1, \Lambda(0) = 0$ and $\Lambda(1) < 1$.[21] Therefore the leader's normalized productivity will approach a unique long-run value monotonically over time. This result, together with equation (18) which makes the frontier growth rate an increasing function of the leader's normalized productivity, implies that the frontier growth rate converges

[21] Proof: Define

$$h(a) \equiv \widetilde{g}(a)/\sigma\mu^1.$$

Because $\widetilde{g}$ is increasing and concave on the unit interval, therefore so is h. Also, by construction:

$$h(0) = 0, \quad h'(0) = 1 \quad \text{and} \quad 0 < h(a) < a \quad \text{for all } a > 0.$$

Because $\widetilde{g}$ solves (16) and (17), the right-hand side of (19) can be expressed as:

$$\Lambda\left(a_t^1\right) = h\left(a_t^1\right)\left[\mu^1 + 1 - \mu^1 h\left(a_t^1\right)\right].$$

It follows that:

$$\begin{gathered}
\Lambda(0) = 0, \\
\Lambda'(0) = \mu^1 + 1 > 1, \\
\Lambda(1) = \mu^1 h(1) + \left(1 - \mu^1 h(1)\right) h(1) < \mu^1 h(1) + \left(1 - \mu^1 h(1)\right) = 1, \\
\Lambda'(a) = h'(a)\left(\mu^1 + 1 - 2\mu^1 h(a)\right) > h'(a)\left(1 - \mu^1\right) > 0 \text{ and} \\
\Lambda''(a) = h''(a)\left(\mu^1 + 1 - 2\mu^1 h(a)\right) - 2\mu^1 \left(h'(a)\right)^2 < 0.
\end{gathered}$$

monotonically to its long-run value g^*. More formally we have:[22]

Proposition 2: *Global growth and the leader's normalized productivity*

The leader's normalized productivity converges monotonically to:

$$a^{1*} = \left(\frac{1}{1+\sigma}\right)\left(1 + \frac{\sigma}{1+\sigma}\mu^1\right) > 0$$

and the frontier growth rate converges monotonically to:

$$g^* = \frac{\sigma}{1+\sigma}\mu^1,$$

where μ^1 is the leader's competitiveness parameter.

Because equations (9) and (4) must hold for the leader as well as for all other countries, the leader's competitiveness parameter equals:

$$\mu^1 = \lambda^{\frac{1}{\eta}}\left(\frac{1-\eta}{1-\phi^1}\beta^1\pi^1\right)^{\frac{1}{\eta}-1}\xi^1 \tag{22}$$

and its profitability parameter π^1 equals:

$$\pi^1 = (\chi - 1)\left(\alpha\psi^1/\chi\right)^{\frac{1}{1-\alpha}}.$$

These two equations and Proposition 2 together imply that the frontier growth rate depends positively on attributes of the leading country such as the various geographic, institutional and policy factors underlying its efficiency parameter (ψ^1), its incentives to save (β^1) and to innovate (θ^1), and the quality/quantity of its education (ξ^1). These results are familiar from closed-economy innovation-based growth theory (Aghion and Howitt, 1998).

3 The introduction of modern R&D

We model the introduction of modern R&D by supposing that before some date t_0 all productivity advances were based on a pragmatic creativity occurring close to the production process, which we call implemen-

[22] To derive the expression for g^* in Proposition 2, note that by the definition of a^{1*}:

$$a^{1*} = \Lambda\left(a^{1*}\right) = \frac{a^{1*}}{1+g^*}\left(\mu^1 + 1 - \mu^1\frac{a^{1*}}{1+g^*}\right); \tag{20}$$

therefore:

$$g^* = \mu^1 - \mu^1\frac{a^{1*}}{1+g^*}$$

Since a^{1*} and g^* satisfy (16) and (17):

$$\mu^1\frac{a^{1*}}{1+g^*} = g^*/\sigma.$$

Therefore:

$$g^* = \mu^1 - g^*/\sigma,$$

from which:

$$g^* = \frac{\sigma}{1+\sigma}\mu^1. \tag{21}$$

To derive the expression for a^{1*}, use (21) to replace g^* in (20).

tation, with innovation-productivity λ. Thereafter, an alternative method of technology investment, called R&D, became available to all countries. R&D produces innovations according to the same process as implementation, using the technology described by equation (5) above, but with an innovation-productivity $\lambda' > \lambda$.

To be viable, however, the new technology requires entrepreneurs to possess a skill level at least equal to some threshold value $\gamma \overline{A}_t$, which depends upon the global technology frontier. If entrepreneurs do not have this threshold level of skills then R&D is impossible, although the original process of implementation remains. Because the entrepreneurial skill in any country is $\xi A_t = \xi a_t \overline{A}_t$, therefore R&D will be possible in the country if its normalized productivity $a_t = A_t / \overline{A}_t$ is at least equal to the critical value:

$$a^c \equiv \gamma/\xi$$

Because R&D is the same as implementation except for its higher innovation-productivity, and because an entrepreneur's expected payoff in any given situation depends positively on her innovation-productivity,[23] all technology investment will take the form of R&D in countries where normalized productivity is at least equal to a^c. A country with normalized productivity less than a^c will lack the absorptive capacity needed to perform R&D, and all technology investment in the country will take the form of implementation.

Suppose that before the introduction of R&D the frontier growth rate was at its steady-state value g^*, which was low enough that every country had a strictly positive steady-state normalized productivity. According to Proposition 1 above this just requires g^* to be less than the competitiveness parameter μ of every country. Suppose also that each country was at its steady state. Then just before t_0 all countries will be on parallel growth paths, with a relatively low growth rate, as depicted in Figure 1 above.

At the time that R&D is introduced, each country's normalized productivity will equal its previous steady-state value a^*. Thus the country will engage immediately in R&D if and only if $a^* \geq \gamma/\xi$; according to Proposition 1 this is equivalent to the condition:

$$(1 + g^*) (1 - g^*/\mu) \geq \gamma/\xi \tag{23}$$

which requires the country to have a large enough combination of competitiveness (μ) and educational attainment (ξ). Assume that this condition is satisfied by the leader country. Then the evolution of the frontier growth rate following t_0 can be analyzed as follows.

[23] According to (7) her expected payoff is:

$$\max_{\{z\}} \left\{ \lambda\beta\pi S_t^{\eta} z^{1-\eta} - (1-\phi) z \right\} = \eta \left(\frac{1-\eta}{1-\phi} \right)^{\frac{1}{\eta}-1} (\lambda\beta\pi)^{\frac{1}{\eta}} S_t$$

3.1 The rise in global growth

Again, g_t will be proportional to the leader's innovation rate, which will be determined as before, but with the new innovation-productivity λ' whenever the leader's normalized productivity exceeds a^c, and the old innovation-productivity λ otherwise. Because the leader starts using R&D at t_0, equation (22) implies that its competitiveness parameter μ^1 will immediately increase to

$$\mu^{1\prime} = \left(\lambda'/\lambda\right)^{1/\eta} \mu^1 > \mu^1$$

at t_0. According Proposition 2 this means that as long as it continues to use R&D (so that its competitiveness parameter remains equal to $\mu^{1\prime}$) its normalized productivity a_t^1 will rise monotonically to the new steady-state value. But this means that the country will indeed continue to use R&D, because a_t^1 will continue to exceed the critical value a^c.

The fact that the leader is now using a more effective method of technology investment will also lead to a steady increase in the growth rate of the global technology frontier. More formally, according to the updated version of equation (18) above, the frontier growth rate from t_0 on will be:

$$g_t = \widehat{g}\left(a_t^1\right) = \left(\sqrt{1 + 4\sigma\mu^{1\prime}a_t^1} - 1\right)/2$$

which implies that the increase in the leader's competitiveness from μ^1 to $\mu^{1\prime}$ will result in an immediate increase in g_t at t_0, even before a_t^1 starts to rise. The subsequent monotonic rise in a_t^1 will cause a further monotonic rise in the frontier growth rate from then on, since $\widehat{g}$ is an increasing function. According to Proposition 2 the new steady-state frontier growth rate will be:

$$g' = \frac{\sigma}{1+\sigma}\mu^{1\prime} = \left(\mu^{1\prime}/\mu^1\right) g^* > g^*$$

Hence:

Proposition 3: *Monotonic increase in the frontier growth rate after the introduction of modern R&D.*

For all $t \geq t_0$, $g^* < g_t < g_{t+1}$, *and* $\lim_{t\to\infty} g_t = g' \equiv \left(\lambda'/\lambda\right)^{1/\eta} g^*$,

where g^* *is the previous steady-state growth rate.*

3.2 Sorting into convergence groups

Starting at t_0, countries will sort into 3 convergence groups, depending on their initial (pre-R&D) competitiveness parameters μ and their educational attainment parameters ξ. Each follower country will start at $a_{t_0} = a^*$, the pre-R&D steady state, and will behave exactly as before but with a new sequence of frontier growth rates, and with the new higher competitiveness parameter at each date when it qualifies to perform

R&D. That is, replacing the old innovation-productivity λ in equation (9) above by its new value λ' yields the new competitiveness parameter for a country performing R&D:

$$\mu' = (\lambda')^{\frac{1}{\eta}} \xi \left(\frac{1-\eta}{1-\phi} \beta \pi \right)^{\frac{1}{\eta}-1} = (\lambda'/\lambda)^{1/\eta} \mu > \mu$$

Thus its productivity parameter will obey a modified version of the law of motion (13) above, namely:

$$a_{t+1} = \frac{a_t}{1+g_t} \left[\widetilde{\mu}(a_t) + 1 - \widetilde{\mu}(a_t) \frac{a_t}{1+g_t} \right] \tag{24}$$

where $\widetilde{\mu}$ is the step-function:

$$\widetilde{\mu}(a) = \left\{ \begin{array}{ll} \mu' & \text{if } a \geq a^c \\ \mu & \text{otherwise} \end{array} \right\}$$

3.2.1 Group 1 - R&D

Consider first all countries which, like the leader, start with sufficient skill levels to perform R&D at t_0. As shown in the previous section, these are the countries satisfying condition (23) above. Like the leader, these countries will all experience a monotonic rise in normalized productivity and in the frequency of innovation, continuing forever to satisfy the criterion for performing R&D, and converging to what we call an R&D steady state.

This can be seen with the aid of Figure 3 below, in which the Φ_0 curve depicts the original asymptotic law of motion (13) that the country was obeying before t_0. The discontinuous curve Φ_0^+ in Figure 3 represents the new law of motion (24) at date t_0, and the discontinuous curve Φ_∞ represents the new asymptotic law of motion, which is (24) with $g_t = g'$, the new steady-state growth rate. For now, consider just the continuous segment of each curve to the right of a^c. In this region each curve is increasing, concave, and below the 45^o line when $a_t = 1$, for the same reasons as before.

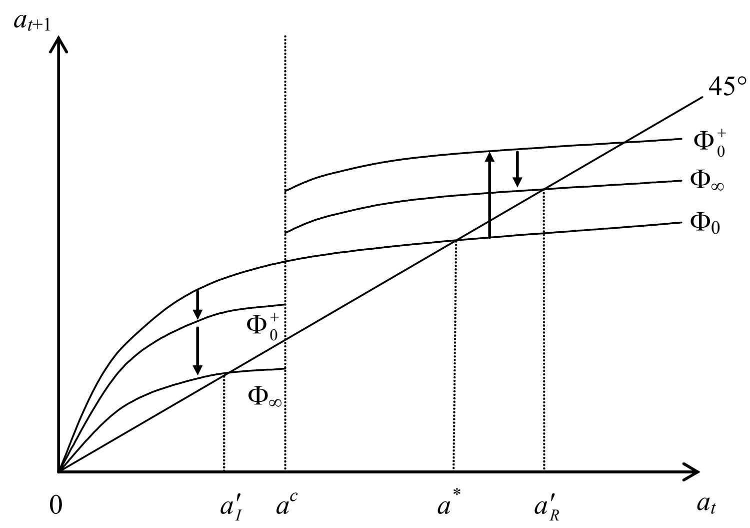

Figure 3: The effect of the introduction of modern R&D in a country in group 1, which converges to an R&D steady state.

If the country performs R&D forever then its new steady-state normalized productivity will be the unique positive steady-state solution to (15) with μ' and g' replacing μ and g^*, namely the "R&D steady state":

$$a'_R = (1 + g')(1 - g'/\mu') \tag{25}$$

Because $g'/g^* = \mu'/\mu^* = (\lambda'/\lambda)^{1/\eta} > 1$, therefore this new steady-state normalized productivity is greater than the pre-R&D steady state a^*:

$$\begin{aligned} a^* &= (1 + g^*)(1 - g^*/\mu) && \text{(from (Proposition 1))} \\ &= (1 + g^*)(1 - g'/\mu') && \text{(because } g'/g^* = \mu'/\mu^*\text{)} \\ &< (1 + g')(1 - g'/\mu') && \text{(because } g'/g^* > 1\text{)} \\ &= a'_R \end{aligned}$$

This implies that the new asymptotic curve Φ_∞ must lie above the original steady state in Figure 3. Moreover, as g_t rises monotonically to g' this causes the curve representing the law of motion (24) in this segment to shift down monotonically,[24] as shown in Figure 3. It follows that a_t will remain to the right of a^c forever and will converge asymptotically to a'_R. Because $a'_R > a^c > 0$ it follows that the country will indeed perform R&D forever, and that its asymptotic growth rate will equal the asymptotic global rate g'.

[24] See footnote 19 above.

3.2.2 Groups 2 and 3 - implementation and stagnation

Now consider all countries which, unlike the leader, start without sufficient skill levels to perform R&D at t_0. These countries fail to satisfy condition (23) above. Such a country will never be able to perform R&D, and will remain performing implementation forever.[25] Whether or not its growth rate converges to the new asymptotic global rate g' will depend on the size of its competitiveness parameter μ, which remains unchanged at the value given by equation (9) above. If the country is sufficiently competitive then it will converge to a steady state with the frontier growth rate g', but otherwise it will converge to a strictly lower growth rate that depends positively on its competitiveness.

This can be seen with the aid of Figure 4 below, in which curves have the same interpretation as in Figure 3. This time we consider just the parts to the left of a^c. Because the country retains the same competitiveness parameter as before in this region, the only thing shifting the Φ curve in Figure 4 over time is the monotonic increase in global growth, which shifts the curve monotonically down.[26] By assumption this country begins to the left of a^c. The downward shift of the Φ curve will therefore drive it further to the left. Intuitively, the acceleration in the global frontier is leaving the country increasingly behind, and the fact that it is not able to take advantage of the new method of technological change means that its growth rate will not start to rise until the gap separating it from the frontier has risen, giving it an advantage of backwardness.

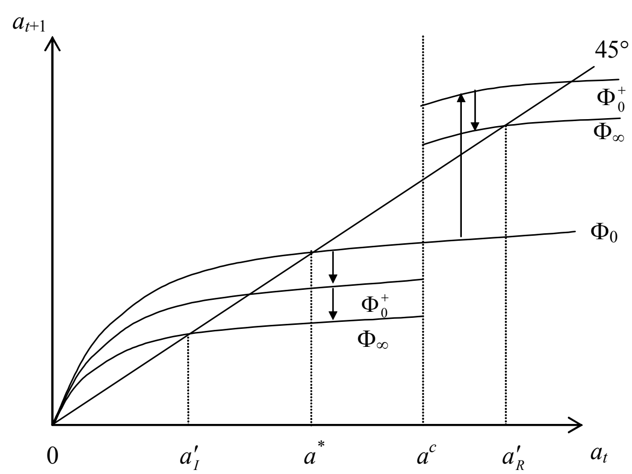

Figure 4: The effect of the introduction of modern R&D on a country in group 2, which converges to an implementation steady state.

The asymptotic behavior of this country will be governed by exactly the same process as we analyzed in

[25] We ignore the possibility that the country could try using the new method aimed at a productivity parameter $B_{t+1} < \overline{A}_{t+1}$ with lower skill requirements, targeting what was the frontier some time in the past. One reason why this possibility might not work is that to make use of R&D a researcher must be be plugged into a global community that is no longer interested in discussing the old frontier. If we were to allow the possibility then instead of a country in group 2 or 3 fallling behind because of a smaller frequency of innovations it would start falling behind because of a smaller size. We leave a more complete analysis for future research.

[26] Again, see footnote 19 above.

section 2 above, except with a new higher asymptotic frontier growth rate $g' > g^*$. It follows then from Proposition 1 that if $\mu \geq g'$ the country will converge to a new "implementation steady state":

$$a_I' = (1 + g')\,(1 - g'/\mu) \geq 0 \tag{26}$$

with a growth rate equal to g'. This is the case shown in Figure 4.

It also follows from Proposition 1 that if $\mu < g'$ then the country will converge to a "stagnation steady state" in which normalized productivity is zero and the country's growth rate equals its competitiveness parameter μ. In Figure 4 such a country would have an asymptotic law of motion represented by a curve Φ_∞ whose slope was strictly less than unity everywhere to the left of a^c.

3.3 Club-convergence and the great divergence

The above results imply that following the introduction of R&D, when countries eventually approach their new steady states, there will be one group of "converging" countries, namely those approaching either an R&D steady state or an implementation steady state, all growing asymptotically at the same frontier rate g'. All other countries will diverge, each approaching a stagnation steady state with a growth rate that depends on local parameters and is strictly less than the frontier growth rate g'. This is the pattern of club-convergence that seems to be have been exhibited by the historical record since the mid 20th Century. Formally we have:

Proposition 4: *Eventual club-convergence following the introduction of modern R&D.*

For all countries such that $(1 + g^*)\,(1 - g^*/\mu) \geq \gamma/\xi$ *or* $\mu \geq g'$, $lim_{t\to\infty} G_t = g'$, *and*

for all other countries, $lim_{t\to\infty} G_t = \mu < g'$.

This proposition is neutral with respect to the recent debate concerning the relative effects of institutions and geography on growth.[27] For it implies that the growth rate of an economy that grows at less than the frontier rate g' in the long run will depend on geographic factors underlying the efficiency parameter ψ, but also on the institutions (and policies) that affect the incentives to save (β) and to innovate (θ), the quality/quantity of education (ξ) and efficiency (ψ). This is because, according to (4) and (9), all of these factors have a positive effect on the country's competitiveness parameter μ. For the same reason, according to (25) and (26) all of these factors will affect the steady-state levels of productivity and per-capita GDP in a country that does grow at the frontier rate, relative to any other country that grows at the same rate.

Club-convergence by itself implies that there will be a fanning out of the cross-country productivity distribution, with an ever growing proportional difference between productivity in the converging countries

[27] See Acemoglu, Johnson and Robinson (2001), Easterly and Levine (2002), Sachs (2003) and Rodrik and Subramanian (2003).

as a whole and productivity in any diverging country. But the fact that introducing modern R&D creates a further separation of countries within the converging group, between those doing R&D and those still doing implementation, induces an even broader fanning out, at least during the transition to the new steady state, with an increase in the proportional difference between productivity in countries doing R&D and in those doing implementation.

To see this more formally, suppose that the leader country has the highest normalized productivity before the introduction of R&D, and define any country's "relative productivity" r_t as the ratio of its normalized productivity to that of the leader: a_t/a_t^1. Note that, from Proposition 1, equation (25) and the fact that $g'/g^* = \mu'/\mu$, therefore the introduction of modern R&D raises the long-run normalized productivity of each country in group 1 by the same factor $\frac{1+g'}{1+g*}$. However, as Figure 4 shows, the introduction of modern R&D reduces the normalized productivity of each country in group 2. Since the leader is by assumption in group 1, it follows that for any country in group 1 the limiting value r^* of r_t will be the same before and after the introduction of modern R&D, while for any country in group 2, r^* will be lower after the introduction of modern R&D than it was before.

If we assumed further that educational attainment was the same in each country then the critical value a^c would be the same in each country, which would imply that the introduction of modern R&D causes the distribution of long-run relative productivities r^* to widen even within the converging countries, falling in the countries where it was below a^c/a^{1*} (group 2) and remaining unchanged in countries where it was above a^c/a^{1*} (group 1), where a^{1*} is the original steady-state normalized productivity of the leader. *A fortiori,* if educational attainment was systematically higher in countries with higher productivity then the same widening would take place within the converging countries. The only way in which the dispersion of relative productivities within the converging countries could be reduced by the introduction of modern R&D would be if, counterfactually, there was a large systematic negative cross-country correlation between educational attainment and productivity. Thus we have:

Proposition 5: *Divergence even within the eventually converging countries.*

(a) Following the introduction of modern R&D, the long-run productivity of any country doing implementation falls relative to that of any country doing R&D.

(b) Assume that the ranking of countries by educational attainment ξ is the same as the ranking by competitiveness μ, and hence by initial steady-state productivity a^*. Then the long-run distribution of relative productivity within the group of countries that eventually converge exhibits a larger variance after the introduction of modern R&D than before.

Of course Propositions 3 $\sim$ 5 assume that all parameters remain unchanged following the introduction of R&D, whereas in fact the increase in global growth might well induce a country to change some of the policy parameters determining its relative position, especially the educational parameter ξ that determines whether or not it can join the leading convergence group. Notice however that a country that leaves its policies unchanged will still be better off in the long run as a result of the increased global growth rate, even if the country is in the last group. That is, although a country in group 3 stagnates *relative to the frontier*, it will nevertheless have a higher growth rate than if R&D had never been introduced because, by assumption μ (its new long-run growth rate) exceeds g^* (its old long-run growth rate).

4 Window of opportunity for lagging economies

For countries that are not sufficiently competitive or do not have a sufficiently good knowledge system when R&D is introduced, there may be only a finite period of time —a window of opportunity— for the country to carry out the needed changes to improve its parameters so as to make R&D viable. After this, the erosion of its absorptive capacity induced by technological advance in the leading country will trap the lagging country in implementation or stagnation.

For example, consider a country whose competitiveness is the same as the one depicted in Figure 3 above, but whose educational attainment ξ is so low that the the critical value $a^c = \gamma/\xi$ is higher than the initial steady state a^* shown in the Figure but lower than a'_R. Then, as we have seen, if this country does not change its competitiveness or its educational attainment it will descend into an implementation or stagnation steady state. If it were to quickly raise its level of educational attainment to that of the country originally depicted in Figure 3 then it would instead go to an R&D steady state. But if it waited until its normalized productivity had fallen below the value of a^c shown in Figure 3 then it would continue its descent into implementation or stagnation. Thus we have:

Proposition 6. *Window of opportunity*

An economy may have a finite time period during which it can change its competitiveness and/or the effectiveness of its knowledge system so as to make its R&D steady state viable, after which it will be trapped in implementation or stagnation.

A related problem occurs if for R&D to be feasible an absolute threshold level of average productivity $A_t \geq A_{\min}$ has to be reached. Then, when a leading economy introduces R&D at time t_0, only the traditional innovation technology will be available to countries with $A_t < A_{\min}$. Their normalized productivity a_t will begin descending towards their implementation or stagnation steady states, and may descend below a^c before their absolute average productivity (at this point $A_t = a^c \bar{A}_t$) rises above $A_{\min}$. Then they will be trapped in implementation or stagnation. Thus

Proposition 7 *Second window of opportunity*

If in addition to a relative skill requirement there is an absolute skill requirement for R&D, a follower economy will be trapped in implementation or stagnation if by the time it reaches the absolute skill requirement it lies below the relative skill requirement.

These results illustrate the importance of historically given initial conditions. A country that starts far enough behind one of the world's leading countries may not be able to attain the same productivity level even if it adopts exactly the same policies and institutions as the leading country. Instead it may have to do even better than the leading country in order to overcome the initial disadvantage of backwardness by building up its absorptive capacity.

4.1 Present Day Windows of Opportunity

The history of the industrialization and development of several countries, among them Denmark, Sweden, Italy, Japan, Korea, Singapore and Ireland has been characterized by periods of high, sustained growth sometimes called miracle growth. Other countries, including Argentina, India, Nigeria, Brazil and Mexico have experienced long periods of sustained economic growth but then failed to reach the status of full development (see Pipitone, 1995 for a historical discussion of the first five and last four cases). These different phenomena may result from technological windows of opportunity that open up and then close at various times. We give an explanation of how this might occur.

The leading edge technological level $\overline{A}_{t+1}$ represents a mix of technologies. During the history of technological growth there has been a sequence of dominant or even general purpose technologies, such as the steam engine, electricity, trains, automobiles, telecommunication, plastics, chemical technologies, information, etc. These have different characteristic innovation productivities for implementation and R&D and different human capital requirement for R&D. Thus, the parameters λ, λ' and γ may shift over time, reflecting medium- to long-term changes in these productivities and requirements as the dominant technologies change. For example, technologies requiring for their implementation a higher level of skills for a larger proportion of the population in effect require a higher human capital threshold level.

What this means is that the critical values for the existence of a low-technology trap may change. If implementation becomes relatively easier, the trap may disappear for countries with better scientific institutions and parameters for growth. To the extent that they increase the world growth rate g_t (of $\overline{A}_t$), however, their success may strengthen the implementation trap for other countries, which will not experience the window of opportunity.

If a country is originally performing implementation and the opportunity appears to transit to the higher equilibrium (because changes in parameters have led to the disappearance of the low technology trap by raising a'_I above a^c), it will first continue implementing and then begin innovating, a well-known pattern in the case of, for example, the Asian growth miracles. Bloom and Williamson (1998) show how growth in these countries coincided with a demographic window of opportunity in which a lower dependency ratio increased the saving rate. Our model provides a reason why not all countries reaching the demographic window of opportunity will develop: they might not find themselves in a position to reach the high technology steady state.

Similarly, the advent of a new technology for which implementation is more difficult may push some countries into stagnation, by making implementation unprofitable (lowering μ below g'). Alternatively, the exhaustion of the easy part of a new technology may close a transition window that may have been open, by shifting the threshold levels necessary for R&D. A whole set of countries could experience a period of sustained growth followed by a period of low growth.

Although the competition of ideas is enough for miracles in some countries to diminish the opportunity for miracles in others, trade in the products which are the subject of technological advance probably strengthens this effect, by discouraging production and innovation in less prepared countries in precisely those technologies which more prepared countries are using to grow.

According to our model, the emergence of Asia, together with the arrival of the general purpose information technologies, could be contributing factors for the lost decades of growth in Latin America, and its consequent permanence in an implementation equilibrium, and for the permanence of Africa in a stagnation equilibrium. Maloney (2002) has used this framework to compare the development of Latin America with countries such as Australia, Sweden and Finland, finding that deficient human capital accumulation determining technological capabilities may have played a role in its failure to develop.

5 Conclusions

We model skill acquisition and technological dynamics when technology investment can take the form of modern R&D or technological implementation. This dichotomy, kept alive by the ever larger skill-level necessary for R&D, gives rise to three convergence clubs, characterized respectively by R&D, implementation and stagnation. Applied to the origin of 20th Century growth, the model explains the simultaneous emergence of large income inequalities between countries. It also implies that after an initial widening of the distribution the most advanced countries (not just those that perform leading-edge R&D) should converge to parallel growth paths, in line with the empirical findings of the convergence literature. Technology transfer is powerful enough to bring about this degree of convergence between the R&D and implementation clubs, but it is not powerful enough to overcome the erosion of absorptive capacity causing divergence between the stagnation club and others. Once R&D takes off, the erosion of absorptive capacity in laggard countries implies that only a finite window of opportunity may exist for them to improve their effectiveness at innovation and knowledge systems so as to join the leading countries in development.

It remains to incorporate physical capital accumulation into the analysis, and to see what difference the degree of capital mobility makes. Our preliminary analysis suggests that the results are robust to capital accumulation. It also suggests that capital mobility tends to amplify the disadvantage of backwardness that is central to our analysis. That is, capital tends to move away from technologically more backward areas and toward the frontier; through a scale effect this reduces the incentive to innovate in the laggard country, causing it to fall even further behind the leader technologically.

The model is consistent with a highly demanding set of facts pertaining to the current distribution of income and factors of production among countries. It explains why economic miracles are possible in modern-day windows of opportunity for development and also why whole sets of countries may be simultaneously afflicted with prolonged periods of slow economic growth when technological implementation becomes more difficult.

The model is also consistent with the results obtained by Acemoglu, Johnson and Robinson (2001). In their study, a mortality variable constructed for the colonial era serves as an instrument for modern institutions, explaining a substantial proportion of modern differences in income. The authors argue that early settler mortality was among the determinants of the characteristics of colonial states, ranging from extractive states to "Neo-Europes" (Crosby, 1986), that this status determined their early institutions, especially with regard to property rights and checks against government power, that the institutions have persisted over time, and that the persistent institutions continue to affect economic growth. We provide an alternative interpretation of their results, which does not rely upon an unexplained persistence of institutions. By their reasoning, colonial mortality and early institutions can be expected to be correlated with the country-specific parameters determining which convergence group it joined when modern R&D was introduced, specifically the incentives to save (β) and innovate (ϕ), the efficiency parameter (ψ) and the effective education level (ξ). The long-term character of these effects results not from institutional persistence but from their effects on human capital and technology dynamics. Our "window of opportunity" result shows that the economic differences caused by colonial experience can persist even if the institutions do not.

Economic policy aimed at fostering growth should stress technological change and skill acquisition. Facilitating technological implementation, opening knowledge flows, fostering knowledge institutions and promoting human capital investment are key factors for increasing productivity. Once good rates of technological implementation are achieved, well-targeted policies may make it easier to identify and overcome specific thresholds constituting obstacles for technological change, thus dissipating low-technology traps. At an average rate of growth of 2%, only 33 countries lagged less than 50 years behind the U.S. in 1995, while the bottom 73 countries in the World Bank data base were more than a century behind. Perhaps the appropriate human capital and technological policies can produce not just parallel economic growth and poverty alleviation but economic miracles.

However, once a country has missed its windows of opportunity, it faces a more difficult task than before, because creating the conditions for an R&D steady state to exist is no longer sufficient for that steady state to be reached. At this point, a "big push" is needed to reverse the erosion of absorptive capacity and to join the leading convergence club. Whether or not a poor country is capable of engineering the push on its own is an interesting and important open question.

References

Abramovitz, Moses. (1986) "Catching Up, Forging Ahead, and Falling Behind." *Journal of Economic History,* 46, 385-406.

Acemoglu, Daron, Philippe Aghion, and Fabrizio Zilibotti. (2002) "Distance to Frontier, Selection and Economic Growth." unpublished, MIT.

Acemoglu, Daron, Simon Johnson, and James A. Robinson. (2001) "The Colonial Origins of Comparative Development: An Empirical Investigation." *American Economic Review,* 91, 1369-1401.

Acemoglu, Daron, and Fabrizio Zilibotti. (2001) "Productivity Differences." *Quarterly Journal of Economics,* 116, 563-606.

Aghion, Philippe, and Peter Howitt. (1992) "A Model of Growth through Creative Destruction." *Econometrica,* 60*,* 323-51.

Aghion, Philippe, and Peter Howitt. (1998) *Endogenous Growth Theory.* Cambridge, MA: MIT Press.

Aghion, Philippe, Peter Howitt, and David Mayer-Foulkes. (2004) "The Effect of Financial Development on Convergence: Theory and Evidence." NBER Working Paper 10358.

Arrow, Kenneth J. (1969) "Classificatory Notes on the Production and Transmission of Technological Knowledge." *American Economic Review Papers and Proceedings,* 59, 29-35.

Azariadis, Costas, and Allan Drazen. (1990) "Threshold Externalities in Economic Development." *Quarterly Journal of Economics,* 105, 501-526.

Barro, Robert J., and Xavier Sala-i-Martin. (1992) "Convergence." *Journal of Political Economy,* 100, 223-51.

Basu, Susanto, and David N. Weil. (1998) "Appropriate Technology and Growth." *Quarterly Journal of Economics,* 113, 1025-54.

Baumol, William J. (1986) "Productivity Growth, Convergence, and Welfare." *American Economic Review,* 76, 1072-1085.

Becker, Gary S. and Robert J. Barro. (1989) "Fertility Choice in a Model of Economic Growth." *Econometrica,* 57, 481-501.

Becker, Gary S., Kevin M. Murphy, and Robert Tamura. (1990) "Human Capital, Fertility, and Economic Growth." *Journal of Political Economy,* 98, S12-S37.

Bénabou, Roland. (1996) "Equity and Efficiency in Human Capital Investment: The Local Connection." *Review of Economic Studies,* 63, 237-64.

Benhabib, Jess, and Mark M. Spiegel. (2002) "Human Capital and Technology Diffusion." Produced for the forthcoming Handbook of Economic Growth.

Bloom, David E., and Jeffrey G. Williamson. (1998) "Demographic Transitions and Economic Miracles in Emerging Asia." *World Bank Economic Review,* 12, 419-55.

Caselli, Francesco, Gerardo Esquivel, and Fernando Lefort. (1996) "Reopening the Convergence Debate: A New Look at Cross-Country Growth Empirics." *Journal of Economic Growth,* 1, 363-389.

Cohen, Wesley M., and Daniel A. Levinthal. (1989) "Innovation and Learning: The Two Faces of R&D." *Economic Journal,* 99, 569-96.

Cohen, Wesley M., and Daniel A. Levinthal. (1990) "Absorptive Capacity: A New Perspective on Learning and Innovation." *Administrative Science Quarterly,* 35, 128-52.

Crosby, Alfred W. (1986) *Ecological Imperialism: The Biological Expansion of Europe, 900-1900.* New York: Cambridge University Press.

Crosby, Alfred W. (1997) *The Measure of Reality: Quantification and Western Society, 1250-1600.* New York: Cambridge University Press.

Durlauf, Steven N. (1993) "Nonergodic Economic Growth." *Review of Economic Studies,* 60, 349-367.

Durlauf, Steven N. (1996) "A Theory of Persistent Income Inequality." *Journal of Economic Growth,* 1, 75-93.

Durlauf, Steven N., and Paul A. Johnson. (1995) "Multiple Regimes and Cross-Country Growth Behavior." *Journal of Applied Econometrics,* 10, 365-84.

Easterly, William, and Ross Levine. (2001) "It's Not Factor Accumulation: Stylized Facts and Growth Models." *World Bank Economic Review,* 15, 177- 219.

Easterly, William, and Ross Levine. (2002) "Tropics, Germs and Crops: How Endowments Influence Economic Development." NBER Working Paper 9106.

Evans, Paul. (1996) "Using Cross-Country Variances to Evaluate Growth Theories." *Journal of Economic Dynamics and Control,* 20, 1027-49.

Evenson, Robert E., and Larry E. Westphal. (1995) "Technological Change and Technology Strategy." In *Handbook of Development Economics* Vol. 3A, edited by T. N. Srinivasan and Jere Behrman, pp. 2209-99. Amsterdam: Elsevier.

Feyrer, James. (2001) "Convergence by Parts." unpublished, Brown University.

Foster, Andrew D., and Mark R. Rosenzweig. (1996) "Technical Change and Human Capital Returns and Investments: Evidence from the Green Revolution." *American Economic Review,* 86, 931-53.

Galor, Oded. (1996) "Convergence? Inferences from Theoretical Models." *Economic Journal,* 106, 1056-69.

Galor, Oded, and Andrew Mountford. (2003) "Trade, Demographic Patterns and the Great Divergence: Why are One Third of People Indian or Chinese?" unpublished, Brown University.

Galor, Oded, and Daniel Tsiddon. (1997) "The Distribution of Human Capital and Economic Growth." *Journal of Economic Growth,* 2, 93-124.

Galor, Oded, and David N. Weil. (1996) "The Gender Gap, Fertility, and Growth." *American Economic Review,* 86, 374-387.

Galor, Oded, and Joseph Zeira. (1993) "Income Distribution and Macroeconomics." *Review of Economic Studies,* 60, 35-52.

Gerschenkron, Alexander. (1952) "Economic Backwardness in Historical Perspective." In *The Progress of Underdeveloped Areas*, edited by Bert F. Hoselitz. Chicago: University of Chicago Press.

Griffith, Rachel, Stephen Redding, and John Van Reenen. (2001) "Mapping the Two Faces of R&D: Productivity Growth in a Panel of OECD Industries." unpublished.

Hall, Robert E. and Charles I. Jones. (1999) "Why Do Some Countries Produce so Much More Output per Worker than Others?" *Quarterly Journal of Economics,* 114, 83-116.

Howitt, Peter. (2000) "Endogenous Growth and Cross-Country Income Differences." *American Economic Review,* 90, 829-46.

Howitt, Peter, and David Mayer-Foulkes. (2002) "R&D, Implementation and Stagnation: A Schumpeterian Theory of Convergence Clubs." NBER Working Paper 9104.

Islam, Nazrul. (1995) "Growth Empirics: A Panel Data Approach." *Quarterly Journal of Economics,* 110, 1127-70.

Jacob, Margaret C. (1997) *Scientific Culture and the Making of the Industrial West.* New York: Oxford University Press.

Klenow, Peter J. and Andrés Rodríguez-Clare. (1997) "The Neoclassical Revival in Growth Economics: Has it Gone too Far?" In *NBER Macroeconomics Annual1997,* edited by Ben Bernanke and Julio Rotemberg, pp. 73-103. Cambridge, MA: MIT Press.

Knight, Malcolm, Norman Loayza, and Delano Villanueva. (1993) "Testing the Neoclassical Theory of Economic Growth: A Panel Data Approach." *IMF Staff Papers,* 40, 512-41.

Lucas, Robert E. Jr. (2000) "Some Macroeconomics for the 21st Century." *Journal of Economic Perspectives,* 14, 159-68.

Maddison, Angus. (2001) *The World Economy: A Millennial Perspective.* Development Centre Studies. Paris: OECD.

Maloney, William F. (2002) "Technology, Growth and Resource Abundance: Observations from Latin America." Unpublished, World Bank.

Mankiw, N. Gregory, David Romer, and David N. Weil. (1992) "A Contribution to the Empirics of Economic Growth." *Quarterly Journal of Economics,* 107, 407-37.

Mayer-Foulkes, David. (2002) "Global Divergence." *Documento de Trabajo del CIDE*, SDTE 250, División de Economía.

Mayer-Foulkes, David. (2003) "Convergence Clubs in Cross-Country Life Expectancy Dynamics." In *Perspectives on Growth and Poverty*, edited by Rolph van der Hoeven and Anthony F. Shorrocks, 144-71. Tokyo: United Nations University Press.

Mokyr, Joel. (2002) *Gifts of Athena: Historical Origins of the Knowledge Economy.* Princeton: Princeton University Press.

Mowery, David C., and Nathan Rosenberg. (1998) *Paths of Innovation: Technological Change in 20th-Century America.* New York: Cambridge University Press.

Murphy, Kevin M., Andrei Shleifer, and Robert W. Vishny. (1989) "Industrialization and the Big Push." *Journal of Political Economy,* 97, 1003-26.

Nelson, Richard, and Edmund S. Phelps. (1966) "Investment in Humans, Technological Diffusion, and Economic Growth." *American Economic Review,* 56, 69-75.

Parente, Stephen L., and Edward C. Prescott. (1994) "Technology Adoption and Growth." *Journal of Political Economy,* 102, 298-321.

Parente, Stephen L., and Edward C. Prescott. (1999) "Monopoly Rights: A Barrier to Riches." *American Economic Review,* 89, 1216-33.

Pipitone, Ugo. (1995) *La salida del atraso: Un estudio histórico comparativo.* Fondo de Cultura Económica, México, segunda edición.

Porter, Michael. (1990) *The Competitive Advantage of Nations.* New York: The Free Press.

Prescott, Edward C. (1998) "Needed: A Theory of Total Factor Productivity." *International Economic Review,* 39, 525-51.

Pritchett, Lant. (1997) "Divergence, Big-Time." *Journal of Economic Perspectives,* 11, 3-17.

Quah, Danny T. (1993) "Empirical Cross-Section Dynamics in Economic Growth." *European Economic Review,* 37, 426-34.

Quah, Danny T. (1997) "Empirics for Growth and Distribution: Stratification, Polarization, and Convergence Clubs." *Journal of Economic Growth,* 2, 27-59.

Rodrik, Dani, and Arvind Subramanian. (2003) "Institutions Rule: The Primacy of Institutions over Geography and Integration in Economic Development." NBER Working Paper 10050.

Rosenberg, Nathan, and L. E. Birdzell Jr. (1986) *How the West Grew Rich: The Economic Transformation of the Industrial World.* Basic Books.

Sachs, Jeffrey D. (2003) "Institutions Don't Rule: Direct Effects of Geography on Per Capita Income." NBER Working Paper 9490.

Tsiddon, Daniel. (1992) "A Moral Hazard Trap to Growth." *International Economic Growth,* 33, 299-321.

Whitehead, Alfred N. (1931) *Science and the Modern World.* New York: Macmillan.

Wright, Gavin. (1999) "Can A Nation Learn? American Technology as a Network Phenomenon." In *Learning by Doing in Markets, Firms, and Countries*, edited by Naomi R. Lamoreaux, Daniel M. G. Raff, and Peter Temin, 295-326. Chicago: University of Chicago Press (for NBER).

Zilibotti, Fabrizio. (1995) "A Rostovian Model of Endogenous Growth and Underdevelopment Traps." *European Economic Review,* 39, 1569-1602.