Cross-Country Variations in National Economic Growth Rates: The Role of "Technology"

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I want to praise "technology" as *the* important factor in the relative growth performance of the nation-states' economies. I want to argue that the conventional wisdom substantially understates the role of differences in total factor productivity in explaining differentials across nation-state economies in GDP per capita. "Technology" in this sense is *more* important, because of the strong endogeneity of population growth and investment rates. Rich economies are economies in which children are much more "consumption" than "investment" goods; these economies have completed their demographic transitions to a régime of low fertility and low population growth. Thus, an economy that initially finds itself with a small advantage in total factor productivity will see that advantage magnified into a larger advantage in output per capita, as it converges to a steady-state growth path with lower population growth and a higher capital-output ratio.

Similarly, a rich economy is one in which the price of capital goods is relatively low: In a rich economy, a given share of national product saved translates into a greater real investment effort than if the economy had the world's average relative price structure. This channel magnifies differences in total factor productivity into larger differences in output per capita, working through the steady-state capital-output ratio.

Researchers in economic growth have been puzzled by the apparent combination of "conditional convergence" with absolute divergence. Economies appear to be moving toward their individual steady-state

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growth paths by about 2 percent per year, yet the spread of relative output per capita levels across the world continues to increase.

A naive interpretation of this pattern would suggest that, at some time in the past, nation-states' savings and population growth rates—and thus their levels of output per capita—were closer together than they are now; that some shock drove savings and population growth rates apart; and that since then the world's distribution of relative incomes has diverged as economies have traversed toward their steady-state growth paths. But what was this shock that drove savings and population growth rates apart? The evolution of the world's cross-country distribution of income and productivity is much more understandable once one recognizes the endogeneity of factor accumulation, and the fact that relatively poor countries have low investment rates and high rates of population growth in large part *because* they are relatively poor.

But I also have a caveat: In another sense, I want to bury "technology." Robert Solow's (1957) seminal article is entitled "Technical Change and the Aggregate Production Function." Certainly since 1957, and perhaps before, economists have used "technical change" and "technology" as shorthand ways of referring to shifts in the aggregate production function. Yet much of the difference seen across nations in aggregate total factor productivity has little to do with *technology*—in the sense of knowledge of the internal combustion engine, continuous-casting, the freeze-drying process, or anything that would be recognizable in a model like that of Caballero and Jaffe (1993). *Technology* properly so-called is the ultimate source of our enormous material wealth today relative to our counterparts of a century or so ago: Economic growth over the past century in the United States is *built* on our knowledge of the internal combustion engine, continuous-casting, freeze-drying, and all of our other technologies. Yet differences across nation-states in total factor productivity seem to be related tenuously, or not at all, to *technology*.

Robert Solow may not have done us a big favor when he convinced us to call shifts in the aggregate production function "technical change"; his doing so may not have helped economists to think clear thoughts over the past 40 years.

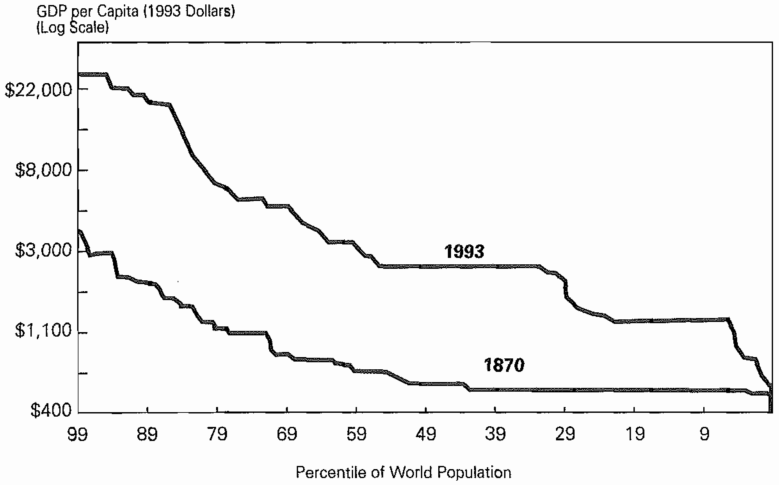
Divergence

As best we can determine from badly flawed data, the economic history of the past century and a quarter is a history not of "convergence" but of "divergence": The different countries and peoples of the world have not drawn closer together in relative living standards, but have drifted further apart.

Figure 1 shows the distribution of world real GDP per capita—by percentage of world population, not by nation-state—in 1993 and in 1870, as best as it can be estimated. The 1993 estimates of real GDP per capita

Figure 1

World Distributions of per Capita GDP, 1870 and 1993 (Purchasing Power Parity Concept)



are purchasing-power-parity estimates, measured in the "international dollar" concept that pegs U.S. GDP per capita to its current-dollar value, but attempts to use the relative price structure not of the advanced industrial economies but of the "world average" economy. They are taken from the 1995 *World Development Report*. The 1870 estimates of real GDP per capita are my own extensions and modifications of those found in Maddison's (1995) *Monitoring the World Economy*; by and large they are constructed by "backcasting" individual, nation-specific estimates of growth rates of real GDP per capita.

Thus, a very large number of caveats must be attached to Figure 1:

- Because estimates of 1870 GDP per capita are "backcast," errors in estimating 1993 GDP per capita are necessarily included in estimates of 1870 GDP per capita as well.
- The individual, nation-specific estimates of growth rates underlying the backcasting are of widely variable quality; they do not use the same methodology.
- Most of the nation-states of today's world did not exist in 1870. Estimates for 1870 cover roughly the same area that the nation-state occupies now.
- Figure 1 suppresses all variability in productivity and real GDP

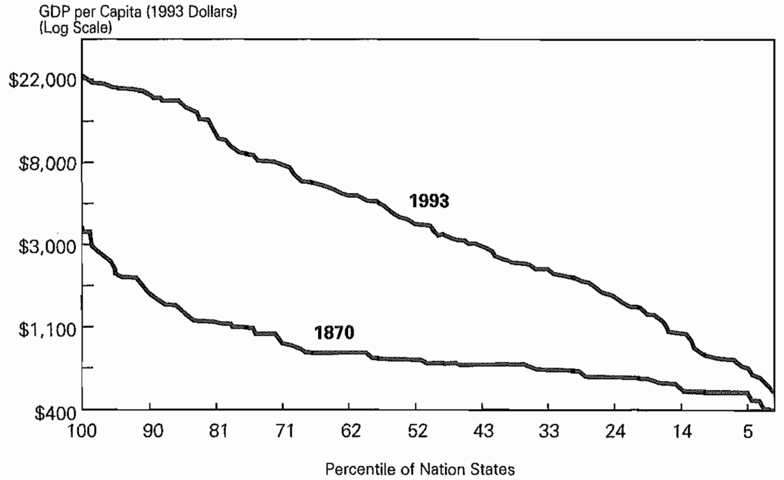
per capita *inside* nation-states: Everyone in China in 1993 is assumed to have the 1993 real GDP per capita of $2,330 estimated using the purchasing-power-parity concept.

- Estimates even for 1993 are very uncertain for developing countries. This applies especially to China which, as the World Bank team politely puts it in a footnote, has a GDP per capita estimate that is "subject to more than the usual margin of error."
- The entire enterprise of computing levels of real GDP per capita using the purchasing-power-parity concept may be seriously biased; it may fail to incorporate appropriate allowances for quality differences between products produced in industrialized and in developing economies. Certainly, purchasing-power-parity estimates made in the 1980s of relative living standards east and west of the Iron Curtain appear, in retrospect, to have wildly exaggerated the levels of productivity and material wealth in the former Soviet Union's sphere of influence.[1]
- Estimates of growth in real GDP per capita between 1870 and 1993 are unlikely to incorporate adequately changes in quality and in the scope of products that are produced. The thought experiment that underlies constant-dollar, cross-time comparisons implicitly involves taking the output produced at a particular date, moving it across time to the base year, and selling it in the base year at the base year's market prices. But suppose you gave me $2,763—the estimate of U.S. GDP per capita in 1870—and told me "By the way, you can only spend this sum on products that existed in 1870 and at the quality levels that were produced then." Under these stringent restrictions on what I could purchase, I might well value that sum as worth much less than $2,763 in today's dollars.
- Figure 1—plotting approximate GDP per capita by percentile of the world's population—looks significantly different in some respects from Figure 2, which plots GDP per capita in 1870 and 1993 by percentile of the world's number of nation-states. Nation-state-based calculations show a nearly uniform distribution of log GDP per capita levels over the observed range, especially for 1993. Population-based calculations show a non-uniform distribution with a pronounced upper tail: The difference, of course, springs from the two very large populations of the nation-states China and India, which are now and were in 1870 relatively poor.

[1] Current exchange rate-based calculations of relative productivity levels and living standards show differences an order of magnitude greater than do purchasing power parity-based calculations; it may be that in some senses the exchange rate-based calculations are more informative.

Figure 2

1870 and 1993 Distributions of GDP per Capita, by Nation-State (Purchasing Power Parity Concept)



Nevertheless, Figure 1 is the best we can do at present. What are the principal lessons of Figure 1? I believe that there are three. The first is the extraordinary pace of real economic growth over the past century. The highest level of GDP per capita attained in 1993 (for the United States) was some $24,470 in 1993-level international dollars; the highest attained in 1870 (for Australia) was some $4,108 in 1993-level international dollars. Using this particular metric, the United States today is some six times as wealthy in a material-product, real-income sense as was Australia in 1870 (and some nine times as well off as was the United States in 1870).[2]

I stress that this pace of growth is not only very fast but also extraordinarily faster than in any previous century that we know of. If 1870–1993 growth were simply a continuation of pre-1870 growth trends,

[2] This pace of real economic growth would be further magnified if the argument turned out to be correct that measured growth in the GDP accounts fails to capture much of the growth in real income that takes form of improvements in the quality and variety of commodities. Such factors *might* lead standard estimates to understate "true" economic growth over the past century by a factor of two or three. See, for example, Nordhaus (1994). On the other hand, Simon Kuznets (1963) argued that the constant-dollar, current-base-year calculations of real GDP that he designed were the most appropriate ones: that we should use the yardstick of the present to assess the past.

then in 1600 the richest economy in the world would have had a real GDP per capita level of some $110 a year—far too low to support human life.[3]

The twentieth century (extended back to 1870) has seen at least a sixfold multiplication of real GDP per capita at the leading edge of the world's economies; the previous century and a quarter had seen perhaps a doubling during the period of the classical Industrial Revolution (Crafts 1985; Mokyr 1985). But before that? Perhaps the most prosperous economy of the mid eighteenth century (probably the Netherlands) held a 50-percent edge over the most prosperous economy of the mid fifteenth century (probably the city-states of northern Italy). But perhaps not.

And looking more than 500 years into the past, it is hard to see any significant advance in living standards or average productivity levels. Human populations appear to have been in a near-Malthusian equilibrium, in which population growth quickly removes the margin for any significant increase in living standards (Kremer 1993; Livi-Bacci 1992; Malthus 1798). It is not clear that a French peasant of the seventeenth century was any better off than an Athenian peasant of the fourth century B.C.

The second important lesson of Figure 1 is the extremely uneven pace of economic growth over the past century. Because the relatively poor economies of the world have not yet completed their demographic transitions to a régime of relatively low fertility, the poorest economies have had the fastest-growing populations over the past century. International migration has not proceeded at a particularly fast pace. Thus, the distribution of economic growth appears more uneven and less widely distributed in Figure 1, which plots GDP per capita by percentile of the world's population, than in Figure 2, which plots GDP per capita by nation-state.

But in both figures, the line plotting the world's economic growth has rotated clockwise about the bottom right corner. The richest economies today have some six to nine times the GDP per capita of their counterparts in 1870; the median economy today has perhaps four times the GDP per capita of its counterpart in 1870; the poorest economies are little advanced over their counterparts of 1870.

To put this another way, the strong economic growth of the past century—the rise in the geometric average of output per capita in the world from some $760 to some $3,150 in 1993 international dollars per year—has been accompanied by a substantial increase in variance as well. In 1870, the standard deviation of log GDP per capita across the world's population was some 0.53; today it is 1.00. The range from one standard deviation below to one standard deviation above the mean in

[3] A point made by Kuznets (1963), and expanded on in considerable depth by Pritchett (1994).

log GDP per capita took up the interval from $450 to $1,310 international dollars in 1870; the same interval runs from $1,160 to $8,510 international dollars today.

The third lesson is that by and large the economies that were rich in relative terms in 1870 are rich in relative terms today, and the economies that were poor in relative terms in 1870 are poor in relative terms today (Figure 3). Barro and Sala-i-Martin (1995) draw a distinction between what they call σ-divergence and β-divergence. They call "σ-divergence" the case where the variance of a distribution grows despite a tendency for any given element to revert toward the mean over time; they call "β-divergence" the case where the variance of the distribution would continue to widen even in the absence of all shocks—when there is no systematic regression toward the mean.

The world since 1870 has exhibited not only σ-divergence but also β-divergence: The world's distribution has a greater spread today because there has been a systematic tendency for the relatively rich economics to grow faster than the relatively poor, and not because shocks to individual nation-states' GDP per capita levels have dominated regression to the mean. Table 1 documents this by reporting simple regressions of nation-states' log GDP per capita levels in 1993 on the level of 1870. If two economies' log GDP per capita levels were separated by an amount X in 1870, they were separated by 1.542(X) in 1993.

The degree of β-divergence is slightly attenuated when continent dummies are added to the right-hand side. The continent dummies have the standard pattern: strongly positive for North America, strongly negative for Africa. More interesting, perhaps, is some evidence that GDP per capita levels have tended to converge over the past century and a quarter, if attention is confined to those economies that were in the richer half of the sample in 1870.[4]

The fact that the distribution of income and productivity levels across nation states has been diverging goes oddly with a large number of studies (see Cogley and Spiegel 1996; Mankiw, Romer, and Weil 1992) that find evidence for "conditional convergence": Gaps between an economy's aggregate income and productivity level, and the level corresponding to the steady-state growth path predicted by its investment and population growth rates, shrink over time by some 2 to 3 percent per year.

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[4] Williamson (1996) and Taylor and Williamson (1994) point to the factors—largely international migration, increasing trade, and thus converging factor and commodity prices—making for "convergence" among relatively well-off economies before World War I. Dowrick and Nguyen (1989) point to similar factors and document similar "convergence" within the club of relatively rich OECD economies after World War II. Lewis (1978) attempts to account for the failure of relatively poor economies to industrialize before and after World War I.

Figure 3A

1870 and 1993 GDP per Capita, Top Third of 1870 Distribution

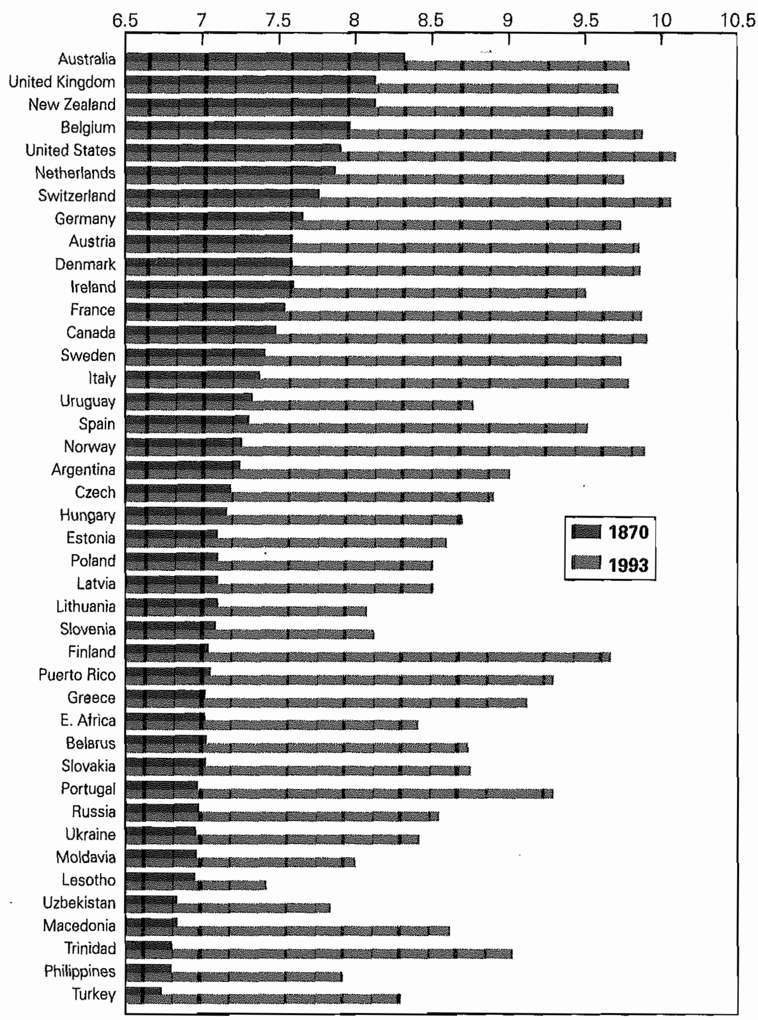


Figure 3B

1870 and 1993 GDP per Capita, Middle Third of 1870 Distribution

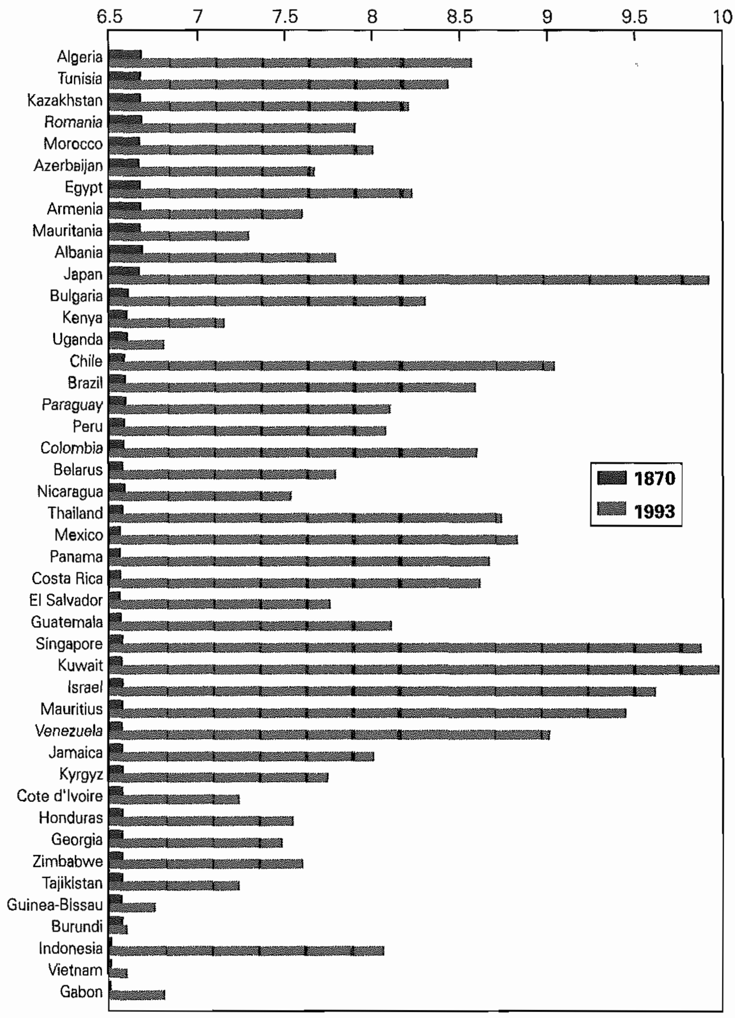
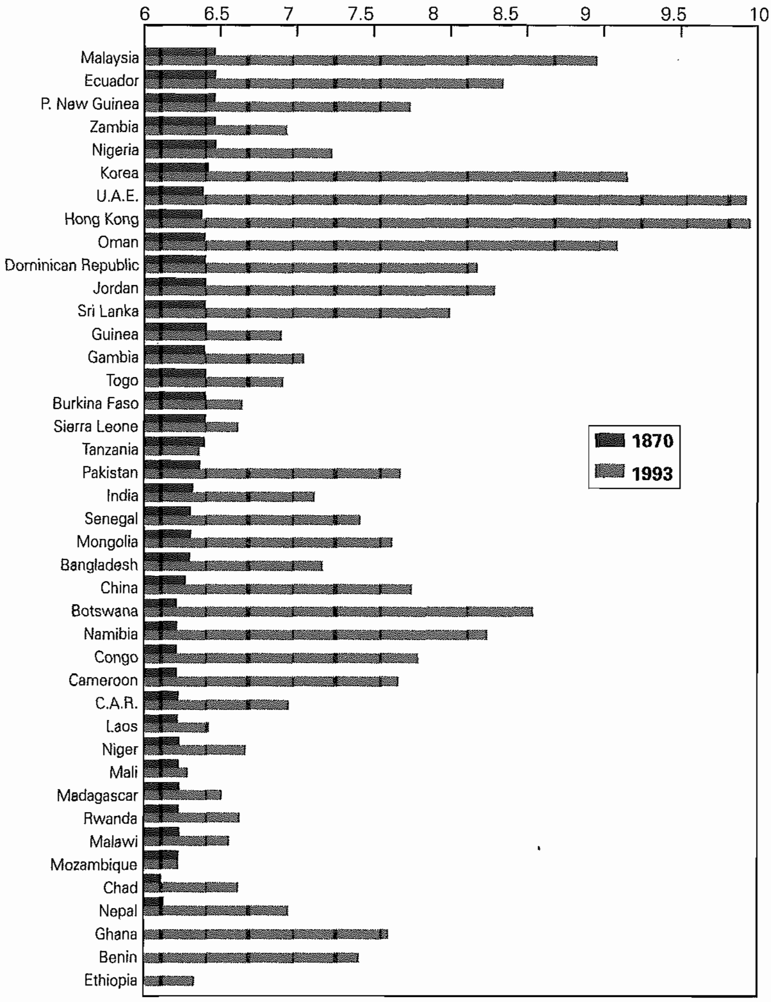


Figure 3C

1870 and 1993 GDP per Capita, Bottom Third[a] of 1870 Distribution



[a]Note change in scale from Figures 3a and 3b.

Table 1
Simple Convergence Regressions, 1870 and 1993

	Log 1870 GDP per Capita	With Continent Dummies		R^2
Full Sample	1.542			.689
	(.145)			
		Full Sample	1.316	.753
			(.197)	
		North America	.501	
			(.381)	
		South America	.174	
			(.252)	
		Asia	.208	
			(.225)	
		Africa	−.592	
			(.226)	
Richer Half	.620			.533
	.126			
Poorer Half	1.252			.466
	(.305)			

Endogenous Factor Accumulation

Conditional Convergence

Barro (1991) and Mankiw, Romer, and Weil (1992) were among the first to stress the existence of *conditional convergence* in the post-World War II growth rates of a cross section of nation-state economies. Mankiw (1995) interprets this finding as indicating that the straightforward Solow growth model is working better and better as time passes: It is becoming more and more the case that differences across nations in relative levels of GDP per capita are reflections of the differences in steady-state capital intensity implied by their rates of factor accumulation and population growth.

Yet the appearance of conditional convergence—a coefficient of between −2 and −3 percent per year when the growth rate is regressed on the difference between an economy's initial level of GDP per capita and the steady-state level implied by its investment and population growth rates—fits oddly with the fact, documented in the previous section, of unconditional divergence. How can economies be traversing toward their steady states *and* at the same time be drawing further and further apart in relative GDP per capita levels?

A naive interpretation of this pattern would suggest that at some time in the past, nation-states' savings and population growth rates must have been much more closely bunched together than they are today. This would mean that at that time, economies' steady-state and actual levels of output per capita also were bunched together more closely than they are today, and that some economic shock or series of shocks has since driven their respective savings and population growth rates apart. Thus, the world's relative distribution of incomes has diverged since, as the world's relative economies have traversed toward their now distantly separated paths of steady-state growth.

But this naive interpretation has a central problem: What was this shock that drove savings and population growth rates apart? The principal candidate would be the Industrial Revolution. But the Industrial Revolution saw not a fall but a sharp rise in population growth rates in the most heavily affected economies (Livi-Bacci 1992). And today very little is left of Rostow's (1957) bold hypothesis that the key to the Industrial Revolution was a sharp rise in investment as a share of national product (Crafts 1985; Mokyr 1985). The shifts in investment and in population growth rates brought about by the Industrial Revolution did not occur in the directions that would support such an interpretation.

Other candidates for a shock sharp enough to drive economies' investment and population growth rates away from one another simply are absent. The overwhelming bulk of the divergence in GDP per capita over the past century and a quarter has been due to the uneven spread of the Industrial Revolution, and to differences in relative national rates of growth in total factor productivity. But why, then, the finding of conditional convergence, and the strong positive association of per capita levels of GDP with investment rates and the negative association with population growth rates?

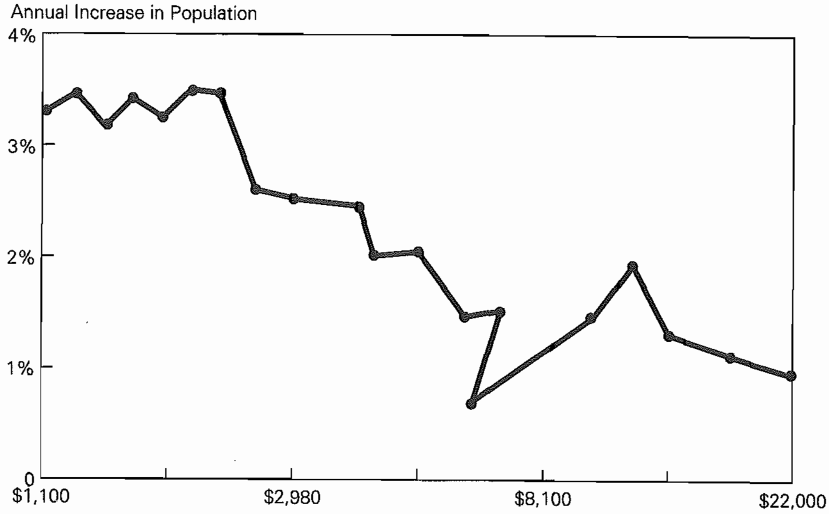
Population Growth and the Demographic Transition

One reason is the endogeneity of population growth. Sometime between the fifteenth and the eighteenth centuries, the human race passed through what we all hope was its last "Malthusian" episode, in which rising population and limited agricultural resources led to nutritional deficits, higher than average mortality, and population stagnation. Since then, the pace of productivity improvement in agriculture has kept ahead of agricultural resource scarcity and the population growth that has carried the world's population from one to six billion, so far. Nutrition has been relatively high by historical standards, natural fertility high as well, and natural mortality low.

In the past, the richest human populations appear to have also seen the fastest population growth. But, starting perhaps in eighteenth century France, a new pattern began to emerge, in which increases in GDP per capita led not to greater fertility and faster population growth but to

Figure 4

U.S. Population Growth and GDP per Capita, 1790 - Present



lower fertility and slower population growth. The number of girls born per potential mother fell, and population growth rates slowed.

Figure 4 shows this pattern at work in the United States over the past two centuries: As GDP per capita has grown, the rate of natural increase of the U.S. population has fallen steadily. Once U.S. GDP per capita grew beyond $2,000 or so (1993 dollars), fertility began to drop sharply enough to offset the declines in mortality that accompanied better medical care and rising material prosperity. The rate of population growth, excluding net immigration, is now little over 1 percent per year—far below the 3.5 percent per year in natural population increase seen in the first half-century of the Republic.

The pattern of rising material prosperity and falling natural population increase has had only one significant interruption in the United States in the past two centuries. The Great Depression of the 1930s saw a very sharp fall in childbearing and a reduction in natural population growth to only 0.7 percent per year. In what Richard Easterlin (1982) sees as a delayed response to the Great Depression that balanced out the birth deficit of the 1930s, births rose in the 1950s "baby boom" to a level not seen since the nineteenth century.

The pattern of increasing material wealth and slowing population growth seen in the United States is completely typical of the pattern followed so far by all nations that have successfully industrialized. Each tripling of GDP per capita has been associated with an approximately 1 percentage point fall in the annual rate of natural population increase.

To my knowledge, no one has ever argued that falling population growth in the United States has any sources other than our increasing material prosperity and the changes in social and economic organization that have followed from it. A richer country has more literate women, and literate women—worldwide—are very interested in effective birth control. In a poorer country, the average level of education is low and children can be put to work at a relatively early age, thus augmenting the production resources of the household. In a richer country, the average level of education is high and children are a major drain on household cash flow for nearly two decades.

Children in relatively poor, low-productivity economies are much like an "investment" good: They are a way to augment the economic resources of the household in a time span of a decade or so. By contrast, children in relatively rich, high-productivity economies are more like a "consumption" good. Thus, we would expect to see—and we do see—a substantial correlation between high GDP per capita and low population growth, arising not so much because low population growth leads to a higher steady-state capital-output ratio but because of the demographic transition: the changes in fertility that have so far been experienced in every single industrialized economy.

The Relative Price of Investment Goods

Begin with the large divergence between purchasing power parity and current exchange rate measures of relative levels of GDP per capita. The spread between the highest and lowest levels of GDP per capita today, using current exchange rate-based measures, is a factor of 400; the spread between the highest and lowest GDP per capita levels, using purchasing power parity-based measures, is a factor of 50. If the purchasing power parity-based measures are correct, real exchange rates vary by a factor of eight between relatively rich and relatively poor economies. And the log GDP per capita level accounts for 80 percent of the cross-country variation in this measure of the real exchange rate, with each 1 percent rise in GDP per capita associated with a 0.34 percent rise in the real exchange rate (Figure 5).

Real exchange rates make the prices of traded manufactured goods roughly the same in the different nation-states of the world, putting to one side over- or undervaluations produced by macroeconomic conditions, tariffs and other trade barriers, and desired international investment flows. Thus, the eightfold difference in real exchange rates between

Figure 5

Log Real Exchange Rate, and Log GDP per Worker

relatively rich and relatively poor economies is a reflection of an approximately eightfold difference in the price of easily traded manufactured goods: Relative to the average basket of goods and prices on which the "international dollar" measure is based, the real price of traded manufactures in relatively rich countries is only one-eighth the real price in relatively poor countries.

This should come as no surprise. The world's most industrialized and prosperous economies are the most industrialized and prosperous because they have attained very high levels of manufacturing productivity. Their productivity advantage in unskilled service industries is much lower than that in capital- and technology-intensive manufactured goods. And a low relative price of technologically sophisticated manufactured goods has important consequences for nation-states' relative investment rates. In the United States today, machinery and equipment account for one-half of all investment spending; in developing economies—where machinery and equipment, especially imported machinery and equipment, are much more expensive—they typically account for a much greater share of total investment spending (Jones 1994; De Long and Summers 1991).

Table 2
Consequences for National Investment of Relative Poverty and a High Price of Capital Goods

Level of Real Exchange Rate-Based GDP per Capita	Price Level of Machinery	Nominal Savings Share of GDP (Percent)	Real Investment Share of GDP (Percent)
$24,000	100	20.0	20.0
$ 6,000	160	20.0	15.4
$ 1,500	257	20.0	11.2
$ 375	411	20.0	7.8
$ 95	659	20.0	5.3

Consider the implications of a higher relative price of capital goods for a developing economy attempting to invest in a balanced mix of machinery and structures. There is no consistent trend in the relative price of structures across economies: Rich economies can use bulldozers to dig foundations, but poor economies can use large numbers of low-paid unskilled workers to dig foundations. But the higher relative price of machinery capital in developing countries makes it more and more expensive to maintain a balanced mix: The poorer a country, the lower is the real investment share of GDP that corresponds to any given nominal savings share of GDP.

Table 2 shows the consequences—the gap between nominal savings and real investment shares of GDP—that follow from the high relative price of machinery and equipment in poor countries that wish to maintain a balanced mix of investment in structures and equipment. For a country at the level of the world's poorest today—with a level of real exchange rate-based GDP per capita of some $95 a year—saving 20 percent of national product produces a real investment share (measured using the "international dollar" measure) of only some 5 percent of national product.

In fact, poor economies do *not* maintain balanced mixes of structures and equipment capital: They cannot afford to do so, and so they economize substantially on machinery and equipment. Thus, here are two additional channels by which relative poverty is a cause of slow growth. First, relative poverty is the source of a high real price of capital, a low rate of real investment corresponding to any given nominal savings effort, and a low steady-state ratio of capital to output. Second, to the extent that machinery and equipment are investments with social products that significantly exceed the profits earned by investors (see De Long and Summers 1991), the price of structures in relatively poor developing economies leads them to economize on exactly the wrong kinds of capital investment.

The Implications

The standard Solow (1956) and Swan (1956) growth model, written in per worker terms and expressed in logs, contains the production function:

$$\ln(y) = \alpha \ln(k) + \tau, \tag{1}$$

where y is output per worker, k is capital per worker, α is the capital share in the production function, and τ is the log of total factor productivity. If the economy has a constant investment rate I, a constant population growth rate n, and labor efficiency growth and depreciation rates g and δ, then in a steady state at any point in time, output per worker will be given by:

$$\ln(y) = \frac{\alpha}{1-\alpha}(\ln(I) - \ln(n + g + \delta)) + \frac{\tau}{1-\alpha}. \tag{2}$$

Suppose, however, that we take account of the feedback from GDP per capita levels on population growth rates:

$$\ln(n + g + \delta) = -\phi \ln(y) + \nu \tag{3}$$

where n is that portion of $\ln(n + g + \delta)$ not accounted for by the combination of the dependence of population growth on output and the background rates of labor efficiency growth and depreciation. The pattern of demographic evolution from the U.S. historical experience suggests that the parameter ϕ is, over the relevant range, approximately equal to 0.2.

And suppose we take account of the feedback from GDP per capita levels to the real investment share:

$$\ln(I) = \ln(s) - \ln(p_k) = \ln(s) + \theta \ln(y) - \eta, \tag{4}$$

where s is the economy's nominal savings share, ρ_k is the real price of capital goods, η is the deviation of the price of capital goods from what would have been predicted given the level of real output, and θ—the elasticity of capital goods prices with respect to output—is roughly equal to 0.3 over the range relevant for developing economies.

Combining (2), (3), and (4) produces an expression for the steady-state level of output, allowing for the endogeneity of population growth rates as a result of the demographic transition and for the dependence of the relative price of investment on output per worker:

$$\ln(y) = \frac{\alpha \ln(s) - \alpha\eta - \alpha\nu + \tau}{1 - \alpha - \alpha\theta - \alpha\phi}. \tag{5}$$

Table 3
Consequences for Steady State of Endogenous Population Growth and Capital Goods Prices

Capital Share α	Denominator of Equation (5)	Effect of s, g, η	Effect of Total Factor Productivity
.20	.70	.29	1.43
.40	.40	1.00	2.50
.60	.10	6.00	10.00
.67	.00	∞	∞

Equation (5) allows us to calculate, for various possible values for the share α of produced capital goods in the production function and for the chosen values of ϕ and θ, the impact on the level of the steady-state growth path of a shift in the exogenous component of savings, capital goods prices, population growth, or total factor productivity. Because they enter symmetrically into equation (5), the effects of the first three are the same.

Table 3 reports that—with a share of produced factor inputs in the production function of 0.4—a 1 percent increase in the savings rate (or a 1 percent fall in the exogenous component of capital goods prices) carries with it a 1 percent increase in the steady-state level of output. But a 1 percent increase in total factor productivity raises the steady-state level of output by fully 2.5 percent. Growth-accounting decompositions would, if applied to such an economy, attribute only 1 percent of the higher level of output to higher total factor productivity—*less than two-fifths* of the total effect. The growth accounting decomposition is not wrong, but incomplete: To the extent that the higher capital stock is a result of higher total factor productivity reducing the relative price of capital, and to the extent that higher total factor productivity pushes an economy further along its demographic transition to low population growth, exogenous shifts in total factor productivity have effects that are orders of magnitude greater than growth accounting procedures suggest, even without any powerful externalities in the production function.

Equally interesting, perhaps, is the case in which there *are* externalities to investment—whether in infrastructure, in research and development, in human capital, or in machinery and equipment—and in which the true capital share α in the production function is substantially greater than the 0.4 found in the usual specifications of the Solow model. The true capital share cannot get as high as 0.67 without triggering explosive paths for output per capita, in which very small boosts to total factor productivity set in motion patterns of population growth reduction and investment increase that converge to no steady state at all, but simply grow until the log-linear approximations in equations (3) and (4) break down.

It is difficult to look at the cross-country pattern of growth over the past century without thinking that the determinants of the steady-state growth paths toward which countries converge must be nearly singular. What differences between Canada and Argentina in 1870 would have led anyone to forecast their now more than two and one-half-fold difference in GDP per capita? Or the twentyfold gap between Taiwan and India? Recognizing the endogeneity of the demographic transition and of investment has the potential to help us understand why the economic history of the past century and a quarter has proceeded as it did, without requiring assumptions of external effects that seem perhaps implausibly large.

The endogeneity of the demographic transition, and of investment, also helps make sense of the odd combination of global divergence together with "conditional convergence." To the extent that relatively low productivity today is a cause of an economy's attraction to a low steady-state growth path, it is less necessary to look for shocks in the past that both pushed economies away from their long-run growth paths and pushed economies' GDP per capita levels together, if we want to account for the evolution of the world's distribution of income.

Caveat

But I still have one important caveat: Do we really want to refer to shifts in the aggregate production function as "technical change" and "technology"? Much of the difference seen across nations in aggregate total factor productivity seems to have little to do with *technology* per se.

Consider Greg Clark's (1987) excellent study of productivity in the cotton textile industry circa 1910. Table 4 reports some of Clark's calculations, most strikingly the sevenfold difference in labor productivity found between mills in the United States and cotton mills in the region of China near Shanghai.

Table 4
International Productivity in Cotton Textiles, circa 1910

Country	Output per Worker-Hour	Staffing Levels (Machines per Worker)
United States	1.78	2.97
England	1.33	2.04
Austria	.60	1.24
Italy	.59	.88
Japan	.33	.53
India	.28	.50
China	.25	.48

Source: Clark (1987).

The most striking thing about this sevenfold differential—the point of Clark's article—is that all of these mills used the same *technology*, if that word has any meaning. Japanese, Chinese, and Indian cotton mills had no local source of capital goods, so they bought and imported textile machinery made in the same machine shops near Liverpool that British manufacturers used. The United States produced its own textile machinery; Belgium, France, Germany, and Austria produced textile machinery as well. But everyone else imported capital goods—and in many cases, according to Clark, paid British mechanics to assemble and install it as well.

Yet with the same *technology*—the same machinery, the same production process, the same automated transformation of raw materials by metal and chemistry into final product—Clark found differences in labor productivity that reached three-to-one even when comparing the United States to Italy, a country with a very long history of textile production.

The key to the differences in labor productivity is found in the last column of Table 4: staffing levels. In the United States, one operative took care of three machines. In China, two operatives took care of one machine. Add this sixfold differences in staffing levels to the perhaps 15 percent lower output per machine-hour near Shanghai to obtain an arithmetic explanation of the sevenfold difference in output per worker.

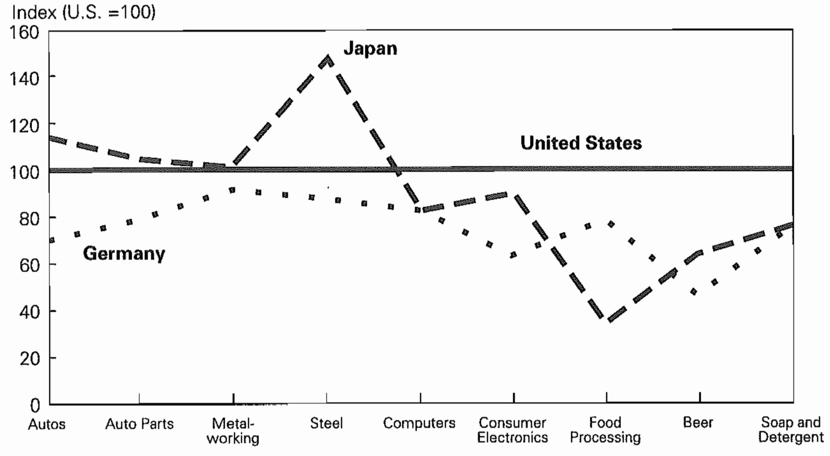
Since Clark wrote his article, a cottage industry has sprung up to try to explain how all of these textile mills could still be operating on the same production function. Perhaps the extra workers in the Asian mills were substituting for a poorer quality of raw materials? After all, poorer-quality raw materials would lead to more breaks, snarls, and machine stoppages that would have to be corrected. Perhaps the extra workers in the Asian mills allowed machines to run faster? Perhaps the extra workers allowed the machines to run with less downtime? Not one of the attempts to establish that these textile mills were working on the same production function, with Asian mills getting increased output (or diminished other inputs) in return for their higher staffing levels, has been convincing. The turn-of-the-last-century cotton textile industry did exhibit very large differences in productivity across countries, yes. But the differences are not readily attributable to differences in anything I would call *technology*.

Or consider the McKinsey Global Institute's (1993) study of manufacturing productivity in the United States, Germany, and Japan—a study carried out with the assistance of Martin Baily and Robert Solow. As best they could estimate, Japanese manufacturing productivity in 1990 varied from 33 percent of the U.S. level in food processing to 147 percent of the U.S. level in steel. German manufacturing productivity varied from 43 percent of the U.S. level in beer to 91 percent of the U.S. level in metalworking (Figure 6).

If we are going to attribute these productivity differences to differ-

Figure 6

Relative Labor Productivities by Industry, 1990



Source: McKinsey Global Institute (1993).

ences in *technology*, it is hard to understand how Japanese businesses can be so successful at learning and developing technologies for making automobile parts, and so inept at learning and developing technologies for freezing fish. True differences in technology surely are a greater factor in comparisons between countries further apart in the world distribution of GDP per capita than Germany, Japan, and the United States: Developing economies do use last generation's or even last century's procedures and practices because they cannot afford the capital goods that embody today's, because they do not have the mechanics to maintain today's, or because they have different factor price structures that make it more costly to use today's best practice. But even identical technologies can yield very different productivities. A lot more is going on.

Conclusion

Thus, the moral of this paper is that "technology" is both more important and less important a factor in accounting for relative national levels of prosperity than the conventional wisdom suggests. *Technology*—in the sense of differences in total factor productivity—is *more* important because of the strong endogeneity of population growth and capital investment rates. Countries that are rich have low rates of population growth: They have completed their demographic transitions to a régime in which fertility is relatively low and their children have become more "consumption" than "investment" goods. Countries that are rich also have relatively low prices of capital goods—a given share of national product saved implies a higher ratio of investment to GDP. Hence, being rich tends to make a nation-state's capital-output ratio high.

Thus, small differences in total factor productivity can translate into large differences in productivity levels and living standards, once the feedback from a richer economy to higher investment and lower population growth rates is taken into account. Studies examining the impact of total factor productivity differences on output per capita that hold savings and population growth rates constant understate the true long-run impact of raising total factor productivity.

On the other hand, *technology*—in the sense of knowledge of the internal combustion engine, continuous-casting, or freeze-drying—is much less important in accounting for differences across nations. Many differences in total factor productivity are related tenuously, or not at all, to differences in technology. All of the textile factories at the turn of the last century were equipped with the same or similar machines, many of them from the same machine shops in Lowell, Massachusetts or Manchester, Lancashire.

This should not be taken to imply that *technology* per se is unimportant in long-run economic growth. It is very important in those particular industries that are near the active edge of technological expansion and intensive in research and development. Indeed, better technology today is the sole important reason why we today have six to 20 times the standard of living of our predecessors in 1870. But it has much less to do with the sources of aggregate productivity differences across nations.

The last wave of research on aggregate growth theory called forth an effort, by Abramovitz (1956, 1986) and Denison (1967) among others, to try to decompose aggregate total factor productivity differences into more interesting and meaningful components. It is too bad that the current wave of research on aggregate growth has failed to generate a corresponding effort.

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Discussion

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Upon my first reading of J. Bradford De Long's paper, my reaction was to be impressed with its clarity and convinced by its basic arguments. He takes on some big ideas regarding the statistical record of cross-country growth rates, and he provokes the reader into new and useful thoughts. I expected, at most, to be pointing out some missing references that are relevant to the central point, the endogeneity of investment and other standard determinants of growth. Upon further thought, I remain impressed by his clarity and stimulated by his ideas, but no longer so convinced of all his conclusions.

The basic starting point is an apparent paradox. On the one hand, countries' income levels have failed to converge over time. In fact, the inequality among nations has actually increased by most standard measures. On the other hand, when we condition on the standard determinants of growth such as investment and population growth, we find a tendency for inequality to diminish—the finding now known as conditional convergence (Barro and Sala-i-Martin 1992; Mankiw, Romer, and Weil 1992). There is no contradiction here, but an interesting pair of major trends remain to be explained. It would be nice to be able to fold them into a single explanation. How can this be done?

De Long's explanation is elegant in its simplicity. Initial differences in technology, for example, Britain's Industrial Revolution, have become increasingly magnified with the passage of time because of two channels. First, higher income levels lead to less rapid population growth. Popu-

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lation growth is, in turn, a standard negative determinant of GNP per capita in the neoclassical growth model of Solow (not to mention in earlier contributions going back to Malthus). The reason is that higher population growth means that more of investment is used up equipping workers with the already existing level of capital, and less is left over to raise the capital/labor ratio. Second, higher income levels lead to lower relative prices of capital goods, so that a given saving rate buys more real investment. Through both channels, the initial divergence in incomes becomes self-reinforcing.

My response falls into several parts. First, I will recall previous authors who have made similar points, together with some additional ways that the standard determinants of growth could in theory be endogenous. Then, I will discuss some empirical evidence: on convergence itself, on the timing of increases in investment, and on what causes some countries to converge and others not.

Doctrinal History

Both the endogeneity of investment and the endogeneity of population growth are points that are long-known and well-known. Perhaps they are better known in the development literature than in the growth literature. In the case of investment, the specific channel mentioned by De Long, via the relative price of capital goods, is new, so far as I know. But many have noted that saving (and therefore investment) might change as income rises.

One possible channel comes out of the same demographic transition described by De Long: A lower ratio of children to working-age population implies a higher saving rate, according to the life-cycle hypothesis (Mason 1987; Leff 1969). Other possible effects have been suggested as well. The development process is often accompanied by the growth of more sophisticated financial systems, as well as pension plans and social security systems. This evolution can lead not only to more saving and investment, but also to lower population growth, since a prime motive in poor countries for having many children is that they provide the only form of insurance against destitution in old age.[1] Investment in human capital is often greater in rich countries than in poor countries, perhaps because education is a superior good.

I would like to add another effect to the list. The growth literature often falls into the habit of speaking of national saving and investment interchangeably. But the two differ; the difference is net foreign borrowing. Countries undergoing rapid growth often find foreign capital increasingly available, perhaps even to a greater extent than they would

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[1] For citations on all these points, see Hammer (1985) or Kelley (1988, pp. 1706–07).

like, as some emerging market countries found in the 1990s. The increased ease of international financing of investment is another way that this key determinant of growth can be endogenous.

Some effects can also go the other way. Not everyone agrees that population growth has a clear negative effect on income per capita. A longer life span leads to an increased ratio of elderly to working-age population, which in turn results in a fall in saving, according to the life-cycle hypothesis. Another effect is symmetric to De Long's effect on the price of capital goods. As he points out, countries as they grow tend to undergo a real appreciation of their currency, and thus an increase in their relative price of nontraded goods and services, versus traded goods. But just as this means cheaper capital goods, it also means more expensive education. Thus, a given saving rate buys less real investment in human capital (as parents of today's students are well aware). I would not argue that either of these two effects dominates the ones that work to reinforce growth, though someone else might.

Perhaps the most important precedent for De Long's argument is research by Richard Nelson.[2] He argued precisely that, because population growth and saving could be endogenous, a takeoff in growth could become self-sustaining. The alternative was what he called a "low-level equilibrium trap," in which a country is unable to achieve growth until it gets its population growth down and its saving rate up, but is unable to get its population growth down and its saving rate up until it achieves growth. This sort of model leads directly to De Long's worldwide divergence.

Before I leave the subject of doctrinal history, I want to make a comment on De Long's characterization of technology. He says, on the one hand, that shifts in total factor productivity are more important than sometimes thought, in that they, rather than added inputs per capita, form the origin of the self-sustaining takeoff. But, on the other hand, he says that Solow's labeling such shifts as technology "may not have helped economists think clear thoughts over the past 40 years." I do not believe Bob Solow needs me to defend him, and in any case I am sure that no lack of respect for his contributions in this area was meant. Nevertheless, I thought I would recall the relevant two sentences from Solow (1957): "I am using the phrase 'technical change' as a shorthand expression for *any kind of shift* in the production function. Thus slowdowns, speedups, improvements in the education of the labor force, and all sorts of things will appear as 'technical change.'" From the start, there has been plenty of awareness that the Solow residual was only "a measure of our ignorance," and that it could be influenced by managerial practices, government-induced distortions, cultural factors, and a hundred other

[2] Nelson (1956 and 1960, p. 378); see also Jones (1976, p. 88).

aspects of how countries organize their economies, as easily as by the mastery of the internal combustion engine or the freeze-drying process.

Empirical Evidence

Now I will turn to empirical observation. The divergence in per capita incomes that De Long identifies is striking, but this generalization is a bit too sweeping and unqualified. Some of the most important trends over the postwar period are obscured.

In 1870, the self-evident generalization would have been that Europe and European-settled regions had achieved remarkable growth and other regions had not. In the middle of this century, the picture did not look very different, with a few exceptions: Japan had industrialized, while Latin America had fallen behind (most dramatically Argentina and Uruguay, which in 1870 had been as rich as Norway, as one can see from De Long's interesting Figure 3a). But when numerous colonies gained their independence in the 1950s and 1960s, the great hopes that many had for their rapid economic development were based on theory, on politics, on hope—on anything but historical experience. By 1980, those hopes had been dashed. It seemed that countries developed if and only if they were European (with Japan the only major exception).

Now, at last, this situation has suddenly changed. A group of East Asian nations, led by the four tigers, have joined the class of industrialized countries. On a per capita basis, Hong Kong and Singapore are now richer than Canada, France, the United Kingdom, and many other industrial countries. At the same time, a group of European nations, led by the former Soviet Union, have joined the class of less-developed countries.

On an aggregate basis, the U.S. share of Gross World Product has declined from almost one-half after World War II to less than one-fourth. China has surpassed Japan and Germany, in terms of total GDP. India has surpassed France, Italy, and Britain. Brazil and Mexico have surpassed Canada. Indonesia has surpassed Spain. Korea and Thailand have surpassed Australia. If the criterion were economic size, three of these countries would have a greater claim to be in the G-7 than does Canada, as would others within the foreseeable future.[3]

Why, then, does De Long find divergence rather than convergence? Romer (1986, 1989), Sala-i-Martin (1995), and others find the same. (This result has been an important stimulus to the recent surge in growth theory.) But still others conclude the opposite. For instance, Baumol

[3] Frankel (1996). These comparisons are on a Purchasing Power Parity basis. If one does the comparison on the basis of current exchange rates, then the Third World countries do not rank as high.

(1986), Dowrick and Nguyen (1989), and others see convergence among developed countries.[4] De Long (1988), in a earlier paper, attributed this finding to sample selection bias. That critique was convincing. Nevertheless, a number of authors have found convergence within groups of countries, such as Europe, or within groups of regions within countries, such as states of the United States, prefectures of Japan, or provinces within other countries. These findings are not due to sample selection bias. Sala-i-Martin describes them as another kind of "conditional convergence," conditioning now on a class of countries or regions, rather than on factor accumulation or other determinants of growth.

I think we have to go at least one cut deeper than simply looking at the variance across all countries. We have to consider which kinds of countries have converged and which kinds have not. Clearly, most East Asian countries have done well, while most African countries have not. Indeed, this last is an understatement. Some Asian countries have virtually completed convergence with European levels of development, while most African countries have made no progress in this regard at all. Why is this?

The large empirical literature on cross-country growth comparisons has found many explanations. The most robust are definitely the rates of investment in physical and human capital, which are high in East Asia. (Population growth shows up much less consistently.) Indeed, Young (1995) and his popularizer Krugman (1994) have startled many people with their claims that factor accumulation explains most or all of the superior performance of the Newly Industrialized Economies of East Asia. Little is left to be attributed to technical change or total factor productivity growth, whether interpreted as technology or Confucianism.

For present purposes, the key question is whether the high rates of investment in East Asia were a cause of the takeoffs of the high-performing economies, as is most often assumed traditionally, or whether they merely resulted from and amplified the high growth rates once they were already under way, as De Long argues (and the same for lower rates of population growth). Both channels that De Long mentions should require time to occur—certainly the demographic transition takes time, and so I think does the process of bidding up the price of nontraded

[4] Helpman (1987), in a different context (the connection between income and trade, discussed below) and with a different measure, found that the dispersion of incomes has fallen over the postwar period. That calculation, like Baumol's, was on a sample of developed countries, but Hummels and Levinsohn (1995) reproduced the result on a sample of developing countries. While difference in sample may play a role, the major explanation for this finding is probably that these authors are looking at countries' total GDPs, while the growth literature works with countries' per capita GDPs. The demographic transition says that rich countries have lower population growth than middle-income countries, so the distribution across countries could become more equal over time for total incomes, even as it becomes less equal for per capita incomes.

goods and services relative to internationally traded capital goods. Thus, one can look to see whether the changes occurred early in the takeoff process, supporting the traditional interpretation, or followed it, supporting De Long's interpretation. The one thing that seems to me missing from this paper is such an attempt to test the timing from the data.

I have plotted the investment rates and population growth rates of the East Asian countries over the past 30 to 40 years, the time span of their takeoffs.[5] (See the Figures, in the Appendix.) Most cases show very little evidence of population growth declining more in the aftermath of the peak in growth rates than it did before. Perhaps most of these countries will complete their demographic transitions in the future, but they have not yet done so. Investment rates show much more evidence of favorable changes after the peak in growth rates. However, they also show large increases in investment that pre-date the peak in growth rates, and these appear to be likely candidates for the cause of the takeoff, contrary to the De Long hypothesis. Perhaps the point about endogeneity of investment rates and self-reinforcing growth is correct, and yet the point about the initial takeoff being due more to exogenous technology than to exogenous investment differences is incorrect. More systematic analysis is needed.

Concluding Remarks

This discussion leaves out many other determinants of growth. I cannot end my comment without calling attention to one of them: openness to trade and investment. Many studies have found that openness, in addition to factor accumulation, is an important determinant of growth. Furthermore, this relationship survives accusations of simultaneity that have been frequently leveled against it, analogously to the point about the endogeneity of investment (Frankel and Romer 1996; Frankel, Romer, and Cyrus 1995). The countries that have converged are those that are open. This observation can explain convergence within the OECD, within Europe, within the United States, and within other countries. It is also part of the success of the East Asian countries. Openness is how countries absorb the best technology from the leaders, whether it is technology in the technological sense, or in more general organizational, managerial, and cultural senses. (See, for example, Grossman and Helpman 1991.)

Openness, by the way, is another self-reinforcing mechanism. While trade promotes growth, without question growth also promotes trade.

[5] This is a more compressed time span than that in which the transition of the industrialized countries occurred. But the time taken by the East Asian tigers to double their incomes has been only about 10 years, whereas it originally took the United States 47 years to do so (from 1839), and the United Kingdom 58 years (from 1780).

Countries tend to lower tariffs, for example, as they become richer. Trade has made East Asia today a powerful, self-sustaining growth area. The trade is the result (as is well-known) of pro-trade policies and also (I would argue) of the proximity of the East Asian countries to each other. At their takeoff stages, they were dependent on the North American market for trade. In the 1990s, however, they have continued to chug along on their own, even when the United States and Japan were in recession—another example of self-reinforcing growth.

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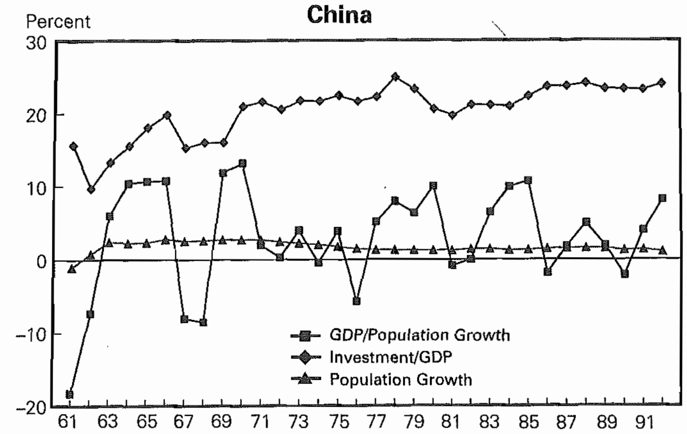
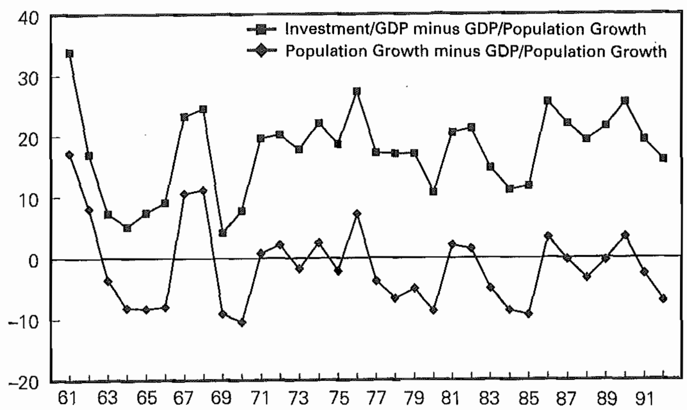
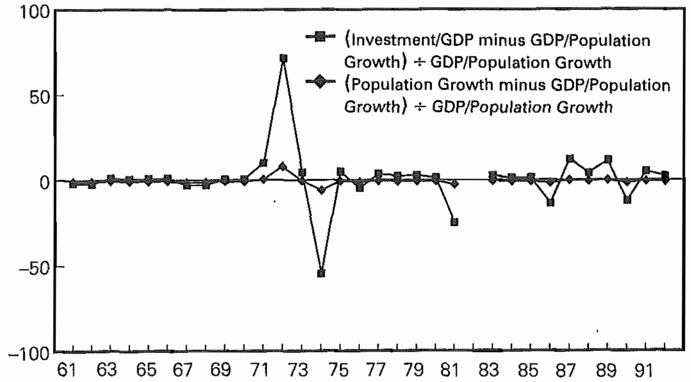
Appendix: Does Investment Rise Before, or After, the Growth Takeoff?

Figure 1
China



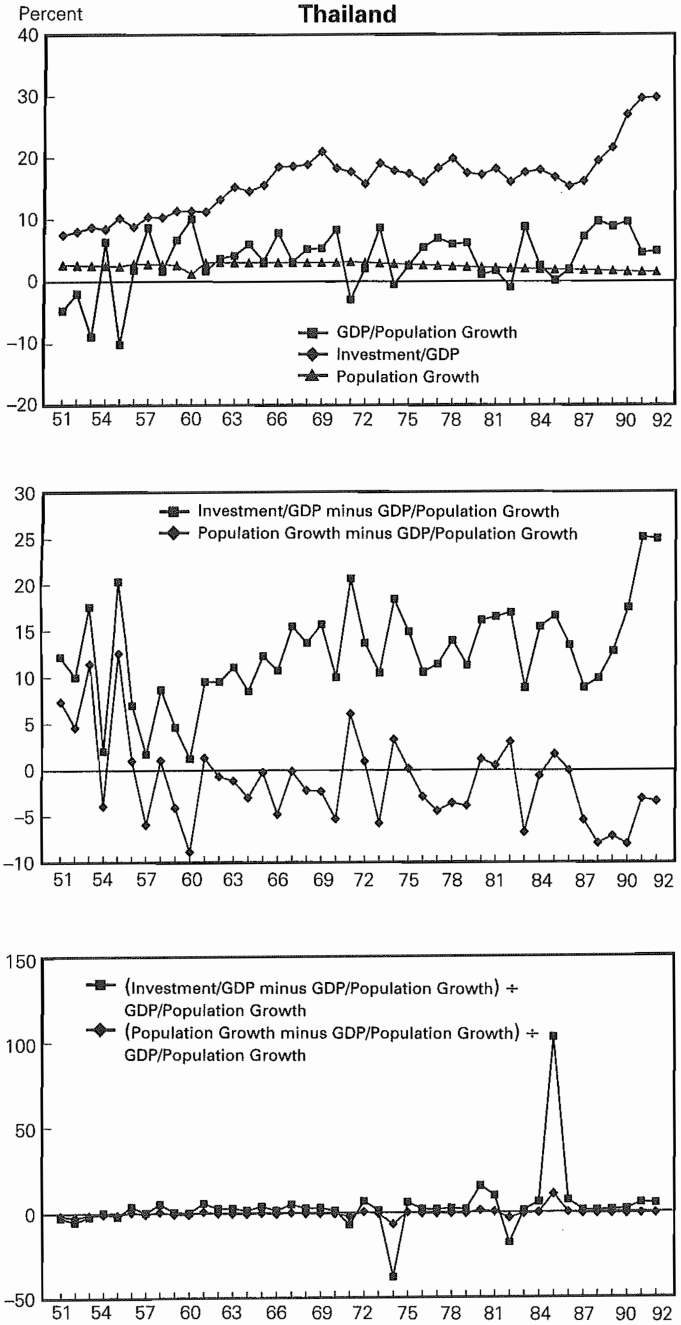




Source of data: Summers and Heston (1991).

Appendix: Does Investment Rise Before, or After, the Growth Takeoff?

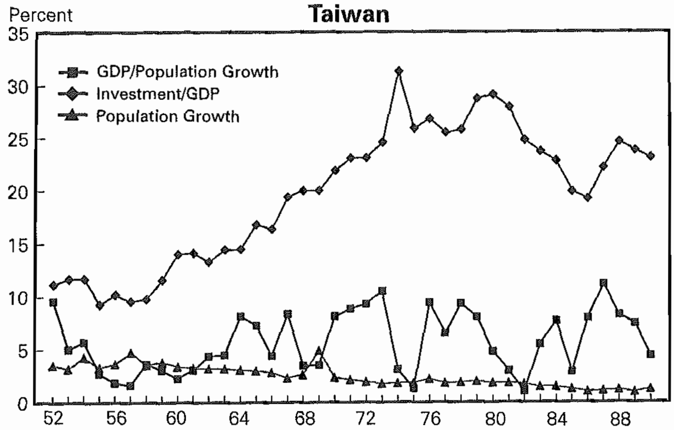
Figure 2
Thailand

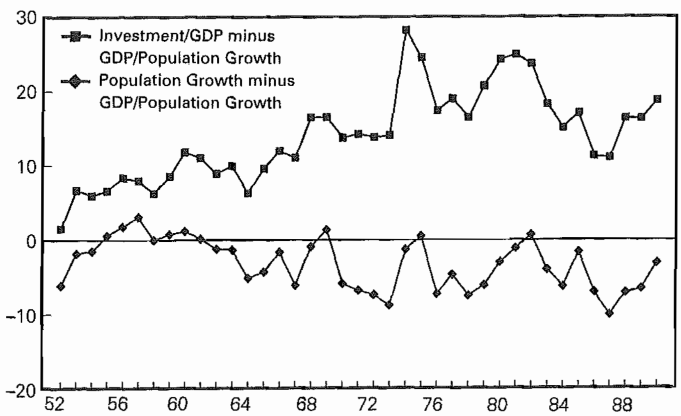


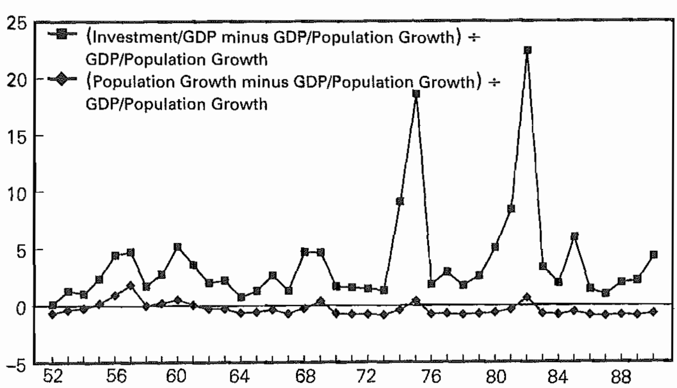
Source of data: Summers and Heston (1991).

Appendix: Does Investment Rise Before, or After, the Growth Takeoff?

Figure 3
Taiwan



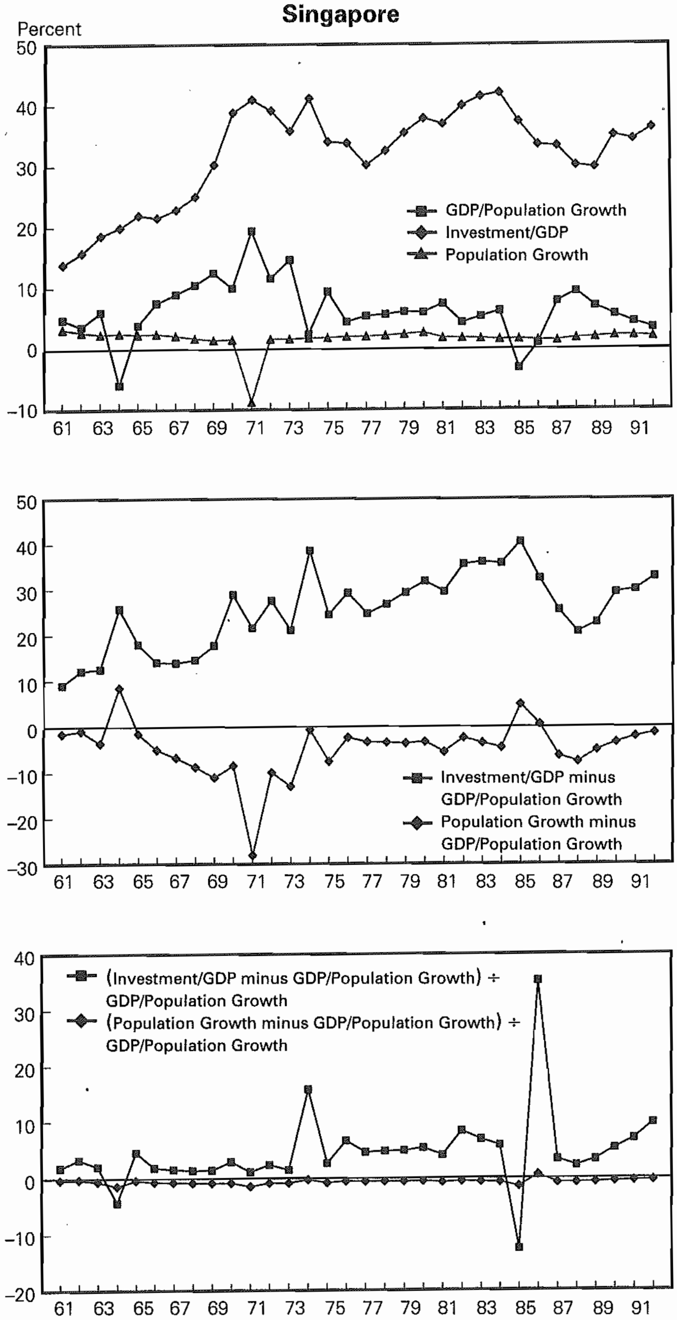




Source of data: Summers and Heston (1991).

Appendix: Does Investment Rise Before, or After, the Growth Takeoff?

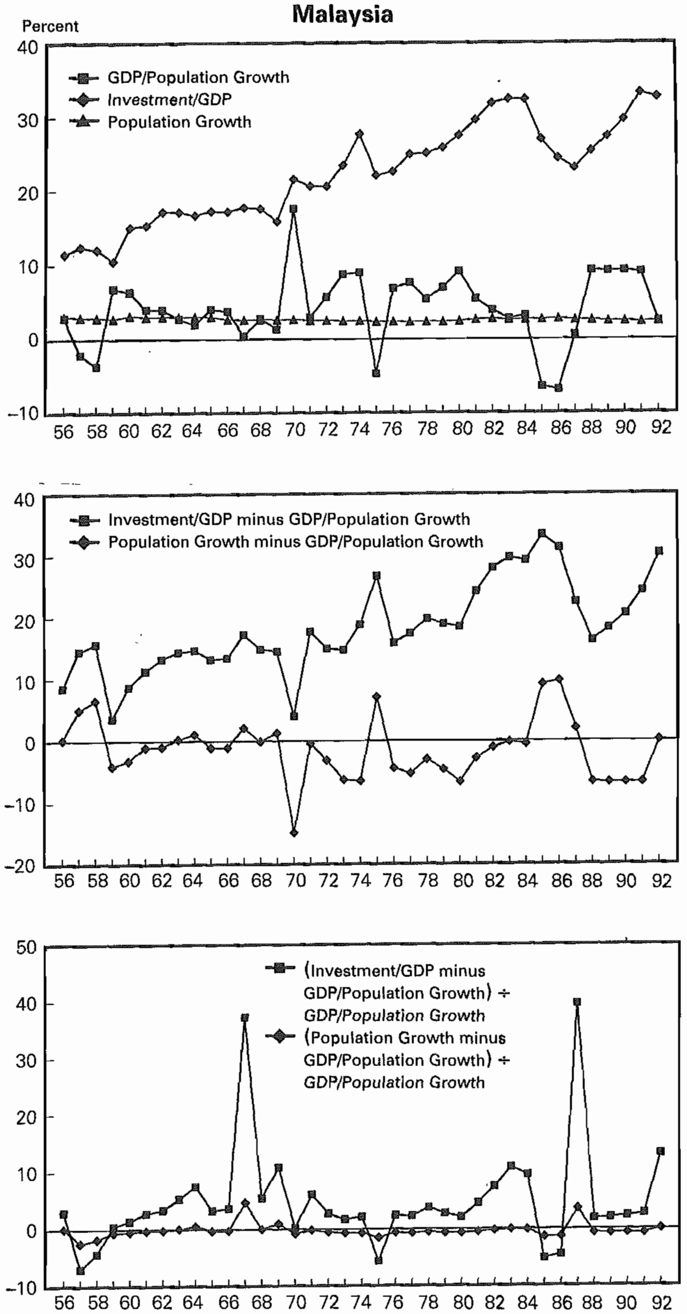
Figure 4
Singapore



Source of data: Summers and Heston (1991).

Appendix: Does Investment Rise Before, or After, the Growth Takeoff?

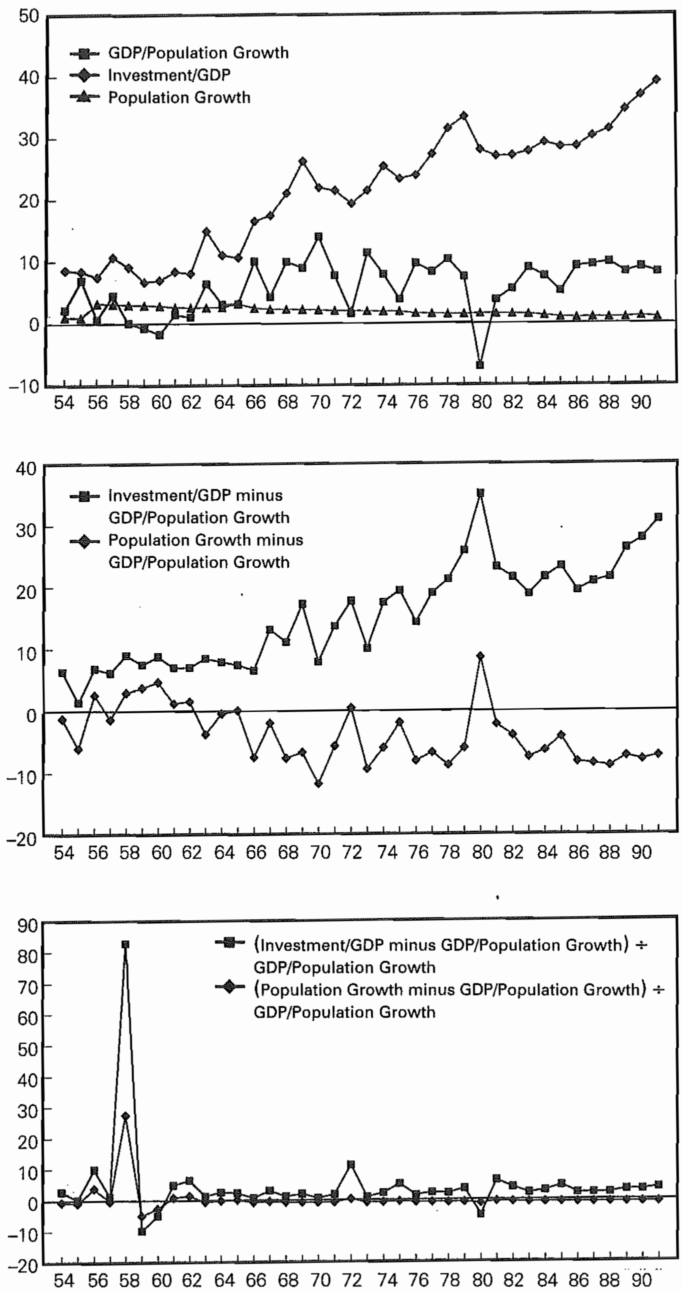
Figure 5
Malaysia



Source of data: Summers and Heston (1991).

Appendix: Does Investment Rise Before, or After, the Growth Takeoff?

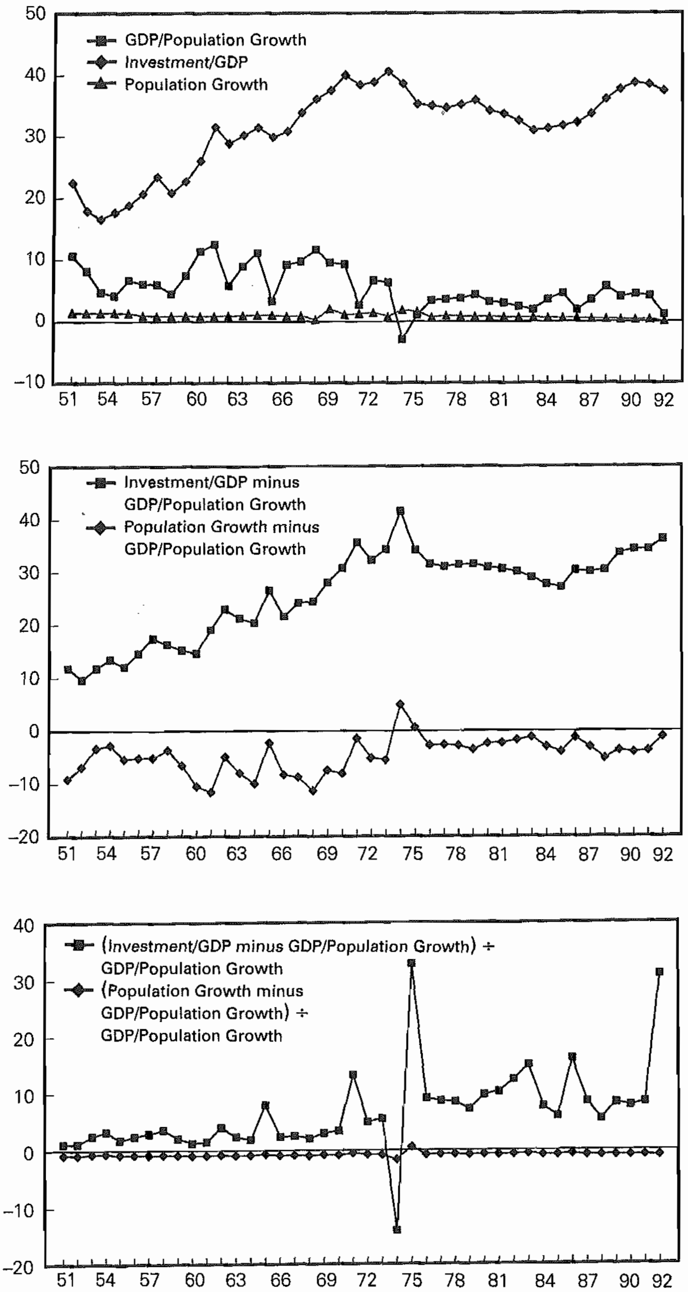
Figure 6
South Korea



Source of data: Summers and Heston (1991).

Appendix: Does Investment Rise Before, or After, the Growth Takeoff?

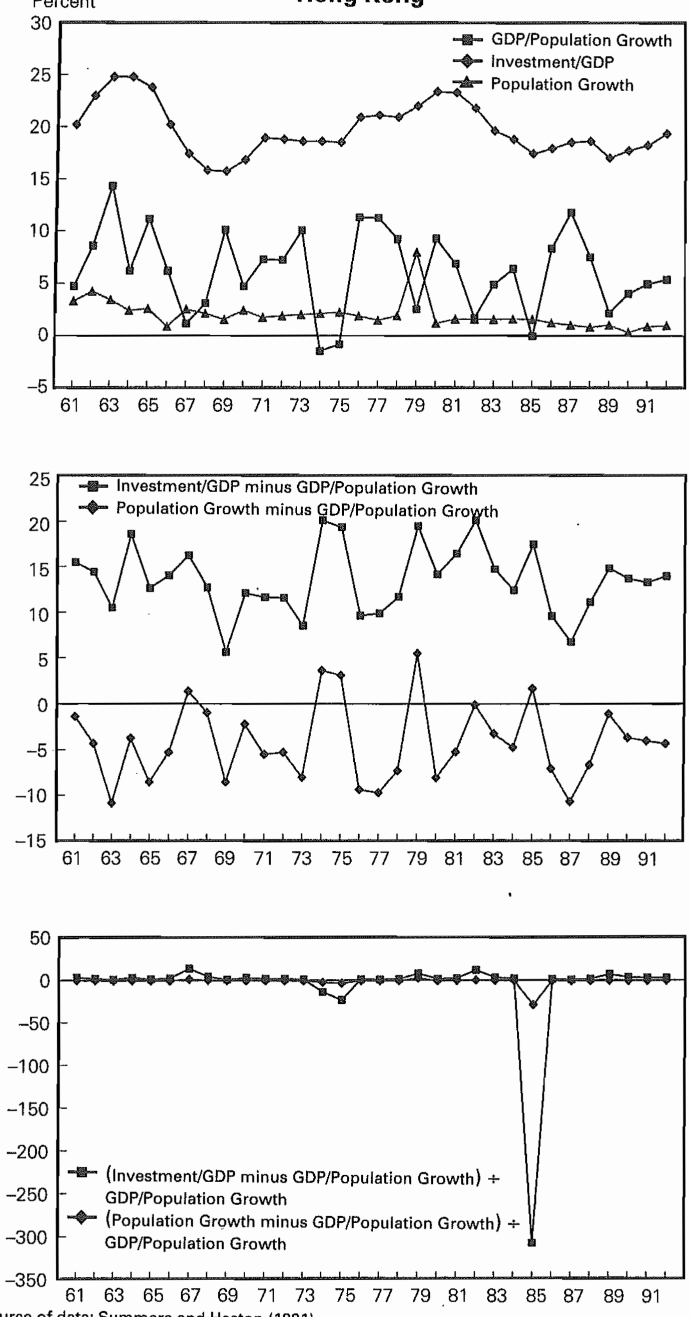
Figure 7
Japan



Source of data: Summers and Heston (1991).

Appendix: Does Investment Rise Before, or After, the Growth Takeoff?

Figure 8
Hong Kong



Source of data: Summers and Heston (1991).

DISCUSSION

Adam B. Jaffe*

This paper by J. Bradford De Long provides a clear and provocative overview of a number of issues related to long-run trends in economic growth. The paper makes five important points. First, the historical record provides us with the task of reconciling the fact that income per capita has been diverging across nations (unconditional divergence) at the same time that countries individually appear to be converging towards the steady-state income levels implied by their savings and population growth rates (conditional convergence). Second, population growth rates are endogenous, tending to decline as per capita income rises. Third, the real price of investment goods is also endogenous, and tending to decline as income rises. Fourth, both of these "positive feedback" effects amplify the impact of differences in productivity across countries. And fifth, such productivity differences are not determined solely, or perhaps even primarily, by "technology" as that term is normally defined.

There is much that I agree with in this presentation, at least qualitatively. In my comment, I wish to make three points that bear primarily on the interpretation and implications of these findings. First, I believe that the evidence for the *qualitative* endogeneity of population growth and the real price of investment goods is compelling. These phenomena undoubtedly are important in understanding the historical record, particularly the dramatic failure of *some* of the world's underdeveloped countries to grow. Second, it is less clear that modeling these phenomena as continuous functions, and analyzing their effects in the steady state, is the most useful approach. The change in population

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growth, particularly, is more likely to behave as a one-time transition, its occurrence facilitated by high income. Finally, I would put aside the semantic question of which shifters of the aggregate production function ought to be labeled "technology" and which "not technology." But I would endorse the charge to disaggregate the different sources of such shifts and to understand how economic incentives and effects differ for different sources of productivity improvements.

The Case for Qualitative Endogeneity Is Compelling

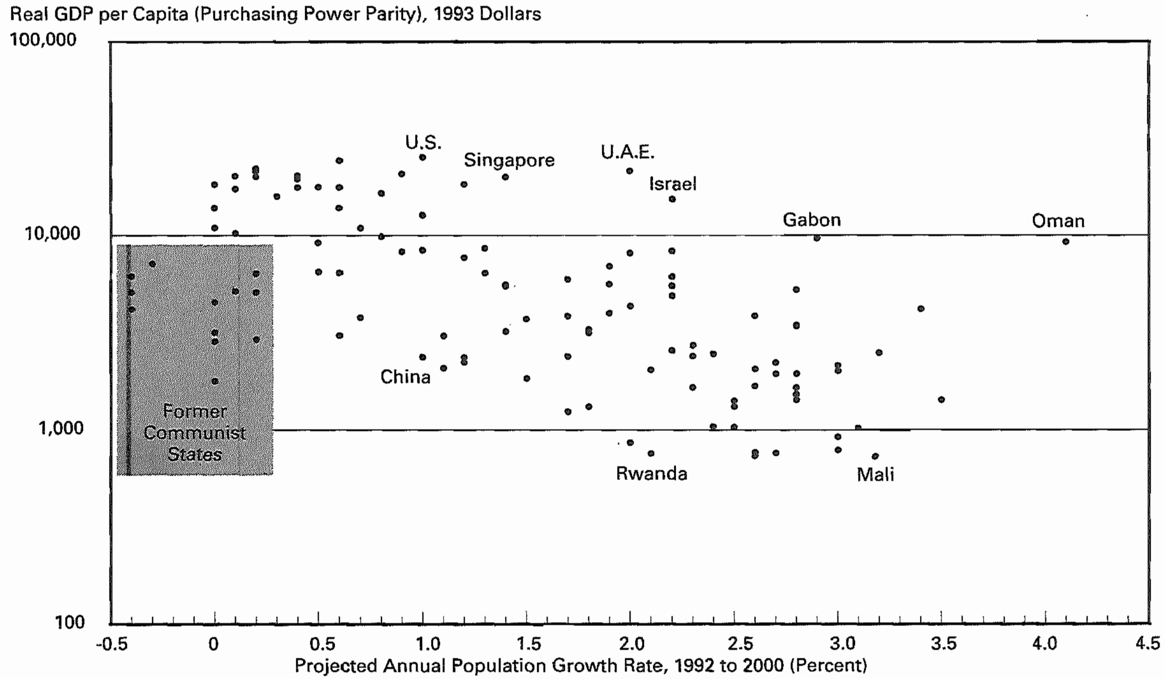
De Long's paper makes the case for the effect of income on population growth primarily by reference to the historical record in the United States. This case can be augmented by the cross-sectional evidence presented in my Figure 1. This plot shows a strong negative relationship between the log of purchasing power parity (PPP) per capita income and the rate of population growth. The simple correlation coefficient between the two series is about −0.6, and a regression line implies that an increase in income from $1,000 to $10,000 per capita is associated with a decline in population growth from about 2.5 percent per year to about 1.5 percent per year. Of course, causality runs in both directions here. But the magnitude of the relationship makes it implausible that it is due entirely to high population growth leading to low income per head. If two countries started out at the same income level, but one had population growth of 1.5 percent and one had population growth of 2.5 percent, it would take 156 years for the per capita income of the less fertile country to reach 10 times that of the other, all else equal. Hence, the cross-section evidence supports the proposition that the countries in the lower right-hand corner of the scatter have high rates of population growth *because* they have low income, to a significant extent.

My acceptance of the effect of income on the price of investment goods has a theoretical rather than an empirical basis. By definition, improvements in productivity make goods and services cheaper (in real terms) than they used to be. It is clear that productivity improvements over the last century have been disproportionately concentrated in manufactured goods, for which the application of non-animal energy and techniques of mass production have dramatically increased output.[1] This means that the real price of manufactured goods has fallen faster than the real price of services. If investment draws on manufactured goods more

[1] The true *extent* of the concentration of productivity improvements in manufacturing is difficult to determine, because output of the service sector is so hard to measure. But the direction of the bias is not in doubt.

Figure 1

The Relationship between per Capita Income and Population Growth



than it draws on services, then it has to be the case that the relative price of investment goods falls as productivity rises.

Note that this positive feedback mechanism, and its resulting implications for unconditional divergence, do not depend on international trade. Completely autarkic economies would enjoy the same positive feedback as productivity rose, and this positive feedback would amplify income differences resulting from productivity differences. The real exchange rate figures provided in De Long's paper are the manifestation of the underlying disproportionate rates of productivity improvement, not the cause.

Feedback Effects Are Not Smooth or Continuous

Referring back to Figure 1, the correlation between log income and population growth falls to −0.3 if only countries above the median income (about $3,000) are considered. For countries above $10,000 (the income level where the regression line crosses the U.S. population growth rate of 1 percent), the correlation is actually +0.15, though this positive correlation is not significantly different from zero. Thus, among the approximately 30 countries with income at least as high as Slovenia or Korea, there appears to be no further depressing effect of income increases on population growth. Hence, rather than a function $\phi \ln(y)$ as modeled by De Long, it would seem more appropriate to think of a demographic transition that countries must traverse, reducing their population growth rate from something like 2.5 percent per year to something like 1 percent or less. With the exception of small, natural resource-rich countries and countries with high immigration rates, all wealthy countries have made this transition. Rising income helps in making this transition, but it is clearly not a necessary condition, as demonstrated by the important examples of China and the other formerly Communist states.[2]

This one-time demographic transition has different steady-state implications than the model analyzed by De Long. Essentially, two classes of steady states exist, one class in which the demographic transition has been made, and one class in which it has not. The two classes will have very different levels of per capita income, but within classes the amplification effect described by De Long for differences in initial productivity levels will not operate. One way to think of it may be that higher productivity increases the *probability* of making the demographic transition, rather than increasing steady-state income per se.

This suggests that the endogeneity of population growth was more

[2] Interestingly, very few countries that have achieved population growth of 1 percent or less are not *either* high-income or once-Communist.

important historically than it will be prospectively. While it clearly helps us in understanding what happened in the United States over the past century and what will happen to the countries of sub-Saharan Africa over the next several decades, it is apparently irrelevant to understanding what will happen in China or the former Soviet Union.

Finally, understanding that income affects population growth, and probably does so in a highly nonlinear way, has implications for the econometric specification of the conditional convergence regressions that De Long discusses. Accepting the population growth rate as a nonlinear function of income suggests that the conditional convergence regressions have to be estimated as part of some kind of nonlinear system of equations.

Sources of Differences in Total Factor Productivity Across Time and Space

I do not think that it is productive to engage in extended debate regarding which factors that shift production functions ought to be labeled technology and which ought to be labeled something else. What I do think is productive is to recognize that production functions differ for several distinct reasons, and with different implications for economic analysis. My personal list would look something like this:

- *Hardware*: technology embodied in equipment;
- *Software*: technology embodied in digital programs, training manuals, textbooks, and other places where knowledge is encoded in ways that can be read by others;
- *Human capital*: skills that can be taught, or acquired through learning by doing;
- *Ideas*: knowledge carried by humans in their minds that cannot be or is not encoded in software;
- *Institutional and market factors*: political, legal, and social forces that affect efficiency;
- *Idiosyncrasies*: everything else.

These shifters of the production function differ in the nature of incentives that surround their creation and in the economic forces that govern their spread. For example, ideas are *nonrival* in use, meaning that their use in one context does not deplete them. Software also is largely nonrival, equipment is less so, and human capital is largely rival. This means that their contribution to output is likely to be characterized by increasing returns to scale, with implications for growth as captured in the new growth theory models.

Another important characteristic is the extent to which factors are *excludable*, meaning that it is possible to prevent people who do not pay for them from using them. Human capital is mostly excludable, but hardware and software are only partially so. This means that their creation produces spillovers, implying that their contribution to output and hence growth exceeds their returns to their creators. Finally, hardware and software are largely portable and tradable, facilitating their diffusion around the world; human capital and ideas are much less so. By identifying and analyzing these distinct categories, we can begin to understand the economic forces driving productivity improvement and hence growth.