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Some Macroeconomics for the 21st Century

Robert E. Lucas Jr.

Economic growth in the second half of the 20th century has been so different from any earlier period in history that anyone educated in the 1950s has been led to a new view of the world economy simply by watching events unfold. During the 30-year period 1960–1990, production in the world as a whole—Communists, former colonies, *everyone*—grew at 4 percent per year, while world population grew at 2 percent per year. The real income of an average person has more than doubled since World War II and the end of the European colonial age.

This remarkable growth in income per person has taken place very unevenly: The average figure combines the experiences of economies that have stagnated at pre-industrial income levels with those of other economies, equally poor in 1950, that have industrialized at unprecedented rates. The stakes in understanding the forces that determine which of these paths a given economy will follow are thus very high, and these high stakes have attracted a great deal of interesting research in recent years. Theorists have proposed a variety of explicit models designed to capture aspects of the diffusion of the industrial revolution that is now taking place, and to see where we may be headed.

In this note I will present a numerical simulation of one such model, a simplified version of the Tamura (1996) model of world income dynamics, based on technology diffusion. The model makes predictions for trends in average world income growth that accord well with observation. It makes predictions about the evolution of the relative income distribution that fit the history documented in Pritchett (1997). I will apply the model to the interpretation of the 1960–90 period, which has been the subject of intense econometric examination based on the Penn World Table data set, described in Summers and Heston (1991). I will also use the

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model to forecast the course of world income growth and income inequality over the century to come.

A Model of Growth

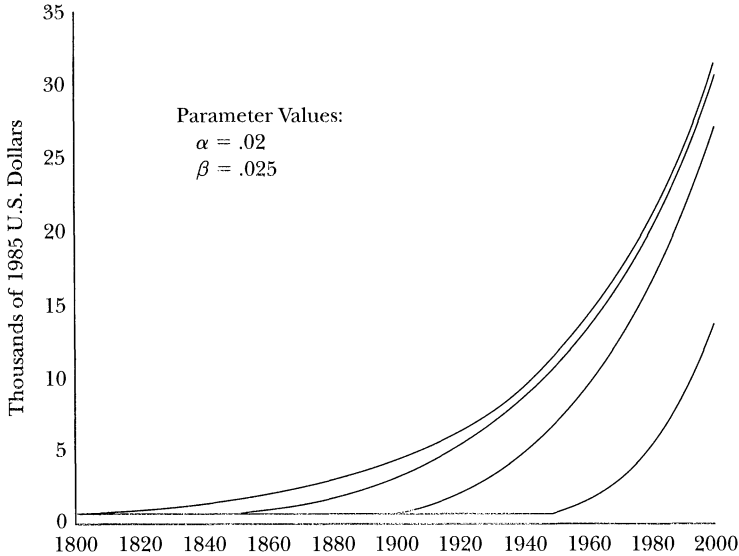
We consider real production per capita, in a world of many countries evolving through time. For modelling simplicity, take these countries to have equal populations. Think of all of these economies at some initial date, prior to the onset of the industrial revolution. Just to be specific, I will take this date to be 1800. Prior to this date, I assume, no economy has enjoyed any growth in per capita income—in living standards—and all have the same constant income level. I will take this pre-industrial income level to be \$600 in 1985 U.S. dollars, which is about the income level in the poorest countries in the world today and is consistent with what we know about living standards around the world prior to the industrial revolution. We begin, then, with an image of the world economy of 1800 as consisting of a number of very poor, stagnant economies, equal in population and in income.

Now imagine all of these economies lined up in a row, each behind the kind of mechanical starting gate used at the race track. In the race to industrialize that I am about to describe, though, the gates do not open all at once, the way they do at the track. Instead, at any date t a few of the gates that have not yet opened are selected by some random device. When the bell rings, these gates open and some of the economies that had been stagnant are released and begin to grow. The rest must wait their chances at the next date, $t + 1$. In any year after 1800, then, the world economy consists of those countries that have not begun to grow, stagnating at the \$600 income level, and those countries that began to grow at some date in the past and have been growing every since.

Figure 1 shows the income paths for four of these economies. The exact construction of the figure is based on two assumptions. (The Appendix to this paper provides an exact statement of the model.) The first is that the first economy to begin to industrialize—think of the United Kingdom, where the industrial revolution began—simply grew at the constant rate α from 1800 on. I chose the value $\alpha = .02$ which, as one can see from the top curve on the figure, implies a per capita income for the United Kingdom of \$33,000 (in 1985 U.S. dollars) by the year 2000. There is not much economics in the model, I agree, but we can go back to Solow (1956) and to the many subsequent contributions to the theory of growth for an understanding of the conditions under which per capita income in a country will grow at a constant rate. In any case, it is an empirically decent description of what actually happened.

So much for the leading economy. The second assumption that underlies Figure 1 is that an economy that begins to grow at any date after 1800 grows at a rate equal to $\alpha = .02$, the growth rate of the leader, *plus* a term that is proportional to the percentage income gap between itself and the leader. The later a country starts

Figure 1
Income Paths, Selected Economies



to grow, the larger is this initial income gap, so a later start implies faster initial growth. But a country growing faster than the leader closes the income gap, which by my assumption reduces its growth rate toward $.02$. Thus, a late entrant to the industrial revolution will eventually have essentially the same income level as the leader, but will never surpass the leader's level. One can see this catch-up behavior in the other three curves of Figure 1, which correspond to economies that began growth in 1850, 1900, and 1950.

To quantify the speed at which this catching up takes place, we need to put a value on the constant of proportionality β that relates the income gap between two countries to their relative growth rates. Consider, for example, the country that begins growth in 1850. In 1850, this country has the pre-industrial income of \$600, whereas the leader has been growing from this base for 50 years at the constant rate $\alpha = .02$. Thus, the leader's income in 1850 is $e^{(.02)50} = e$ times the pre-industrial level. The *percentage* gap is the natural logarithm of this multiple, $\ln e$, which equals 1. I set the parameter β equal to $.025$, which amounts to assuming that the new entrant in 1850 grows initially at the rate $\alpha + \beta = .02 + .025 = .045$. Every 50 years, this late entrant bonus increases by another $.025$, so that the entrant in 1900 begins growth at $\alpha + (2\beta) = .07$, the 1950 entrant begins at $\alpha + (3\beta) = .095$, and so on. These are the assumptions underlying Figure 1: They capture the well-known facts that the late entrants have much higher initial growth rates than the early entrants but do not surpass their income levels.

At any date from 1800 on, the world described by the model that generates

Figure 1 is made up of economies that began to grow in 1801, those that began in 1802, and so on into the future—for there are still pre-industrial economies in the world today. The world economy is a kind of weighted average of the economies shown in Figure 1. To predict the course of the world economy, we need to know these weights, to know how many economies fall into each of these income categories.

Initially I tried a constant hazard rate model of starting times. That is, I assumed that *if* a country has not begun to develop by date t , the probability it starts to grow at that date—its “hazard rate”—is some value λ that is independent of t . This model failed to fit the facts that the industrial revolution spread very slowly at first, requiring a small value of λ for the 19th century, and has diffused rapidly in the postwar period, requiring a high λ for the late 20th century. For this reason, I assumed a variable hazard rate, beginning at the level $\lambda_m = .001$ in 1800, and gradually evolving upward towards a maximum value of $\lambda_M = .03$.

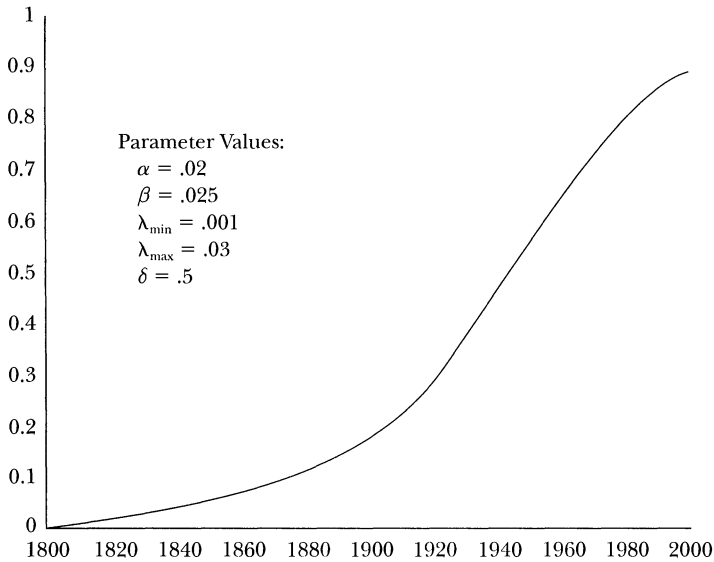
To describe the transition of λ from .001 to .03, I used the model of the diffusion of the industrial revolution proposed by Tamura (1996). In Tamura’s model, an economy departs a stagnant equilibrium and begins to grow when the world stock of knowledge attains a critical level. Assuming that these critical levels differ across the economies that have not yet begun to grow, the model implies a distribution of starting dates. Specifically, I assumed that the hazard rate $\lambda(t)$ applying to an economy that has not yet begun to grow is a weighted average of the two hazard rates λ_m and λ_M , where the weight that applies to the high hazard rate λ_M is assumed to be an increasing function of the average *level* of income in the world at date. In 1800, when all economies have an income level of \$600, this weight is zero and the hazard rate is .001. As average income in the world grows, the weight on λ_M increases towards one. I gave the formula a little extra flexibility by leaving a parameter δ governing the effect of world income on the hazard rate free to be determined. (Again, see the Appendix for details.)

With this information, I constructed Figure 2, a plot of the fraction of economies that have begun to develop against time. This curve describes the *unconditional* probabilities, built up in the usual way from the model of hazard rates—*conditional* probabilities—described in the last paragraph. Note that Figure 2 cannot be drawn without the information obtained from the construction of Figure 1: Under the Tamura (1996) model, the probability that a stagnant economy begins to industrialize depends on the level of world income, which in turns depends on the past experience of the growing economies.

The shape of the cumulative distribution function that is plotted in Figure 2 captures the idea that the industrial revolution diffused slowly in the 19th century and then accelerated dramatically through much of the 20th century. Toward the end of this century the diffusion slows, but only because there are so few people left in stagnant, pre-industrial economies. According to the figure, almost 90 percent of the world is now growing.

Everything is now in place to calculate the past, present, and future of this world economy. Figure 1 displays the growth of economies that differ by the dates at which they began to industrialize. Figure 2 describes the distribution of econo-

Figure 2
Fraction of Economies Growing, by Year

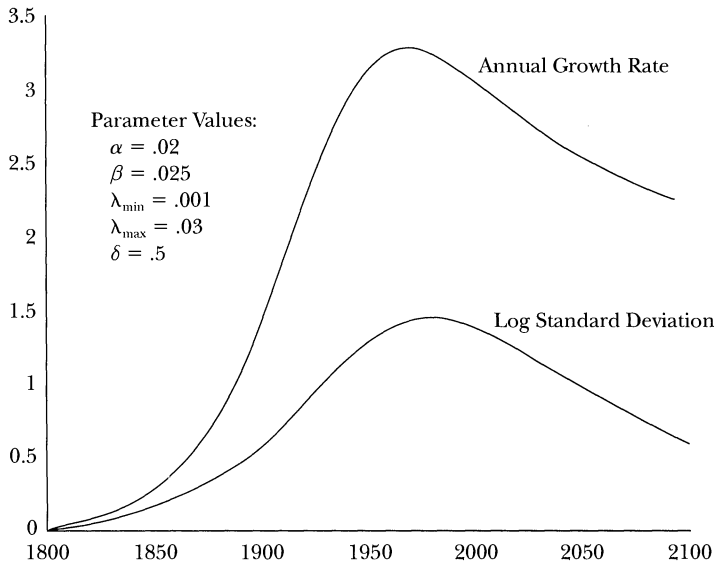


mies over different dates for the onset of industrialization. Figure 3 combines this information to display two time series. One is the rate of growth of average world production. The other is a particular measure of the degree of inequality in the world economy: the standard deviation of the logarithm of income levels at each date. (See equation 6 in the Appendix.) Both series are extended through the coming century, to 2100.

According to Figure 3, the growth rate of world production per person peaked out around 1970, at something like 3.3 percent, and can be expected to decline thereafter. From the underlying theory, we know that if the figure were extended past 2100, it would approach 2 percent, the assumed growth rate of the leading economies and hence the asymptotic growth rate of all economies. The log standard deviation of incomes, the measure of inequality I am using, begins at zero, reflecting the assumption that all economies were at the common, constant income level of \$600 before 1800. This inequality measure rose at an increasing rate until well into the 20th century, and peaked sometime in the 1970s. It, too, is now declining, and according to the theory it will ultimately return to zero.

This is not the place for a detailed discussion of the evidence that bears on the parameter values I have used in this simulation, but I would like to say a few words about accuracy. The value of \$600 in 1985 U.S. dollars is about right (plus or minus \$200) for traditional agricultural societies, contemporary and ancient. The growth rate $\alpha = .02$ was chosen to get the per capita income levels of the leading economies about right for 1990, given the \$600 level assumed for 1800. But the per capita income growth

Figure 3

World Growth Rate and Income Variability

in the leading economies is more like .015 in the postwar period, and even slower than that since 1970. This leads to an overstatement (.033) of peak world growth, and probably a growing overstatement of growth in the coming century. These deficiencies are surely correctable with four free parameters, but diminishing returns set in quickly in calibrating a model as mechanical as this one.

The model that generates these figures is a model of spillovers, in two ways. The probability that a pre-industrial economy begins to grow is assumed to depend on the level of production in the rest of the world. Once an economy begins to grow, its income growth rate is assumed to depend on its income level *relative to* incomes in the leading economies. Tamura (1996) puts a human capital externality interpretation on these spillovers: The idea that knowledge produced anywhere benefits producers everywhere. Other interpretations have been proposed and are being actively pursued in current research. One approach is to put a political interpretation on spillovers: Governments in the unsuccessful economies can adopt the institutions and policies of the successful ones, removing what Parente and Prescott (1994) call “barriers to growth.” Still a third approach emphasizes diminishing returns and the flow of resources: High wages in the successful economies lead to capital flows to the unsuccessful economies, increasing their income levels.

Gaining a quantitative understanding of all of these forces for diffusion—and, as Parente and Prescott (1994) would stress, the forces that oppose them—is the central question of the theory of economic growth and development. My own emphasis would agree with Tamura’s (1996), but there is no reason to pursue this

interesting, unresolved debate here. All three sources of diffusion are surely present, important, and complementary. For the purposes of this paper, there is no need to know their relative strengths.

Discussion

The behavior of the model described in the last section is consistent with most of what we know about the behavior of per capita incomes in the last two centuries. Per capita income growth, beginning in one economy, diffuses gradually to other economies. As this occurs, average income growth rises from zero to higher and higher levels. Eventually, the rapid, catch-up growth of late entrants leads to world average income growth exceeding the growth rate of the leading economies. All of these events have already occurred, though the last emerged only since World War II.¹

The long phase of increasing income inequality predicted by the model has also occurred. This is the point of Pritchett (1997) and is documented in many other sources. In the model, this phase comes to an end smoothly, so there is a phase in which inequality is neither growing or shrinking. As I have calibrated the model, the years 1960–90 make up such a phase. The model is thus consistent as well with the fact that the question of whether inequality is shrinking, or whether convergence is occurring, can be a subtle statistical question if the answer is sought in a data set covering only a few decades.

Some other phenomena that have been remarked on in the empirical literature based on the Penn World Tables also are present in the world of Figures 1–3. For example, the model fits the fact that in the postwar period growth rates vary much less among the advanced economies than among the poor and middle income economies. It presupposes the existence of an ever-growing “convergence club”: a set of rich economies within which income inequality is falling, even in a world in which overall inequality is rising or not changing very much. It can be interpreted as implying a focus on *conditional* convergence, since conditional on both having left the stagnation state, any two economies are getting closer to each other. But of course, the much more interesting implication of the model is that convergence is *unconditional* as well.

An observer of the 1960–90 time series generated by the model might conclude from the approximate constancy of the log standard deviation of income over this period that he was observing 30 consecutive drawings from an unchanging distribution of relative incomes, even though the position of individuals within the distribution was changing. This is the way Jones (1997), Quah (1997), and Chari, Kehoe and McGrattan (1996) viewed observations from the Penn World Table. But we obviously cannot interpret income data over the last century and a half in this

¹ In the model, world average annual growth exceeds 2 percent before 1920. In general, the model assigns too much economic development, relative to what actually happened, to the interwar period and too little to the postwar period. Since the model has neither wars nor depressions, perhaps this is not surprising.

way, or we would predict a relative income variance for 1850 that is equal to today's, and thus much higher than the variance in the data reviewed by Pritchett (1997). I think Jones (1997) makes exactly the same mistake when he runs his Markov model forward and obtains the prediction that no variance reduction can be expected in future decades.

The model underlying Figures 1–3 is mechanical, without much in the way of explicit economics. It lacks an explicit description of the preferences, technology, and market arrangements that give rise to the implied behavior. Its parameters are not (I hope!) invariant under changes in policy. It entirely omits factors, like capital flows and the demographic transition, that continue to play essential roles in the diffusion of the industrial revolution. It treats important unpredictable forces as though they were deterministic, and other effects that might be predicted as though they were random draws. The model does not address, or attempt to address, many of the central questions of the industrial revolution: why it began in England, why it began in the 18th century, why it spread first to other European economies, or why it diffused so slowly for so long.

But for all these deficiencies, it is undeniably an *economic* model: No one but a theoretical economist would have written it down. It is not a theory formed by statistical methods from the Penn World Table or any other single data set. Despite its obvious limitations, the model has nontrivial implications about the behavior of the world economy over the next century. It predicts that sooner or later everyone will join the industrial revolution, that all economies will grow at the rate common to the wealthiest economies, and that percentage differences in income levels will disappear (which is to say, return to their preindustrial levels).

My conjecture is that these predictions are not due to the mechanical character of the model I have developed here, that on the contrary they will hold up as our theories of growth and development are refined, as explicit preferences, technologies, and market structures are introduced, and economic equilibria calculated. The central presumption of the general equilibrium models that are in wide use in macroeconomics today is that people are pretty much alike, that the differences in their behavior are due mainly to differences in the resources that history has placed at their disposal. Of course, there is a vast class of specific theories that are consistent with this presumption, but how can any such theory generate large, permanent differences in incomes across societies that interact in a world economy? Ideas can be imitated and resources can and do flow to places where they earn the highest returns. Until perhaps 200 years ago, these forces sufficed to maintain a rough equality of incomes across societies (not, of course, within societies) around the world.

The industrial revolution overrode these forces for equality for an amazing two centuries: That is why we call it a “revolution.” But they have reasserted themselves in last half of the 20th century, and I think the restoration of inter-society income equality will be one of the major economic events of the century to come. Of course, this does not entail the undoing of the industrial revolution. In 1800 all societies were equally poor and stagnant. If by 2100 we are all equally rich and growing, this will not mean that we haven't got anywhere!

Conclusions

How did the world economy of today, with its vast differences in income levels and growth rates, emerge from the world of two centuries ago, in which the richest and the poorest societies had incomes differing by perhaps a factor of two, and in which no society had ever enjoyed sustained growth in living standards? I have sketched an answer to this question in this note, an answer that implies some very sharp predictions about the future. If you are reading this in the year 2100, in a retrospective issue of the *Journal of Economic Perspectives*, I ask you: Who else told you what the macroeconomics of your century would look like, in advance, with such accuracy and economy?

Appendix

The equations used to generate Figure 1–3 are as follows. Let $y(s, t)$ denote production per capita in economy s at date t , where each economy is named by the date s at which it switched from stagnation to sustained growth. For the leading economy, $s = 0$, assume that

$$(1) \quad y(0, t) = y_0(1 + \alpha)^t.$$

For economies $s = 1, 2, \dots$ assume that

$$(2) \quad \frac{y(s, t+1)}{y(s, t)} = (1 + \alpha) \left(\frac{y(0, t)}{y(s, t)} \right)^\beta.$$

Figure 1 plots $y(s, t)$ against t for $s = 0, 50, 100$, and 150 , with $y_0 = .6$ (that is, 0.6 thousand) and $\alpha = .02$ and $\beta = .025$.

Let $\pi(t)$ be the probability that an economy begins to grow at date t , and let $\lambda(t)$ be the probability that growth begins at t conditional on stagnation up to t . Then

$$(3) \quad \pi(t) = \lambda(t) \left[1 - \sum_{s < t} \pi(s) \right].$$

Let $x(t)$ be average world income at t :

$$(4) \quad x(t) = \sum_{s \leq t} \pi(s) y(s, t) + \left[1 - \sum_{s \leq t} \pi(s) \right] y_0.$$

I assume that this stock $x(t)$ defined in equation 4 determines the fraction of economies that begin to grow at date t according to the formula:

$$(5) \quad \lambda(t) = \lambda_m \exp(-\delta(x(t) - y_0)) + \lambda_M [1 - \exp(-\delta(x(t) - y_0))],$$

where the parameters δ , λ_m , and λ_M are all positive, and $\lambda_m < \lambda_M$. At $t = 0$, before any economy has begun to grow, $x(t) = y_0$ and $\lambda(0) = \lambda_m$. As $t \rightarrow \infty$, $x(t) \rightarrow \infty$ and $\lambda(t) \rightarrow \lambda_M$.

Now suppose the numbers $\{y(s, t)\}$ are calculated using (1) and (2). Then the series $x(t)$, $\pi(t)$, and $\lambda(t)$ are determined recursively using (3)–(5), as follows. For $t = 0$, $x(0) = y_0 = 600$. Then (5) gives $\lambda(0) = \lambda_m$ and then (3) gives $\pi(0) = \lambda_m$. Now for $t > 0$, suppose that $\{x(s), \pi(s), \lambda(s)\}$ have been calculated for $s < t$. Then using $\{y(s, t)\}$ and (4), $x(t)$ is calculated; using this value and (5), $\lambda(t)$ is calculated; using this value and (3), $\pi(t)$ is calculated. This algorithm, with the parameter values indicated, produced Figure 2.

The log standard deviation $V(t)$ of income levels is defined as:²

$$(6) \quad [V(t)]^2 = \sum_{s \leq t} \pi(s) \left[\ln \left(\frac{y(s, t)}{x(t)} \right) \right]^2 + \left[1 - \sum_{s \leq t} \pi(s) \right] \left[\ln \left(\frac{y_0}{x(t)} \right) \right]^2.$$

■ *The model described in this note was developed in the course of stimulating discussions with V. V. Chari, Patrick Kehoe, and Ellen McGrattan, during my 1997 visit at the Federal Reserve Bank of Minneapolis.*

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² Note that I have made the entirely arbitrary choice to use an arithmetic, not a geometric, average to define $x(t)$.