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Susanto Basu
David N. Weil

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ABSTRACT

We present a model of growth and technology transfer based on the idea that technologies are specific to particular combinations of inputs. We argue that this model is more realistic than the usual specification, in which an improvement in any technique for producing a given good improves all other techniques for producing that good. Our model implies that technology improvements will diffuse only slowly, even if there are no barriers to the flow of knowledge and no adoption costs. On the other hand, although our basic production technology is of the "Ak" variety, technology diffusion implies that countries with identical policies and different initial incomes do eventually converge to the same level of per-capita income. We argue that a model with appropriate technology and technology diffusion is more appealing, and has more realistic predictions for long-run convergence and growth, than either the standard neoclassical model or simple endogenous-growth models.

Susanto Basu
Department of Economics
University of Michigan
611 Tappan Street
Ann Arbor, MI 48109-1220
and NBER
sbasu@umich.edu

David N. Weil
Department of Economics
Box B
Brown University
Providence, RI 02912
and NBER
david_weil@brown.edu

Do all countries in the world use the same technology? Many would view even the posing of this question as absurd. In India, fields are harvested by bands of sweating workers, bending to use their scythes. In the United States, one farmer does the same work, riding in an air-conditioned combine. Yet an economist might argue that the two countries do have access to the same technology and simply choose different combinations of inputs (points along an isoquant) due to differences in factor prices. But this stance raises a new problem when one considers technological change: do technology improvements that raise the productivity of combines in America also improve the productivity of farmers in India? The answer obviously seems to be No. However, standard models of economic growth, which index technology by a single coefficient that is independent of factor proportions, would say Yes. In these models, technology improvements in the United States should immediately improve total factor productivity in India — which seems counterfactual. To escape this problem, standard models often assume that technological improvements are country-specific. But since there are many examples of technology transfer within countries, why should the flow of technology stop at national boundaries?

We provide a new way out of this quandary by focusing on the issue of appropriate technology. We believe it is reasonable to model technological advances as benefiting certain types of technologies and not others. For example, an advance in transportation technology in Japan may take the form of a refinement of the newest maglev train. Such an advance may have very few spillovers to the technology of the transportation sector in Bangladesh, which relies in large part on bicycles and bullock carts. As a convenient shortcut for modeling "appropriateness," we index technologies by capital intensity, where in the definition of capital we include both human and physical capital. Each technology is thus appropriate for one and only one capital-labor ratio. We also model technological improvements as expanding the production possibilities frontier for a given capital-labor ratio. This is reasonable if one thinks of technological improvements as taking place because of learning by doing. It may also be a reasonable reduced-form model of the outcome of investment in R&D. So in our model technology transfer is not immediate because countries take time to achieve a level of development that can take advantage of the progress being made by the technology leaders.[1]

Of course, we are not the first to consider the issue of technology transfer. The models of Romer [1986, 1990] and Grossman and Helpman [1991] stress the importance of spillovers within countries. Various mechanisms have been proposed for why technology does not quickly spill over between countries. Parente and Prescott [1994] present a model in which there is a world "best practice" technology and in which different countries erect barriers that raise the cost of adopting a higher level of technology. They use their calibrated model to calculate the size of barriers to technology adoption for a number of countries. The quality-ladder models of Stokey [1991] and Grossman and Helpman [1991, ch. 9] simply assume that a fixed amount of time must elapse before high-technology "Northern" innovations spread to the labor-intensive "South." Another explanation is that countries need to invest resources to adapt a technology for their use.[2] This is an explanation in the tradition of R&D-based models. Barro and Sala-i-Martin [forthcoming] present such a model of technology diffusion based on costly imitation. In their model, increasing marginal cost of technology adoption stops the convergence rate from being infinite. Yet another possibility is that new technology is embodied in capital goods: in order to achieve state-of-the-art technology, a country needs to import state-of-the-art equipment. If there are borrowing constraints or adjustment costs, investment rates will be bounded away from infinity and technology transfer will proceed at a finite rate (Lee [1995], Mazumdar [1996]).

We view the mechanism presented in this paper as complementary to these other models of impediments to technology transfer. The existing literature focuses on the impediments to the transfer of a specific technology. We, by contrast, assume that all technology is freely available and

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[1] The concept of appropriate technology that we use is related to that of Schumacher [1973], although there are significant differences between the two. Schumacher critiqued development policies that stressed large, capital-intensive projects as a means of technology transfer. He argued that in poor countries capital-intensive processes would be unproductive due to lack of marketing and financial infrastructure, inappropriate inputs, and untrained workers. The intermediate technology movement Schumacher founded attempts to create new technologies and to locate and transfer existing technologies for small-scale, low-capital-intensive rural production. The model that we present here shares the property that capital-intensive technologies are inappropriate for poor countries, but in our model there is never a problem of countries using technologies that do not match their level of development.

[2] See, e.g., Barro and Sala-i-Martin [1995, ch 8]. Benhabib and Spiegel [1994] present empirical evidence supporting the idea that a country needs to accumulate human capital in order to increase its rate of adoption of foreign technology.

instantly transferred. But a country may nonetheless refrain from using a new technology until it reaches a level of development at which this technology would be appropriate to its needs.[3]

Within any given country, our model of technological progress is similar to that of "localised learning by doing," as introduced by Atkinson and Stiglitz [1969].[4] They argue that the standard Harrod-neutral view of technical progress — in which improvements in technology increase the productivity of all techniques of production — is not credible. They examine the opposite extreme, in which a firm (or economy) learns over time to improve the productivity of the particular mix of capital and labor that it is currently using in production. The model of learning-by-doing that we present is simply a less extreme version of the Atkinson-Stiglitz model: firms improve the productivity not only of the specific capital-labor mix that they are using, but also the productivity of similar productive techniques. When we consider a world with many countries, we assume that technological improvements made in one country are immediately available to all.

Our model of technical progress combines properties of the endogenous-growth and neoclassical growth models. As in endogenous-growth models, the long-term growth rate in our model depends on the saving rate (which is the only exogenous variable in our model). However, as in the neoclassical growth model, countries that differ in their saving rates may share a common growth rate in steady state and differ only in their levels of output. This result follows from the fact that spillovers are usually not symmetric in our appropriate-technology model: A country that is the technology leader benefits less from its followers than they benefit from it.

Since a follower country can use the technology of the leading country only if it has a sufficiently high level of development, the relation between growth and saving can be highly non-linear. Over a range of parameters, changes in the saving rate just change the steady-state level of income relative to the income of the technology leader. But outside that range, changes in the saving rate affect the growth rate. This result suggests that empirical tests of endogenous growth that attempt to estimate simple saving-growth relations might be severely misspecified.

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[3] Benhabib and Rustichini [1993] present a similar model, focusing mostly on welfare issues.
[4] See also Stiglitz [1987]. Lucas [1993] presents a similar model, in which learning by doing applies only to a specific factor mix and output good.

The observation that follower countries can benefit from the technologies developed by the leaders raises the possibility that lower-saving countries can have higher steady-state consumption. For certain parameter values, this indeed turns out to be the case. Although we do not study welfare issues in this paper, it is clear that this externality can lead countries to have lower saving rates than is socially optimal.

Our results lead us to reappraise the implications of the "conditional convergence" literature (e.g. Barro and Sala-i-Martin [1991, 1992], Mankiw, Romer and Weil [1992]). A common finding in this literature is that countries are converging to different steady-state relative income levels but to the same long-run growth rate. This result is often taken to be evidence against endogenous-growth models. Such an interpretation is not necessarily true in a world with technology transfer.[5] For example, our model generally displays exactly the same property — different relative incomes and a common growth rate — but the growth rate is endogenous. Thus, in our model, government interventions that change the national saving rate can affect the long-run growth rate. In fact, as we discuss, our model allows for the possibility of "miracles" in the sense of Lucas [1993]: countries that make rapid income gains with relatively small changes in national policies. Not only does our model predict that small increases in saving in poor countries can sometimes lead to striking income gains, it also says that such gains can come as a surprise given the parameters an econometrician would estimate in a world described by our model.

Our paper is organized as follows. In Section I we present a simple one-country model of growth in which technology advances through learning-by-doing and where the level of technology is specific to a particular degree of capital intensity. In Section II, we consider the same model in a world with two countries, in which technology moves freely. We examine the conditions under which the two countries will have different growth rates in steady state, and the conditions under which they will have different income levels but the same growth rate. We also examine the conditions under which the "follower country" can have higher consumption than the leader. Section III examines a world with more than two countries, and demonstrates the possibility that "convergence clubs" of

[5] Barro and Sala-i-Martin [forthcoming] make the same observation in a model where technology diffusion requires costly imitation.

countries with similar growth rates will arise. Section IV discusses the empirical implications of the model. We first study what it implies for the usual cross-country growth regression, and then ask whether it can explain miracles. Section V concludes.

I. The One-Country Model

Although we focus on technology spillovers between countries, we first develop our model in the context of economic growth in a one-country world. In order to highlight the novel features of our model of appropriate technology, we keep the structure very simple. For example, rather than modeling preferences explicitly, we assume a fixed saving rate. (Of course, for certain parameter values a constant saving rate may be optimal.)

In each country, many firms i produce output per worker according to the production function:

$$Y(i) = A(K,t)F(K(i)). \tag{1'}$$

$Y(i)$ and $K(i)$ are the per-firm quantities of output and capital per worker; K is the economy-wide capital-labor ratio; and t is time. We assume that $F' > 0$ and $F'' < 0$. As we noted above, we do not distinguish between human and physical capital: K comprises both. Each firm chooses its inputs taking the economy-wide level of technology, A, as given. Since firms are identical, in equilibrium $K(i) = K$.

Assuming that the firm-level production function is Cobb-Douglas and has constant returns to scale in capital and labor, the aggregate production function for per-capita output in the economy is

$$Y = A(K,t)K^{\alpha}, \tag{1}$$

where α is the share of capital in output.

As equation (1) shows, we have made one of the standard assumptions in the endogenous-growth literature, namely that there are spillovers to capital input. Our reason why the aggregate capital/labor ratio affects firm-level productivity is, however, quite different from those advanced in previous papers (e.g. Romer [1986] and Rebelo [1991]). In our model, capital accumulation allows less-developed countries to use technologies that were developed by industrialized countries, since these technical developments assume a high ratio of capital per worker. The work of DeLong and Summers [1991, 1993] supports the proposition that there are positive spillovers to capital accumulation (at least for the fraction of capital that is equipment). Clark [1987] provides a case study of textile mills in the early twentieth century, showing that mills in different countries that used the same capital equipment nevertheless had very different levels of productivity. He argues that this difference was not due to variations in other firm-level inputs, such as the quality of labor. Clark's findings are thus broadly supportive of the proposition that the productivity of individual plants depends on the general level of development of the countries in which they are located.

Capital accumulation in our model is very simple:

$$\dot{K} = sY - \delta K, \tag{2}$$

where s is the exogenous saving rate and δ is the rate of depreciation. (For simplicity, we assume that there is no population growth.)

As noted, the distinguishing feature of our model is that we allow the level of technology, $A(K,t)$, to change over time. However, we assume that there is some maximum level of the technology parameter, denoted A^*, for every value of capital per worker. This specification captures the idea that there are always new productive techniques to be developed, but after a point there is no new technique that uses a given level of capital per worker — that is, the oxcart can only be improved so much. However, we also assume that A^* increases with K, which captures the idea that technologies have increasingly high potential at higher levels of development — the maglev train can be improved more than the oxcart. One simple specification is $A^*(K) = BK^{\eta}$. We assume $\alpha + \eta = 1$.[6]

Thus, if technology were always at its maximum level, then the production function would be just $Y = BK$, as in Rebelo [1991]. In this case the growth rate of the economy would be given by

$$\frac{\dot{Y}}{Y} \equiv \dot{y} = sB - \delta .$$

(We henceforth use lower-case letters to represent natural logs of their upper-case counterparts.)

We now specify the process by which technology improves. We assume, for reasons we do not

[6] We could arrive immediately at our aggregate model by assuming that $Y(i) = AK(i)$, as in Rebelo's [1991] model, and taking A^* to be constant, but that would imply (counterfactually) that the *firm-level* marginal product of capital is constant.

model explicitly, that producing at some level of capital per worker raises the level of technology appropriate for capital/labor ratios within a neighborhood of a country's current capital/labor ratio. Specifically, we model the growth rate of technology as positive if the log distance between the country's current capital/labor ratio (henceforth called the "capital stock") and the capital stock that lets a country use a given technology is less than or equal to some positive parameter γ:

$$\begin{aligned} \dot{A}(j,t) &= \beta\left(A^{*}(j) - A(j,t)\right) && \text{if } k-\gamma < j < k+\gamma \\ &= 0 && \text{otherwise.} \end{aligned} \tag{3}$$

β is a parameter of our model. We naturally assume $\beta > 0$. The initial capital stock is k_0. We assume that, beyond a certain range, technologies were completely undeveloped at the beginning of time: i.e. we assume there exists some $x > k_0$ such that $A(j,0) = 0 \ \forall j > x$. We also assume that $A(k_0, 0) > 0$.

Equation (3) implies that a country uniformly improves technologies that are related to the technology it is currently using. We use the uniform distribution for simplicity but one could use others. For example, a triangular distribution would capture the idea that the usefulness of spillovers is proportional to the distance between a technology and the technique currently being used. Our qualitative results would not be affected by this change.

Our assumptions about how technology improves can best be understood by examining the shapes of isoquants and how they change over time. In Figure 1 we draw these isoquants, putting the *logs* of capital and labor on the axes and showing the evolution of the isoquant for producing one unit of output.[7] 45-degree lines represent constant ratios of capital to labor, with higher lines representing lower capital-labor ratios. The vertical line represents the isoquant for producing a unit of output in the standard Rebelo model, while the two convex curves are representative isoquants in our model at two different points in time. At time 0, the capital-labor ratio is K_0/L_0, and each unit of output requires inputs of capital and labor shown by point X. The line $K_0/L_0 - \gamma$ represents the lowest capital-labor ratio whose associated technology is being improved. Technologies utilizing even lower capital-labor ratios are more nearly mature and therefore closer to the isoquant of the Rebelo model. Technologies that are more capital-intensive than $K_0/L_0 + \gamma$ have not been developed

[7] Note that we temporarily depart from our convention of using "capital" to denote the capital-labor ratio. For simplicity of exposition, we implicitly use a discrete-time model.

at all, and thus the time-zero isoquant is infinitely far from the origin.[8]

The improvement in technology between time 0 and time 1 is represented by an inward movement of the isoquant along 45-degree lines. Thus, the technology corresponding to each capital-labor ratio that is "in range" is being improved by a constant fraction of its distance from the mature technology represented by the Rebelo isoquant. However, since technologies corresponding to higher capital-labor ratios are less mature, they improve by a larger absolute amount. At time 1, the economy produces with unit requirements of capital and labor shown by point Y. (In the picture as we have drawn it, point X is directly above point Y, thus implying that the maturity of each technology is constant over time. This property holds in the steady state, as we show below.)

The Steady State of the One-Country Model

The steady state of the one-country model is characterized by a constant growth rate of output and a constant ratio of the existing level of technology to the maximum level of technology. Define g as the growth rate of output and R as the ratio of technology to its maximum level: $R = A(k,t)/A^*(k)$.

The ratio R is determined by a country's growth rate. If a country grows rapidly, it will have relatively little time to improve the technology at any given capital/labor ratio j. The intuition is that the faster the growth rate the less time a country will be "in range" — within distance γ — of a given capital/labor ratio. Thus R is a negative function of the growth rate.

Given the specification of $\dot{A}(j,t)$ in equation (3), the steady-state $A(k,t)$ (which we write simply as just $A(k)$) is given by

$$A(k) = \left(1 - e^{-\beta\gamma/g}\right)A^*(k). \qquad (4)$$

Hence, in steady state,

[8] The assumption that "virgin" technologies start at zero productivity is made only for convenience; if they started at some non-zero level, the isoquant would become a vertical line where it intersects the capital-labor ratio $K_0/L_0 + \gamma$.

$$R(k) = \left(1 - e^{-\beta\gamma/g}\right). \tag{5}$$

As we saw before, the growth rate of an economy in steady state is a positive function of the level of technology:

$$g = sRB - \delta. \tag{6}$$

Figure 2 shows the determination of growth and technology in the single country case as the solution to equations (5) and (6). Note that a higher saving rate will rotate the $g(R)$ line counterclockwise, thus increasing the growth rate of output but lowering the technology ratio. A higher rate of technology improvement (larger β) rotates the $R(g)$ curve clockwise, simultaneously increasing both the growth rate and the level of technology.

II. The Two-Country Model

The only difference between the one- and two-country models is in the technology growth equation. Allowing for more than one country creates the possibility that technology at a given capital ratio may be simultaneously improved by spillovers from multiple countries. Letting i index countries, we thus have

$$\dot{A}(j,t) = \beta\left(A^*(j) - A(j,t)\right)\sum_i I\left(k_i - \gamma < j < k_i + \gamma\right), \tag{7}$$

where $I(\ )$ is the indicator function. Countries can also interact even if they are not simultaneously improving the same technique: for example, a "follower country" can benefit from technology improvements made by a "leader country" in the past. In a multi-country world we need to keep careful track of the history of technology changes; this is why A is also a function of time.[9]

There are two kinds of steady states in the two-country model: ones in which the two countries have the same growth rate of output, and ones in which they do not. Which one of these kinds of steady states is observed will depend on the parameters of the model, but not on initial conditions.

[9] We always examine a world with a fixed number of countries. If the number of countries is variable, one obviously needs to normalize the effect of each country on world technology by some scale variable to avoid nonsensical results.

We first consider the steady state in which the two countries have the same growth rate. Let g be the common growth rate, s_1 and s_2 the saving rates for the two countries, and R_1 and R_2 the steady state ratios of $A(k)/A^*(k)$ for the two countries. Without loss of generality, assume $s_1 > s_2$.

We show below that if both countries grow at the same rate, then the country with the higher saving rate must have a higher capital/labor ratio.

The common growth rate for the two countries in steady state is given by the following equations:

$$g = s_1 R_1 B - \delta \tag{8}$$

and

$$g = s_2 R_2 B - \delta . \tag{9}$$

Country One has a higher saving rate than Country Two. If they are to have a common growth rate, then Country One must have a lower level of technology at each capital ratio. This can happen only if Country One is always "in the lead," i.e. if at all times Country One has a higher level of capital per worker than does Country Two. Intuitively, Country One "passes over" a given capital ratio and leaves an improved level of technology for Country Two to use, allowing Country Two to grow at g despite its lower saving rate.

Define d as the log distance between the capital stocks of the two countries in steady state: $d = k_1 - k_2$. Figure 3 illustrates the relation between the two countries' capital stocks. Technologies with capital intensity greater than $k_1 + \gamma$ are not affected by either country. Technologies with capital intensity between $k_2 + \gamma$ and $k_1 + \gamma$ are affected only by Country One. Technologies with capital intensity between $k_1 - \gamma$ and $k_2 + \gamma$ are affected by both countries. Technologies between $k_1 - \gamma$ and k_2 are affected only by Country Two.

Thus the two countries have steady-state ratios of current to maximum technologies of:

$$R_1 = 1 - e^{-\beta(2\gamma - d)/g}, \tag{10}$$

and

$$R_2 = 1 - e^{-\beta(2\gamma + d)/g}. \tag{11}$$

Combining the four equations (8), (9), (10), and (11) yields solutions for the four endogenous variables, R_1, R_2, d, and g.

We are now in a position to say when the steady state will be characterized by a single common growth rate for the two countries. Specifically, there will be a common growth rate if the implied value of d from the equations above is less than γ. If this condition is violated, then (10) and (11) are no longer correct. Instead, R_1 and R_2 are given by

$$R_1 = 1 - e^{-\beta\gamma/g_1}$$

and

$$R_2 = 1 - e^{-\beta(\gamma/g_2 + 2\gamma/g_1)}.$$

Note that the equation for R_1 is the same as equation (5) in the one-country case. The reason is that if the two countries grow at different rates, then in the steady state Country One (which by virtue of its higher saving rate grows faster) does not receive any benefit from Country Two. Country Two, on the other hand, receives the maximum benefit from Country One as well as the benefit from its own technology improvements. In this steady state, the two countries will have different growth rates, given by equations analogous to (6) in the one-country case:

$$g_1 = s_1 R_1 B - \delta,$$

and

$$g_2 = s_2 R_2 B - \delta.$$

One natural question that might arise is whether the follower country should "convexify" — use some of its capital stock to set up a high-tech enclave with a high capital-labor ratio that can use cutting-edge technologies, and leave the rest of the country with a lower capital-labor ratio. In the steady state the follower country will never wish to convexify: since the technology being developed by the leader is farther from $A^*(k)$ than the technology used by the follower, a convex combination of the two will leave the follower with worse average technology.[10]

[10] The reason for this result is that, from the point of view of the follower country at any point in time, the $A(k,t)$ function is concave in k. With more than two countries, however, this condition is not guaranteed. In particular, one country might find itself between two large groups of countries, both of which have improved their technology to a high level. In that case, the country in between may want to take advantage in this non-convexity of A by splitting into two sections, one with higher-than-average k and the other with lower-than-average k. We rule out this behavior by assumption; one way of justifying it is to hypothesize that there are strong sectoral

Comparative Steady States of the Two-Country Model

In this section we examine the effect of changes in saving rates on the steady states of the two-country model. Changing saving in a single country will change the distance between the two countries' capital stocks in steady state, and also change their common growth rate. Changes in saving can also move the steady state from being one with common growth rates to being one in which the countries have different growth rates.

Figure 4 shows the growth rates of Countries One and Two as functions of the saving rate in Country One, holding constant the saving rate in Country Two (we no longer assume that $s_1 > s_2$).[11] For a sufficiently low saving rate in Country One, the steady state will be such that Country One grows more slowly than Country Two. Increases in the saving rate in Country One will increase the growth rate in Country One, but leave Country Two's growth rate unaffected. At a critical level of saving $\underline{s_1}$ the steady state switches to one in which the two countries grow at the same rate, and the distance d between their capital stocks is less than γ.

At this point, further increases in s_1 have two effects. First, for a given R_1, increases in saving increase the growth rate. Second, and partially offsetting, however, the higher growth rate pushes the two countries closer together, decreasing R_1. Thus the overall effect of increases in s_1 is to raise the common growth rate of the two countries and to narrow d, the distance between them.

If s_1 increases beyond a critical value $\overline{s_1}$, the two countries again grow at different rates in steady state, with Country One now growing faster. Note that, as s_1 rises above $\overline{s_1}$, dg_1/ds_1 increases. The logic for this result is as follows: For saving rates below $\overline{s_1}$ Country One is benefiting from Country Two's presence in the world, and Country One's growth rate is higher than it would be if it were in autarky. As s_1 rises toward $\overline{s_1}$, however, this benefit diminishes gradually, since Country One receives less and less spillover benefit from Country Two. This reduced spillover depresses dg_1/ds_1. Once its

complementarities within a country, so that all sectors have to improve together to adopt a better technology.

[11] All figures and simulations use parameter values of $\gamma = 1$, $B = 1$, $\delta = 0.05$, and $\beta = 0.01/n$, where n is the number of countries.

saving rate is beyond $\overline{s_1}$, Country One is effectively in a one-country world, and its growth rate responds to its saving rate as if Country Two did not exist.

An important effect to note is that when s_1 increases beyond $\overline{s_1}$, the growth rate of Country Two falls. The rationale for this result is as follows: at the point where $d = \gamma$, Country Two is getting the maximum benefit from the spillover from Country One (and Country One is getting no benefit from Country Two). As the growth rate of Country One increases further, it will spend less time improving the technology at any given capital ratio, and thus Country Two will inherit technology that has been improved less than it would have been if Country One were growing more slowly.

Relative Consumption

Consider two countries that are growing at the same rate. When one country raises its saving rate, it both raises its level of income relative to the other country, and also raises their joint growth rate. The effect on relative consumption in the two countries is ambiguous, however. By saving more, a country uses productive technology that is less mature, and also consumes a smaller fraction of its income — factors that can offset the positive effect of a higher capital stock on output.

Our previous analysis indicates that there is a positive externality from the saving of at least the leading country in the two-country model. In steady states where both countries grow at the same rate there are positive spillovers from saving in both countries. This situation can lead each country to try to free-ride off the other, by being a follower and inheriting the leader's improved technology. An analogy is bicycle-racing, where one wishes to follow rather than to lead in order to conserve energy and still maintain speed by using the slipstream of the leader.

Figure 5 explores this issue of relative consumption using our baseline set of parameters. The vertical axis measures the log of C_1/C_2, so positive values indicate that Country One has higher relative consumption. We consider consumption in Country One relative to consumption in Country Two, as a function of the saving rate in Country Two. We plot this function for three different saving rates in Country One. Obviously, if the two countries have equal saving rates they will have equal consumption. For a low saving rate in Country One (0.15), relative consumption in Country One is a negative function of Country Two's saving. In other words, if Country Two saves more than Country One, it will have higher relative consumption. For a high saving rate in Country One (0.25), the opposite holds: Country Two will have higher relative consumption if it saves *less* than Country One.

The intuition for this result is straightforward. If Country One has a low saving rate, it has already substantially improved the technology it leaves Country Two by spending a long time "within range" of each capital-labor ratio. Thus Country Two has little to gain by keeping its own saving rate low and trying to improve the technology further; it is better off by increasing savings and moving to a higher capital-labor ratio. But the logic is just the reverse when Country One has a high saving rate; in that case Country Two can do better (relatively) by having a low saving rate itself, improving its technology further and securing higher consumption.

A natural scenario to consider is the case where saving is set taking into account only relative consumption. It is clear from Figure 5 that one Nash equilibrium in this case will be the saving rate s^*. If both countries save at this level, then neither can raise its relative consumption by changing its saving rate slightly.[12]

III. Many Countries and Convergence Clubs

One of the themes in the recent growth literature has been the possibility that countries will endogenously clump into discrete "convergence clubs."[13] In Durlauf and Johnson [1995] this clumping takes place because nonconvexities in the aggregate production function create multiple locally stable steady states. In our model, the possibility of converge clubs arises because of spillovers between countries. Countries with small differences in saving rates will tend to have the same growth rate, since the lower-saving country will benefit from spillovers from higher saving one. But if countries differ by too much in their saving rates, then they will grow at different rates. Thus a

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12 For the parameters that we use, s^* is approximately 0.204.

13 Quah [1993, 1996] argues that countries are converging into two such clubs, one where the poor are getting poorer and the other where the rich are getting richer.

world made up of numerous countries that have slightly different saving rates might be expected to break up into a number of discrete clumps, within each of which countries would differ only in their levels of income, while clumps would differ from each other in their growth rates.

To explore this possibility, we examine a world with three countries, in which equations analogous to (8)-(11) can be solved analytically.

Figure 6 shows how the steady state configuration of growth rates depends on saving rates in the three countries. The figure is generated by holding constant the saving rate in a single country (Country Three, with a saving rate of 0.20), and varying the saving rates in the other two countries. For each pair of saving rates in Countries One and Two, we indicate the configuration of the world economy. There are four possibilities: first, each country can grow at its own rate; second, there can be a convergence club of the two low-saving countries, with the highest-saving country growing at its own, faster rate; third there can be a convergence club of the two high-saving countries, with the low-saving country growing at a slower rate; and finally, there can be a single worldwide convergence club. For the parameters we examine, all four cases are present.

In Figure 7 we consider the experiment of varying a single country's saving rate, holding constant the saving rates of the other two countries in the world. Specifically, we hold the saving rate of Country Two constant at 0.07 and the saving rate of Country Three constant at 0.30, and vary the saving rate of Country One between 0.06 and 0.22. When Country One has a sufficiently low saving rate, Country One and Country Two have a common growth rate, while Country Three grows faster. As Country One's saving rate rises, the convergence club of Countries One and Two breaks up, and all three countries grow at different rates. As Country One's saving rate rises even further, Countries One and Three form a convergence club with a common growth rate, while Country Two grows more slowly.

Note that the relation between saving and growth rates in Country One: at the point where Country One breaks out of its convergence club with Country Two, the effect of saving changes on the growth rate rises. When Country One joins a convergence club with Country Three, the size of the effect of saving on growth falls. For the parameters that we use, the derivative of Country One's growth rate with respect to its saving rate is 0.05 just before it leaves the lower convergence club, rises from 0.20 to 0.25 over the period when it is in its own "convergence club," and is 0.09 immediately after it joins the upper convergence club. We discuss this feature of the model in Section IV. Also worthy of note is the effect of increases in saving in Country One on the growth rate of Country Two. When the two countries have similar saving rates, increasing saving in Country One raises the growth rate of output in Country Two. As saving increases in Country One, and as the lower "convergence club" breaks up, increases in saving in Country One harm Country Two not only in terms of its position relative to the rest of the world, but in absolute terms as well.

IV. Empirical Implications

A. Cross-country Growth Regressions

There is now a large literature using cross-country growth regressions to test for "conditional convergence."[14] Here we discuss what such regressions would show if the world behaves as our model.

The standard growth regression uses a country's average growth rate of output as the dependent variable and its saving rate and initial income as the right-hand-side variables.[15] Mankiw, Romer and Weil [1992] (henceforth MRW) find a positive effect of saving on growth and a negative effect of initial income on growth. Both of these results are consistent with the hypothesis that each country is an independent economy that is well-described by the Solow growth model. Using the framework of the Solow model, MRW interpret the coefficient on the saving rate as a measure of the output elasticity of capital. They find that this elasticity is significantly smaller than 1, which is the minimum value that would give endogenous growth, and argue that the size of the elasticity they estimate is consistent with the rate of conditional convergence implied by the coefficient on initial income. Further, they find that the coefficient on the initial level of income is negative, which is inconsistent

[14] See, e.g. Mankiw, Romer and Weil [1992] and Barro and Sala-i-Martin [1991, 1992, 1995].

[15] These regressions also include country-specific population growth rates, but these are all zero in our model.

with standard endogenous growth models. Thus, they argue that the evidence supports an extended version of the Solow model, where "capital" encompasses both human and physical capital.

We argue that such tests are not dispositive in a world with technology diffusion. Data generated from our model would display a pattern similar to the one that MRW found, but the policy implications of our model are quite different from those of the Solow model.

Note first that countries in our model display conditional convergence, since two countries with the same saving rate will eventually converge to the same level of income. The reason is that at each point in its development the poor country is able to use more mature technology than the rich one, so it grows faster. Barro and Sala-i-Martin [forthcoming] obtain a similar result in a model with costly imitation. In their model, convergence is driven by the assumption that there are diminishing returns to imitation.

It is also clear that in our world the saving rate enters a cross-country growth regression with a positive sign: If two countries have the same level of income, the higher-saving country grows faster. But the estimated coefficient on the saving rate will typically not reveal the "AK" structure of production present in our model. Since higher-saving countries will typically have higher capital stocks, and thus less mature levels of technology, cross-country regressions will tend to show an output elasticity of capital smaller than 1, which is its true value for any given technology. From the point of view of policy, it will not be apparent from the usual cross-country regressions that policies can affect long-run growth.

Thus, although the work of MRW and others has cast doubt on the plausibility of closed-economy Ak models, we believe that our model, which is based on a similar production function, is quite consistent with the accepted empirical findings. Sharper tests are needed to discriminate between a world where convergence takes place because of diminishing returns, and one where convergence is due to technology diffusion.

B. Implications for "Miracles"

Much of the recent growth literature has investigated the subject of "miracles:" countries that make a rapid transition from poverty to relative affluence, seemingly without taking extraordinary measures.[16] We discuss the implications of our model for such miracles, under the assumption that all countries in the world belong to a single convergence club and thus grow at the same rate in the steady state.[17] Consider the different effects of an increase in the saving rate (which in our model is a metaphor for a variety of improvements in economic policy), depending on whether the country is toward the front or the back of the pack. An increase in saving on the part of the leading country has a relatively small effect on its income, since an increase in the capital-labor ratio leads the country to produce with significantly less mature technology. A poor country raising its saving rate, by contrast, will experience a period of rapid growth, as it moves quickly to the front of the pack taking advantage of the relatively mature technology at the rear. Thus, our model predicts that miracles should occur through a process of "catch-up:" countries that can make rapid gains in per-capita income through small changes in policy must be poor, not rich. This prediction is certainly consistent with the facts of miracles: no rich country has experienced the kind of sustained rapid per-capita income growth displayed by countries like Korea, Hong Kong, and Taiwan.

Why is rapid catch-up called a miracle? The reason is that the technologies we estimate from the data suggest that such events are improbable.[18] Suppose that the world is in a stochastic steady state where countries have small, stationary fluctuations in their saving rates. Estimates of the elasticity of growth with respect to saving (which in a model with a neoclassical production function also imply the output elasticity of capital) will be averages across the rich and poor countries.[19] In our model, however, this parameter is not equal across countries. In particular, in rich countries, the effect of saving on growth will be small for the reasons we discussed in the previous section. Thus the large effect of saving on growth in a poor country will appear miraculous: treating countries symmetrically

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[16] See Lucas's [1993] discussion and comparison of the growth histories of South Korea and the Philippines. Parente and Prescott [1993] document some of the stylized facts.

[17] Parente and Prescott [1993] argue that there is no tendency for the distribution of country incomes to spread out over time, which seems to argue in favor of a common growth rate. However, Quah [1996] comes to the opposite conclusion.

[18] These events are also quite infrequent in the data: Quah [1996] finds that the probability of going from the 10th percentile in world income to anywhere above the 90th percentile in 60 years is about 5 percent.

[19] They will actually be weighted averages, where the weights depend on the relative variances of countries' saving rates.

would not uncover the state-dependent effects of saving on output that make it easier for poor countries to become rich than for rich countries to become richer.[20]

Our model also has an interesting implication: it predicts that miracles may become easier as more countries experience them. If one country increases saving, it improves the level of technology available to other poor countries. This then makes it easier for these countries to have miracles of their own (in the sense that they require smaller increases in their saving rates to achieve the same increase in relative income). Of course, the poor countries are better off whether or not they increase savings, since they now inherit more mature technology at each level of capital.[21]

V. Conclusion

Consider a world with two countries: a wealthy country with a relatively low saving rate (e.g. the United States) and a poorer, faster-growing country with a higher saving rate (e.g. Japan). According to the Solow model, Japan will be growing faster than the United States because it is further below its steady-state level of output. This model predicts that Japan will pass the United States, and that Japanese growth will slow down as it reaches its steady state. Eventually the ratio of output per capita in the two countries will stabilize. The fact that Japan is passing it by will have no effect on the growth rate of output in the United States. Endogenous-growth models also predict that Japan will pass the United States and that this overtaking will have no effect on growth in the United States. But these models do not predict any subsequent slowing in Japan's growth: over time the gap between the levels of per-capita output in the two countries is supposed to grow arbitrarily large.

The predictions of the model presented in this paper seem more reasonable than those of either

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20 Recall from our discussion of Figure 7 that the effect of a country's saving rate on even its *steady-state* growth rate can vary a great deal, depending on its position in the world economy. Differences in the transitional dynamics following a change in the saving rate are naturally even more pronounced.

21 This prediction depends on our assumption that all countries in the world are in fact members of a single convergence club. If there are two (or more) such clubs and miracles take the form of leaving the lower club to join a higher one, then poor countries that experience miracles worsen the situation of the countries they leave behind. First, as we discuss in Section III, they will lower growth rates for the countries left behind. Second, since they grow at a faster rate, they do not improve the technologies they use as much as they otherwise would. The first effect lowers the welfare of countries left behind, and the second makes it harder for the remaining low-growth countries to create miracles of their own.

the Solow or endogenous-growth models. Our model predicts, first, that the two countries will eventually reach a steady state in which the ratio of their per capita incomes is constant (assuming that the gap in saving rates between the two countries is not too large). Second, the fact that Japan passes it in terms of income per capita will be good for the United States: growth will accelerate as Japan takes over the burden of technology leadership. In the steady state, the common rate of growth in the two countries will be higher than growth in the United States when it was the technology leader, but lower than growth in Japan when it was the technology follower. Our result that being overtaken by Japan is good for the United States is one that finds little support in the popular press, although it is more widely accepted by economists — see, for example, Krugman [1996].

In order to highlight the implications of our appropriate-technology model for relative income and growth rates across countries, we have kept the model as simple as possible. In particular, we have used a simple learning-by-doing model to describe the process of technological advancement, rather than explicitly modeling expenditures on research and development. Similarly, we have assumed that technology is instantly and freely mobile across countries, rather than modeling technology transfer as requiring time or expenditures. And finally, we have taken saving rates to be exogenous and constant, rather than modeling them as the outcome of optimization. All three of these areas hold the potential for interesting extensions of the model that we present.

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Figure 1: Isoquants at Two Points in Time

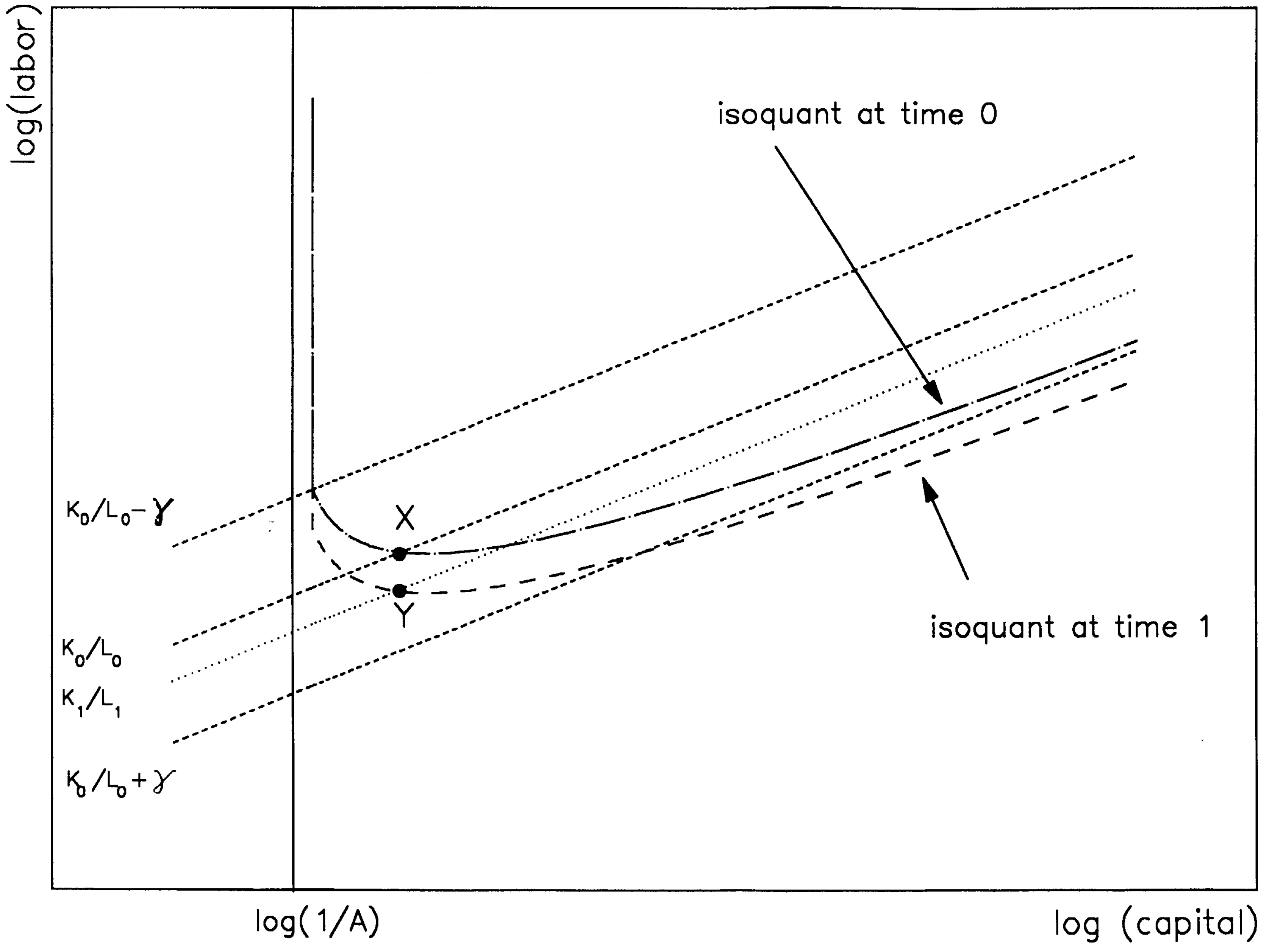


Figure 2
Determination of the Steady State for a Single Country

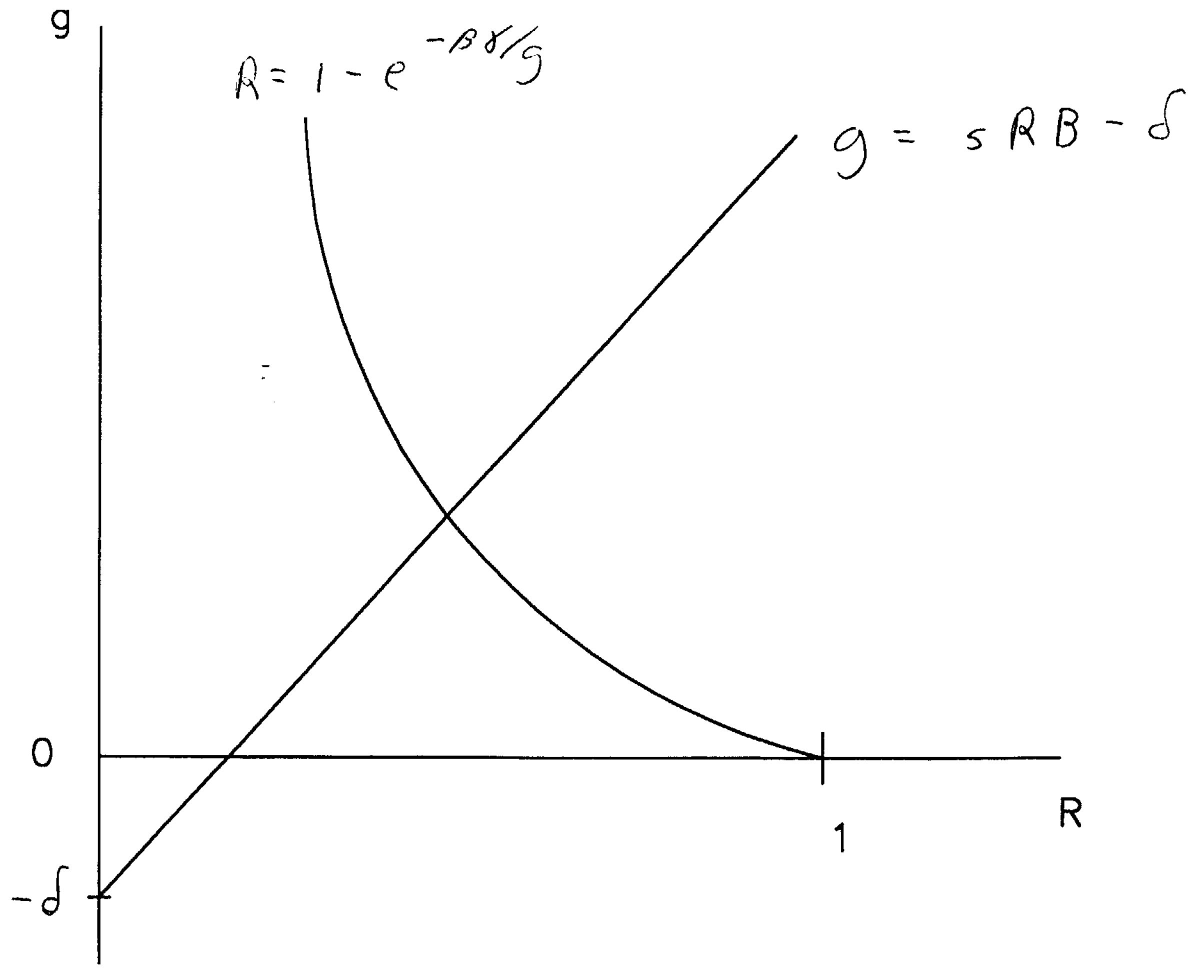


Figure 3: The Two Country Model

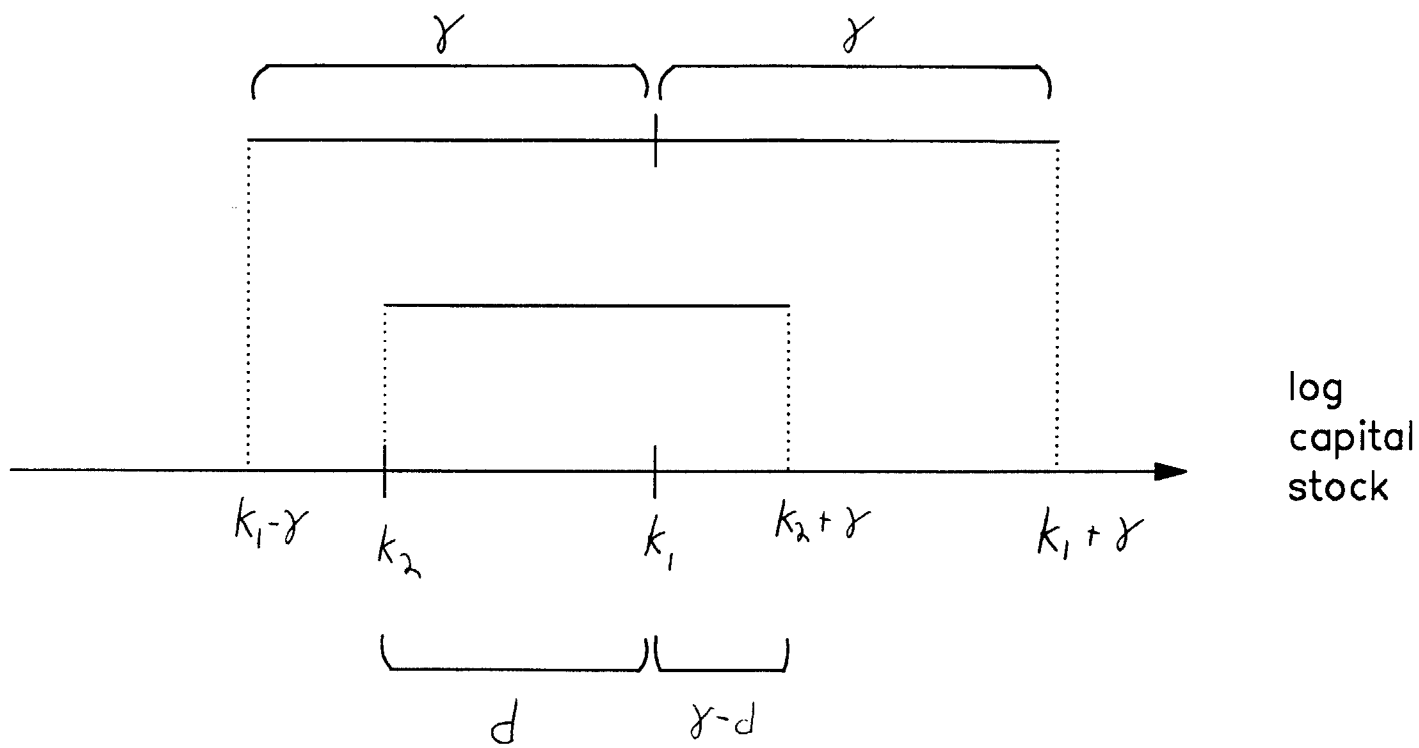
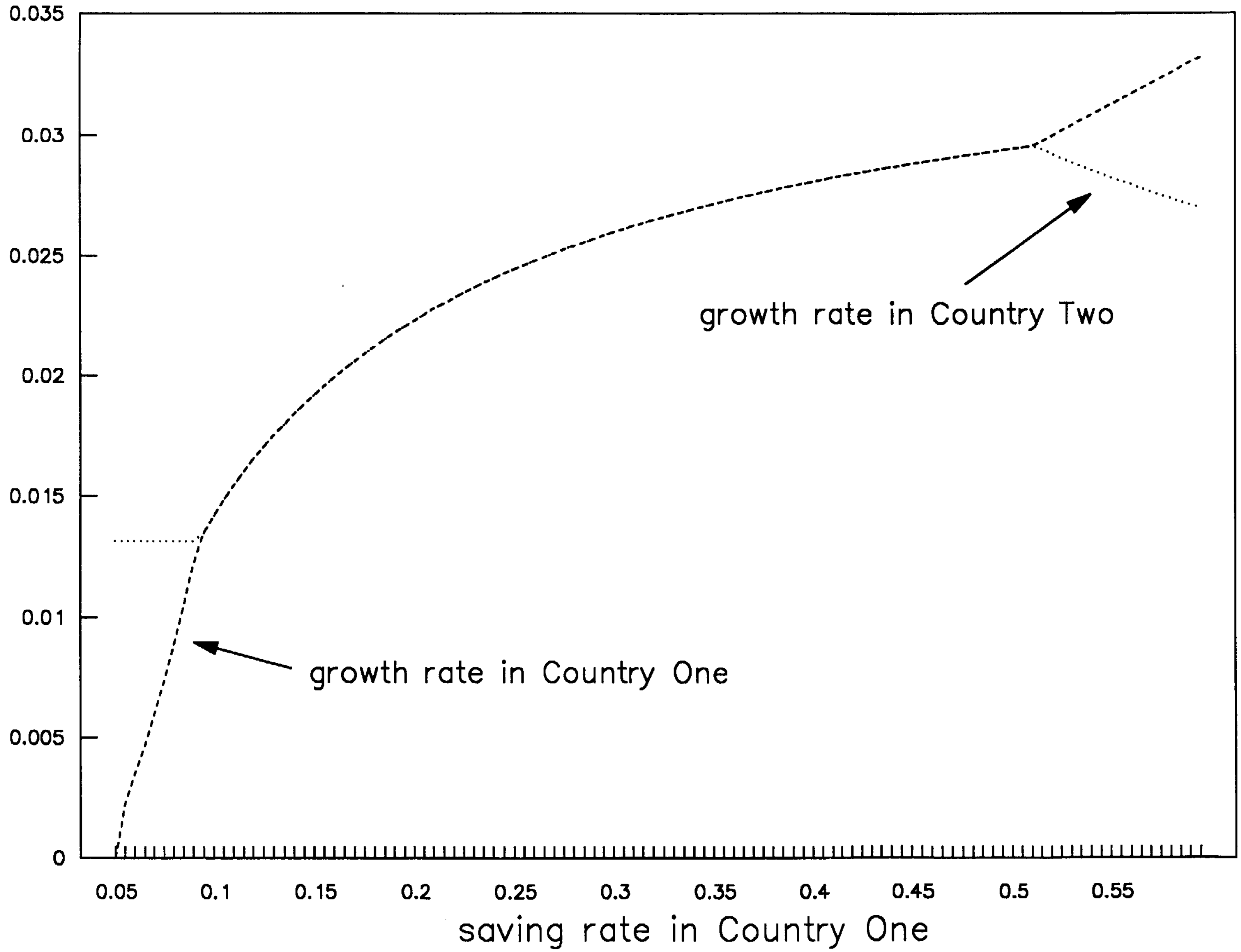


Figure 4: Growth as a Function of Saving in the Two Country Model



Note: the saving rate in Country Two is .2

Figure 5: Relative Consumption in the Two Country Model

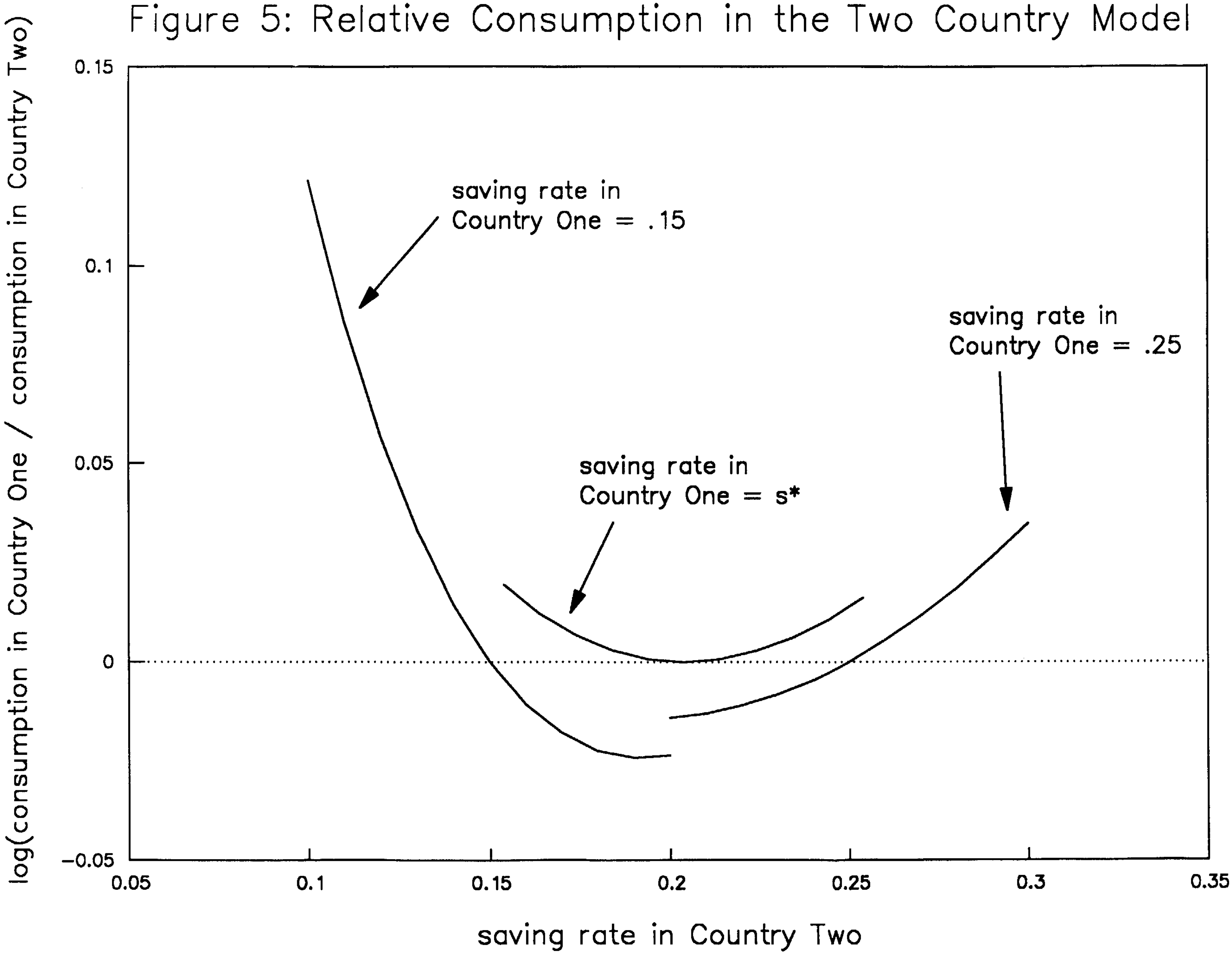
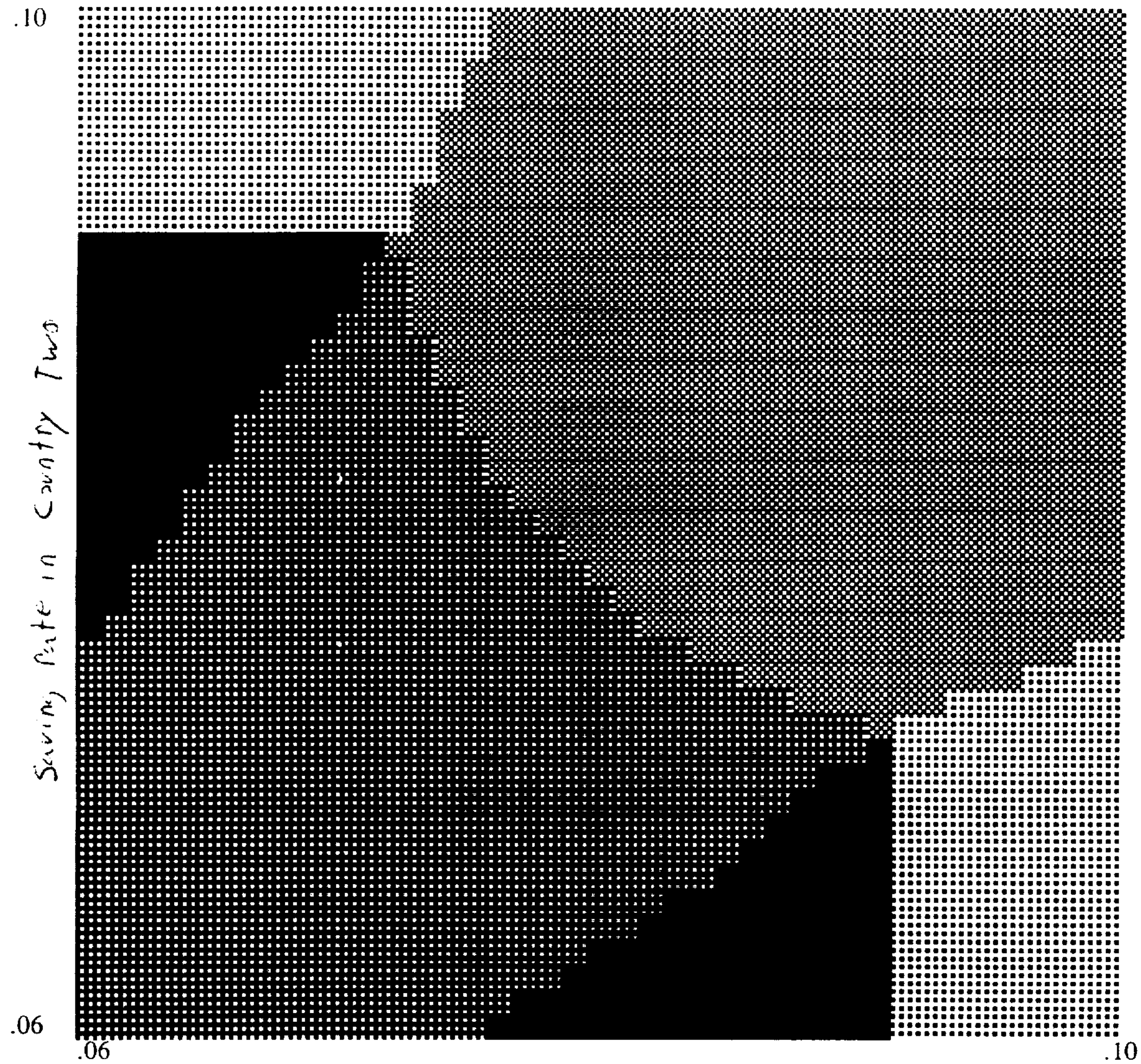


Figure 6

Convergence Clubs in the Three-Country Model

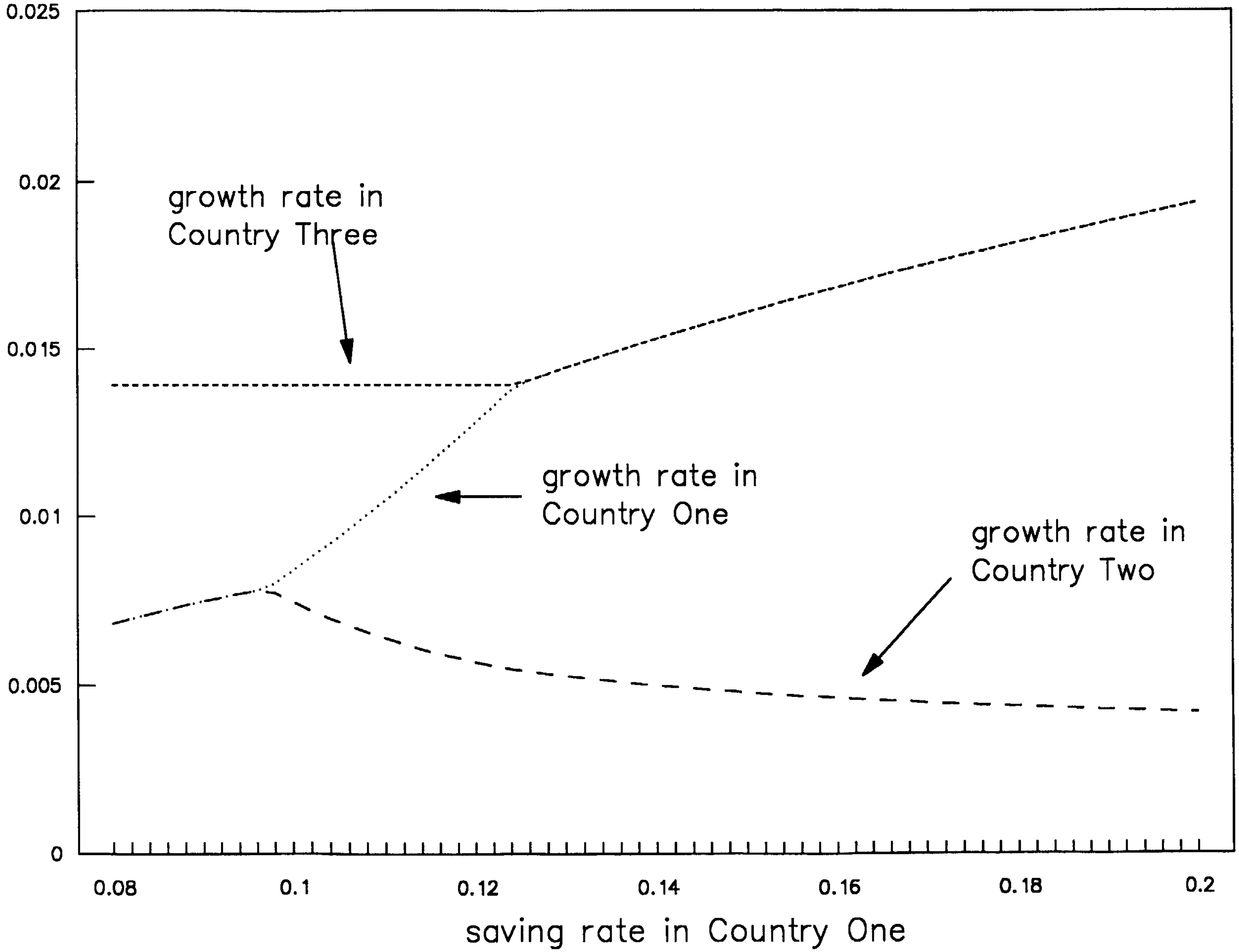


saving rate in Country One

all three countries grow at same rate
convergence club of two richest countries
convergence club of two poorest countries
each country grows at a different rate

Note: saving rate in Country Three is .2.

Figure 7: Growth as a Function of Saving in the Three Country Model



saving rate in Country Two is .07 and in Country Three is .30