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Barriers to Technology Adoption and Development

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We propose a theory of economic development in which technology adoption and barriers to such adoptions are the focus. The size of these barriers differs across countries and time. The larger these barriers, the greater the investment a firm must make to adopt a more advanced technology. The model is calibrated to the U.S. balanced growth observations and the postwar Japanese development miracle. For this calibrated structure we find that the disparity in technology adoption barriers needed to account for the huge observed income disparity across countries is not implausibly large.

I. Introduction

A major task facing economists is to explain the wide disparity in per capita income across countries. The standard neoclassical growth model has a difficult time accounting for this disparity in the sense that, given a plausible disparity in tax rates on capital income, this

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model generates much less income disparity than is found in the data. Counter to the expectations of Mankiw, Romer, and Weil (1992, p. 433), this is true even if the reproducible capital share is doubled by including human capital. Only if the share of reproducible capital is near one does a plausible disparity in tax rates generate as much income disparity as in the data. But then the convergence to the balanced growth path is slow, far slower than is consistent with the post-World War II development experience of Japan. Development miracles such as Japan's are just not possible with the reproducible capital income share near one.

If we are to account for both the huge observed income disparity and development miracles, it seems a new theory must be developed. In this paper we put forth a theory and show that it is quantitatively consistent both with the great disparity of per capita income across countries and with the rapid development of Japan and several other countries during the postwar period. The focus of our theory is the technology adoption decision by firms and the barriers to such adoption that are often placed in the paths of entrepreneurs. These barriers take different forms such as regulatory and legal constraints, bribes that must be paid, violence or threat of violence, outright sabotage, and worker strikes. Whatever their form, each has the effect of increasing the cost of technology adoption. Our theory is that differences in these barriers account for the great disparity in income across countries and that large persistent reductions in these barriers induce development miracles.

In emphasizing barriers to technology adoption and their relation to the process of development, we echo a theme advocated by several economic historians including Morison (1966), Rosenberg and Birdzell (1986), and Mokyr (1990). Rosenberg and Birdzell argue, in fact, that the reason why the West grew rich first was that effective resistance to technology adoption was weaker there. And all these authors document cases in which the adoption of technologies was met with fierce resistance. This paper can be viewed as an attempt to formalize and quantify some of these arguments.

We assume in the model that a firm must make an investment to advance its technology level. At a point in time the amount of investment required by a firm to go from one technology level to a higher level depends on two key factors: the level of general and scientific knowledge in the world and the size of the barriers to adoption in the firm's country. General and scientific knowledge, or *world knowledge*, is assumed to be available to all in the model and to grow exogenously. With growth in this knowledge, the amount of required investment that a firm must make to go from a particular technology level to a higher level is assumed to decrease.

An implication of this last assumption is that when income levels and technology adoption barriers are held fixed, development rates increase over time. When just income levels are held fixed, we see that development rates have indeed increased over the last 170 years. This increase is documented in figure 1, which plots the number of years it took a country to go from 10 to 20 percent of 1985 U.S. per capita income against the year in which that country first had a per capita income level 10 percent of the 1985 U.S. level. Before 1913, the median length of this development period for a country was 45 years. Subsequent to 1950, the median length of this development period was 18 years. This is a dramatic reduction in the time taken to achieve this doubling of income.¹

We emphasize that our theory is a theory of relative income levels and not growth rates. If the distribution of technology adoption barriers is constant over time, an implication of our theory is that the cross-country distribution of the log of per capita income shifts up over time with no increase in its range. Parente and Prescott (1993) document that this is precisely how the distribution of the log of per capita income in the 1960–85 period behaved for the 102 large countries in the Summers and Heston (1991) data set.

In order to quantify the model, we calibrate it to U.S. balanced growth observations and the postwar development experience of Japan. By construction then, the calibrated model is consistent with both U.S. development observations and the Japanese postwar development miracle. The critical test of our theory is whether it is also consistent with the huge observed income disparity across countries. We find that it is. For a plausible disparity in technology adoption barriers, our model generates disparity in per capita income across countries of the magnitude observed in the data.

This paper is organized as follows. Section II describes the economy. Section III calibrates the model to U.S. balanced growth observations and the postwar experience of Japan. Section IV examines the quantitative effects of differences in tax rates and barriers to technology adoption on balanced growth path output levels. Section V uses the calibrated model to interpret the postwar recovery of France and Germany and the development miracles of South Korea and Taiwan. Section VI consists of some final remarks.

¹ Figure 1 is based on a set of countries from the Summers and Heston (1991) data set, which had 1969 populations greater than 1 million and 1960 per capita income of at least 10 percent of the 1985 U.S. level. Guatemala is the only country in this set that did not achieve 20 percent of the 1985 U.S. level by 1985. A detailed description of the set of countries used to construct fig. 1 is in the Appendix.

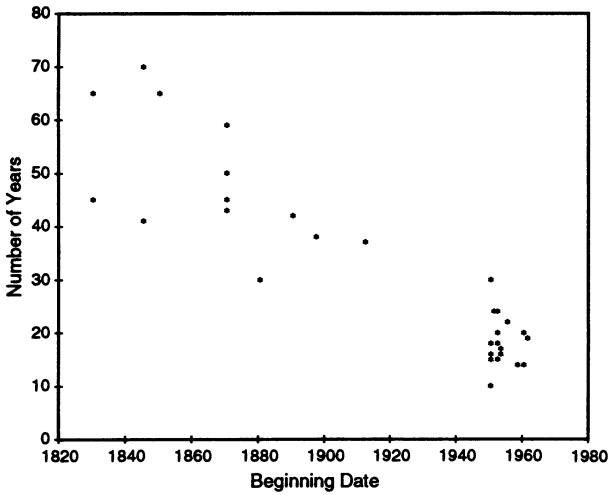


FIG. 1.—Rapid growth experiences: number of years to develop from low- to moderate-income economy.

II. Model Economy

The economy is a generalization of the Parente (in press) technology adoption model. There is a business sector with a distribution of firms indexed by their initial technology levels. There is a household sector with measure L homogeneous households who value private consumption, leisure, and services generated from household physical capital. And there is a government sector that taxes income, provides public consumption, and makes transfers. The economy is described as follows.

A. Business Sector

Each firm in the distribution has an initial technology level. A firm's technology level at date t is denoted by A_t . If a firm with technology level A_t operates h_t hours, employs $N_t \in \{0, \bar{N}\}$ workers, and has K_t units of physical capital, it produces output

$$Y_t = h_t \cdot A_t \cdot N_t \cdot K_t^{\theta_k}, \quad 0 < \theta_k < 1. \quad (1)$$

This output can be used for either consumption or investment.

There are no aggregate increasing returns to scale in our economy. The commodity space has many commodities. Workweeks of different lengths are different commodities, and firms with different technology levels have different types of technology capital. Thus there

is a continuum of different types of both labor and technology capital inputs.² Given certain restrictions on technology parameters, there is an optimal firm size, and it is small relative to the economy. As the size of the economy increases, the number rather than the size of firms adjusts. A proportional increase in every input results in the same proportional increase in the number of firms and aggregate output. In the aggregate, then, there are constant returns to scale. As in the neoclassical model, the aggregate production possibility set is a convex cone.

A firm can advance its technology level between time t and $t + 1$, provided that the firm is operated at date t and makes an investment at date t . The increase in a firm's technology level resulting from an investment of X_A units of output depends on the firm's level of technology relative to the level of world knowledge at the time of the investment as well as the size of the barriers to technology adoption in the country in which the firm is located. These barriers to technology adoption reflect the various ways governments and groups of individuals increase the amount of investment a firm must make to adopt a more advanced technology.

World knowledge, which we denote by W , is meant to represent the stock of general and scientific knowledge in the world (i.e., blueprints, ideas, scientific principles, and so on). We assume that all firms have access to this knowledge. Thus general and scientific knowledge spills over to the entire world equally.³ We assume that world knowledge grows at the constant rate of $\gamma > 0$.⁴ Thus

$$W_t = W_0(1 + \gamma)^t. \quad (2)$$

Given the level of world knowledge at date t and given a firm's current technology level, A_t , the amount of investment a firm must make to realize a technology level of $A_{t+1} > A_t$ at time $t + 1$ is

$$X_{A_t} = \pi \int_{A_t}^{A_{t+1}} \left(\frac{S}{W_t} \right)^\alpha dS, \quad (3)$$

where π is the parameter that indexes the size of barriers to technology adoption in the firm's country. As (3) makes clear, the technology

² Rosen (1974) deals with an equilibrium with a continuum of differentiated products. Mas-Colell (1975) introduces this feature into general equilibrium theory. For a formal general equilibrium analysis with such commodity space, see Hornstein and Prescott (1993).

³ This is clearly a simplifying assumption. The amount of spillover will depend on a variety of factors, including the movement of individuals between profit centers. In an interesting paper, Schmitz (1989) studies an economy in which the amount of spillover depends on the technological closeness of industries.

⁴ For theories of the growth of world knowledge, see Romer (1990) and Grossman and Helpman (1991).

for adoption is such that it takes fewer resources to move from A_t to A_{t+1} as the level of world technology grows higher. This feature generates the result that development rates increase over time when development levels and technology adoption barriers are held fixed. This result is consistent with the development experiences reported in figure 1.

Integration of (3) yields

$$(\alpha + 1)X_{At} = \pi \frac{A_{t+1}^{\alpha+1} - A_t^{\alpha+1}}{W_0^\alpha (1 + \gamma)^{\alpha t}}. \quad (4)$$

Let

$$Z_t \equiv \frac{A_t^{\alpha+1}}{W_0^\alpha (1 + \gamma)^{\alpha(t-1)} (1 + \alpha)}, \quad (5)$$

$X_{zt} \equiv X_{At}$, and $\theta_z \equiv 1/(1 + \alpha)$. Then equation (4) becomes

$$Z_{t+1} = \frac{1}{(1 + \gamma)^{(1-\theta_z)/\theta_z}} \cdot Z_t + \frac{1}{\pi} X_{zt} \quad (6)$$

and equation (1) becomes

$$Y_t = \mu \cdot h_t \cdot (1 + \gamma)^{(1-\theta_z)t} \cdot \bar{N} \cdot K_t^{\theta_k} \cdot Z_t^{\theta_z} \quad (7)$$

when $N_t = \bar{N}$ or $Y_t = 0$ when $N_t = 0$. In (7), μ is a constant that depends on W_0 , γ , and α .

Variable Z will have the interpretation of a firm's stock of technology capital relative to world knowledge and variable X_z will have the interpretation of a firm's investment in that capital. In this representation, the stock of technology capital, Z_t , at date t is measured in terms of the composite output good Y_t . If technology capital is measured in this way, the ratio of technology capital to output, Z_t/Y_t , remains constant along the balanced growth path. If technology capital were instead measured as $A^{\alpha+1}$, technology capital would grow faster than output along the balanced growth path and its relative price would decrease at a rate equal to the growth rate of world knowledge.

There is an optimal-size firm in this economy if and only if the coefficients on physical capital and technology capital in (7) sum to less than one. The sum of θ_k and θ_z is strictly less than one if and only if $\alpha > \theta_k/(1 - \theta_k)$. In what follows, we make such a restriction on the values of α and θ_k .

In the model, a firm's technology capital is assumed to be embodied in the organization. Furthermore, we assume that all this capital is lost if the firm is not operated. These assumptions simplify model notation and analysis. Our results would not change if part of a firm's

technology capital could be transferred to other firms if that firm were to be shut down.

The dividend of an operated firm at date t is

$$V_{ft} = Y_t - w_t(h_t)\bar{N} - r_{kt}K_t - X_{zt}. \quad (8)$$

In (8), $w_t(h)$ is a function that gives the real rental price at date t of a worker who works an h -hour workweek, and r_{kt} is the real rental price of physical capital at date t . Because workweeks of different lengths are interpreted as different commodities, there is a real rental price for each length of workweek. If $V_{ft} > 0$, the firm is paying a dividend to holders of equity; if $V_{ft} < 0$, the firm is issuing new equity.

The problem facing a firm is to maximize the present value of its dividends,

$$V(Z_0) = \max \sum_{t=0}^{\infty} p_t V_{ft}, \quad (9)$$

subject to constraints (6), (7), and (8) and the constraints $Z_{t+1} = 0$ when $N_t = 0$. Here $\{p_t\}$ is the sequence of Arrow-Debreu prices of the composite commodity. In maximizing (9), the firm takes the prices $\{p_t, w_t(h), r_{kt}\}_{t=0}^{\infty}$ as given.

We assume that at date $t = 0$ there are L/\bar{N} firms in the economy, where L is the measure of households in the economy and L/\bar{N} is large. Moreover, we assume that all firms have the same initial technology level. No exit or entry occurs in equilibrium. Because the firm's problem has a unique solution, in equilibrium firms that start alike stay alike.⁵ In equilibrium each firm hires $N_t = \bar{N}$ workers, and the time t product of each firm is given by equation (7). Equilibrium aggregate output for this economy is thus the measure of firms, L/\bar{N} , times the firm's output, Y_t , and the aggregate per capita production relation is

$$y_t = \lambda \cdot h_t \cdot (1 + \gamma)^{(1-\theta_z)t} \cdot k_t^{\theta_k} \cdot z_t^{\theta_z}, \quad (10)$$

where $\lambda \equiv \mu \bar{N}^{\theta_k + \theta_z}$, $k_t = K_t/\bar{N}$, and $z_t = Z_t/\bar{N}$. Variable k_t is interpreted as the per capita aggregate business physical capital stock, and variable z_t is interpreted as the per capita aggregate technology capital stock. (Here, and in subsequent analysis, lowercase letters denote per capita values of the corresponding variables.) We select the units in which output is measured so that per capita output is

$$y_t = h_t \cdot (1 + \gamma)^{(1-\theta_z)t} \cdot k_t^{\theta_k} \cdot z_t^{\theta_z}. \quad (11)$$

⁵ If there were population growth in this economy, then there would be entry. As long as population growth were not too large, in the subsequent periods new firms would be identical to existing firms.

Although the assumption concerning the initial distribution of firms seems restrictive, in actuality it is not. A key feature of the investment technology is that the return associated with a given investment is higher the lower the firm's current technology level. Parente (in press) shows that one implication of this type of investment technology is that it is optimal to allocate investments across firms so that the lower support of the distribution of technologies across operated firms is as large as possible. Since the highest investment will occur at those firms with the lowest levels of technology, it follows that after a finite number of time periods all firms will have identical technology capital stocks, provided that investment is uniformly bounded away from zero.

B. Household Sector

In this paper, we abstract from population growth and assume a continuum of infinitely lived households of measure L . We cannot and do not abstract from the labor/leisure decision or from household physical capital. The reason is that our estimate of the income disparity induced by a given disparity in the size of barriers to technology adoption would be quite different were we to abstract from these decisions. We introduce leisure and services generated from the stock of household physical capital to preferences in the standard way. The discounted utility stream of a household over its infinite lifetime is

$$\sum_{t=0}^{\infty} \beta^t [\ln(c_t) + \phi_d \ln(d_t) + \phi_l \ln(1 - h_t)], \quad (12)$$

where c_t denotes the consumption good at time t , d_t denotes the stock of household physical capital at date t , $1 - h_t$ denotes leisure at date t , $\phi_d, \phi_l > 0$, and $0 < \beta < 1$.

Each household is endowed with one unit of productive time in each time period to be divided between leisure and labor. At date 0, households are endowed with household physical capital and business physical capital. Business physical capital, which we denote by the letter k , is rented to firms.⁶ All households have the same initial endowment of the two types of physical capital goods and have equal claims to the dividends of firms.

The stocks of household physical capital and business physical capital are assumed to depreciate at rates δ_d and δ_k , respectively. If x_{dt}

⁶ Because in equilibrium the aggregate per capita business physical capital stock and the household's stock of business physical capital are equal, we use the letter k to denote both variables.

denotes investment in household physical capital measured in units of the composite commodity at date t , then household physical capital at time $t + 1$ is

$$d_{t+1} = (1 - \delta_d)d_t + x_{dt}, \quad (13)$$

and if x_{kt} denotes investment measured in units of the composite commodity in business physical capital at time t , then business physical capital at time $t + 1$ is

$$k_{t+1} = (1 - \delta_k)k_t + x_{kt}. \quad (14)$$

At date t , a household that works an h_t -hour workweek receives labor income equal to $w_t(h_t)$, physical capital income $r_{kt}k_t$, and dividends from firms v_{ft} . Labor income, physical capital, rental income less depreciation, and dividend income are all taxed at the rate τ . All households receive identical lump-sum transfers from the government, v_{gt} .

The problem of the household is to maximize (12), subject to its household physical capital constraints (13), subject to its business physical capital constraints (14), and subject to its budget constraint of

$$\sum_{t=0}^{\infty} p_t \cdot (c_t + x_{dt} + x_{kt}) \leq \sum_{t=0}^{\infty} p_t \cdot \{w_t(h_t) + r_{kt}k_t + v_{gt} + v_{ft} - \tau \cdot [w_t(h_t) + (r_{kt} - \delta_k)k_t + v_{ft}]\}. \quad (15)$$

The household, like the firm, takes prices $\{p_t, w_t(h), r_{kt}\}_{t=0}^{\infty}$ as given.

C. Government Sector

Government policy is a sequence $\{g_t, \tau_t, v_{gt}\}_{t=0}^{\infty}$, where the τ_t are the income tax rates, the g_t are the government expenditures per household, and the v_{gt} are the lump-sum transfers per household. For all $t \geq 0$, we assume that $\tau_t = \tau$ and that $g_t = \sigma \cdot (y_t - x_{zt})$ for some $\sigma > 0$. The government's budget constraint at date t is

$$g_t + v_{gt} = \tau \cdot [w_t(h_t) + (r_{kt} - \delta_k)k_t + v_{ft}]. \quad (16)$$

D. Equilibrium

The following equations along with equations (7), (8), (11), (13), (14), and (16) and the transversality condition are necessary and sufficient conditions for a competitive equilibrium:

$$i_t \equiv \frac{p_t}{p_{t+1}} - 1, \quad (17)$$

$$r_{kt} = \frac{i_t}{1 - \tau} + \delta_k, \quad (18)$$

$$r_{dt} \equiv i_t + \delta_d, \quad (19)$$

$$r_{zt} \equiv [(1 + i_t)(1 + \gamma)^{(1-\theta_z)/\theta_z} - 1]\theta_z, \quad (20)$$

$$r_{kt}k_t = \theta_k y_t, \quad (21)$$

$$r_{zt}z_t = \theta_z y_t, \quad (22)$$

$$w_t(h_t) = (1 - \theta_k - \theta_z)y_t, \quad (23)$$

$$\frac{c_{t+1}}{c_t} = \beta(1 + i_t), \quad (24)$$

$$\frac{r_{dt}d_t}{c_t} = \phi_d, \quad (25)$$

$$\frac{\phi_l c_t}{1 - h_t} = \frac{w_t(h_t)(1 - \tau)}{h_t}, \quad (26)$$

$$c_t + x_{dt} + x_{kt} + g_t = y_t - x_{zt}. \quad (27)$$

Equation (17) is the definition of the interest rate. From the household's maximization problem, (18) is the rental price of business physical capital. Equations (19) and (20) are the implicit rental prices of d and z . Equations (21) and (22) follow from the firm's maximization of the present value of dividends. Equation (23) follows from aggregate constant returns. Equations (24), (25), and (26) follow from the household's maximization, where in (26) we use the fact that the derivative at h_t of the firm's reservation demand for workweeks of different lengths h is $hw(h_t)/h_t$. Equation (27) is the goods market-clearing condition.

E. *Balanced Growth*

Along the balanced growth path, per capita output $\{y_t\}$, per capita expenditure categories $\{c_t, x_{dt}, x_{kt}, x_{zt}, g_t\}$, per capita capital stocks $\{d_t, k_t, z_t\}$, per capita income categories $\{w_t(h_t), r_{kt}k_t, v_{ft}\}$, and government per capita lump-sum transfers $\{v_{gt}\}$ all grow at the same time. This growth rate is equal to

$$(1 + \gamma)^{(1-\theta_z)/(1-\theta_k-\theta_z)} - 1. \quad (28)$$

The growth rate given by (28) depends only on the technology parameters, θ_z , θ_k , and γ . Thus in this model, savings rates have level effects only: differences in policy do not affect growth rates along the balanced growth path.

III. Model Calibration

U.S. balanced growth observations do not identify the parameters of the model because technology investment, x_z , is not reported in the national income and product accounts. Given a value of the technology capital share parameter, θ_z , however, U.S. balanced growth observations do identify all other model parameters. The value of θ_z is crucial. Only if its value is large is the model consistent with great disparity in incomes across countries. But if its value is too large, rapid growth such as that experienced by Japan in the 1960s is inconsistent with our theory. In this section, we first specify how to calibrate the model to U.S. balanced growth observations given θ_z , and then we see what values of θ_z are consistent with postwar Japanese development.

A. U.S. Balanced Growth Development Observations

The empirical counterparts of the model variables are as follows: Consumption, c , is nondurable good expenditures plus service expenditures less real estate services. The reason we subtract real estate services is that we do not impute rents to owner-occupied houses. We include residential capital as part of the household physical capital stock. Investment in household physical capital, x_d , is consumer durable expenditures plus residential structures investment. Investment in business physical capital, x_k , is investment in physical equipment and nonresidential structures plus inventory investment plus government investment. We assume that 10 percent of government purchases is investment. Government consumption, g , constitutes the other 90 percent of government purchases. Measured output, $y_m \equiv y - x_z$, equals the sum of c , x_k , x_d , and g . Taxes, τy_m , are government receipts. The values to which we calibrated the model are 1987 U.S. statistics. The source of these values is the 1990 *Economic Report of the President* (tables C1, C79).

Business physical capital stock, k , is the value of equipment plus the value of nonresidential capital plus one-half the value of land. Household physical capital, d , is the value of consumer durables plus residential housing plus one-half the value of land. These too are 1987 values. The source of these numbers is Musgrave (1992).

The real interest rate, $i_t \equiv (p_t/p_{t+1}) - 1$, is the average of the historical real return on equity and corporate debt. The fraction of time allocated to market, h , is the workweek divided by 100, since people have about 100 hours of nonsleeping and personal care time per week. The source of the workweek number is the 1991 *Statistical Yearbook of the United Nations*. The balanced growth rate is the average

annual growth rate of real per capita gross domestic product (GDP) in the United States between 1950 and 1988. The source of the average annual growth rate is Summers and Heston (1991).

Given a value of θ_z , the U.S. observations above identify the values of all other model parameters as well as the balanced growth path values of the unreported variables, x_z , y , and z . The units in which technology capital and output are measured depend on the value π . Without loss of generality we select units so that $\pi = 1$ for the United States. Subsequently, π refers to the size of technology adoption barriers relative to the United States.

The following steps describe our calibration to U.S. balanced growth observations: First, values for the depreciation rates δ_k and δ_d are identified from equations (13) and (14) and U.S. observations for x_k , k , x_d , d , and the growth rate of per capita output. Second, values for policy parameters, σ and τ , are determined. The value of σ follows immediately from the U.S. observation for g . The value of τ follows from equations (16) and (8), U.S. observation, τy_m , and the value of δ_k . Third, the value of β is determined from equation (24) and U.S. observations for i and the growth rate of per capita output. Fourth, the rental price of business physical capital, r_k , is determined from equation (18), using values for τ and δ_k , and the U.S. observation for i . Fifth, equations (7), (20), (21), (22), (28), and $y_m = y - x_z$ are solved using values for r_k and θ_z and U.S. observations for y_m and the growth rate of per capita output to determine values for θ_k , γ , y , z , r_z , and x_z . Sixth, values for y , θ_k , and θ_z are used with equation (23) to determine the value of $w(h)$. Finally, a value for r_d is determined from (19), and this value—together with values for $w(h)$, τ , and U.S. observations for c , d , and h —is used with equations (25) and (26) to yield values for ϕ_d and ϕ_l .

B. Postwar Japanese Development

We now determine for which θ_z the model is consistent with postwar Japanese development, including its development miracle, as well as with U.S. balanced growth observations.⁷ If the Japanese barriers to technology adoption, π , were constant for some reasonably long period in which there was a significant decline in annual growth rates and if the Japanese people expected π to remain at that level in subsequent periods, the Japanese growth path along with the U.S. balanced growth path observations would identify all model parameters including θ_z and the Japanese π . But the assumption that we can

⁷ The per capita income levels of Japan as well as per capita income levels of the other countries analyzed in Secs. IV and V come from Summers and Heston (1991).

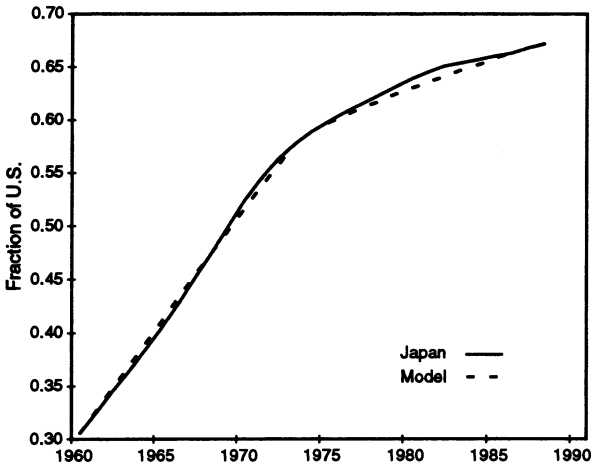


FIG. 2.—Per capita output relative to U.S. level, Japan and model economy for $\theta_z = .55$, 1960–88.

view the entire 1960–88 path of Japanese per capita output as though it were converging to some balanced growth path is not reasonable. An examination of figure 2, which plots Japan's per capita GDP relative to the U.S. level, suggests that a more reasonable working assumption is that in 1960–73, Japan was converging to some balanced growth path and in 1974 there was a *regime change*, that is, a persistent and unanticipated change in the magnitude of the technology adoption barrier parameter π .⁸ As a result of this regime change, the Japanese economy was converging to a different balanced growth path during 1975–88. This leads us to treat the Japanese economy as though it were converging to the balanced growth path associated with some π in 1960–73 and as though it were converging to the balanced growth path associated with some other π for 1975–88.

For a given technology capital share, θ_z , and the corresponding calibrated parameters, we find the value of π and beginning-of-period capital stocks for which the model's beginning- and end-of-period incomes match those of the Japanese economy. We emphasize that the values for all parameters, with the exception of policy parameter π , are assumed to be the same for the American and Japanese economies. Tax rates and government product shares are comparable but not identical for the two countries. As the results are not sensitive to these policy parameters, the abstraction of identical values for τ and σ is employed. We also emphasize that we are assuming that the

⁸ The Japanese data, as well as the data used in Sec. V, were smoothed using the Hodrick-Prescott filter, with the smoothing parameter equal to 25.

Japanese behaved in each period almost as though they expected the current value of π to persist indefinitely.

In choosing the capital stocks, we assume that the initial mix of household physical capital, business physical capital, and technology capital is such that the nonnegativity of investment conditions is not binding in the initial period. In no case that we considered was the nonnegativity of investment conditions binding at any point along the path. Table 1 reports for several values of the technology capital share parameter, θ_z , the values of π for which the model matches Japanese beginning and ending relative income levels in 1960–73 and in 1975–88. Table 1 also reports the balanced growth path income level relative to that of the United States for each of these (θ_z , π) pairs.

Values of $\theta_z > .55$ are unreasonable because they imply implausibly large changes in π between 1960–73 and 1975–88. When $\theta_z = .60$, for example, π must increase by 37 percent to match beginning and ending Japanese income levels in these two periods. Such an increase implies a change in the balanced growth path to which Japan was converging from 1.82 to 0.87 of the U.S. level.

Values of $\theta_z < .50$ also are unreasonable because they imply too large a decline in annual growth rates over the 1960–73 period relative to the data. For Japan, the difference between the annual average growth rate over the 1960–63 subperiod and the annual average growth rate over the 1970–73 subperiod is 2.7 percentage points. This is essentially the difference in average annual growth rates for these two subperiods implied by the model if $\theta_z = .55$. For $\theta_z = .45$, however, the difference in these average annual growth rates over these subperiods is 3.9 percentage points; when $\theta_z = .40$, this difference is 5.1 percentage points. This leads us to conclude that only θ_z 's in the range of .50 and .55 are consistent with both the U.S. balanced

TABLE 1
VALUES OF θ_z AND π THAT MATCH THE JAPANESE
DEVELOPMENT EXPERIENCE AND IMPLIED
RELATIVE INCOME LEVELS y^{ss} , 1960–88

| θ_z | 1960–73 | | 1975–88 | |
|------------|---------|----------|---------|----------|
| | π | y^{ss} | π | y^{ss} |
| .60 | .77 | 1.82 | 1.06 | .87 |
| .55 | .85 | 1.35 | 1.10 | .82 |
| .50 | .93 | 1.15 | 1.18 | .78 |
| .45 | 1.05 | .95 | 1.26 | .76 |
| .40 | 1.20 | .84 | 1.39 | .74 |

TABLE 2
 CONVERGENCE TO BALANCED GROWTH PATH: $\theta_z = .55$

| Year | y_m/y_m^{ss*} | x_k/y_m | x_d/y_m | x_z/y_m | k/y_m | d/y_m | z/y_m | h |
|----------|-----------------|-----------|-----------|-----------|---------|---------|---------|-----|
| 0 | .226 | .20 | .16 | 1.01 | 1.11 | .77 | 8.03 | .53 |
| 5 | .305 | .19 | .16 | .91 | 1.20 | .88 | 9.02 | .51 |
| 10 | .383 | .18 | .16 | .83 | 1.27 | .98 | 9.85 | .49 |
| 15 | .457 | .18 | .16 | .76 | 1.32 | 1.06 | 10.55 | .48 |
| 20 | .525 | .17 | .16 | .71 | 1.36 | 1.13 | 11.13 | .46 |
| 25 | .588 | .16 | .15 | .67 | 1.39 | 1.19 | 11.62 | .45 |
| 30 | .644 | .16 | .15 | .61 | 1.42 | 1.24 | 12.03 | .43 |
| 50 | .809 | .15 | .15 | .51 | 1.47 | 1.37 | 13.11 | .42 |
| ∞ | 1.00 | .14 | .15 | .41 | 1.50 | 1.50 | 14.19 | .40 |

* y_m/y_m^{ss*} denotes year t income as a fraction of the balanced growth level. The subscript m denotes measured output and does not include investment in technology capital.

growth observations and the 1960–88 development experience of Japan.

The larger θ_z is, the greater the disparity in balanced growth income levels induced by a given disparity in barriers π . Because we are testing whether our theory is consistent not only with U.S. and postwar Japanese development but also with the observed disparity in income across countries, our subsequent analysis centers around the case in which $\theta_z = .55$. Table 2 reports the equilibrium convergence path for this technology capital share parameter, and figure 2 plots the path of per capita income over the 1960–73 and 1975–88 periods for this technology capital share and the values of π reported in table 1.⁹

What we find is that growth rates are lower the closer a country is to its balanced growth path, but the *speed of convergence*—that is, the fraction of the gap that is closed—is higher the closer a country is to its balanced growth path. For the calibrated model with $\theta_z = .55$, the speed of convergence goes from 2 percent per year at 25 percent of balanced growth income to 2.6 percent per year at 50 percent of balanced growth income to 4.0 percent per year at 95 percent of balanced growth income. Barro and Sala-i-Martin (1992) get an average convergence rate slightly less than 2 percent per year. Our model, therefore, implies faster convergence than the Barro and Sala-i-Martin estimate, except at very low percentages of the balanced growth income.

We note that if $\theta_z = .55$, the theory persists that the Japanese workweek should have declined from 52.1 hours per week in 1961

⁹ The calibrated values are $\delta_k = .07$, $\delta_d = .08$, $\theta_k = .16$, $\phi_d = .40$, $\phi_l = .75$, $\beta = .98$, $\gamma = .0125$, $\tau = .39$, and $\sigma = .20$, when $\theta_z = .55$.

to 41.6 hours per week in 1988, with most of the decline occurring in 1961–70. According to the *Statistical Yearbook of the United Nations*, the average length of the manufacturing workweek in Japan went from 47.0 hours per week in 1961 to 41.3 hours per week in 1988, with most of the decline occurring in 1961–70. Thus, while our model's workweek prediction is too long in the beginning years of the 1961–88 period, it accurately predicts 1988 hours and predicts that most of the decline in hours occurred before 1975.

IV. Output Disparity

We now examine whether our theory is consistent with the huge observed disparity in incomes across countries. In particular, we analyze how the balanced growth income levels in the calibrated model depend on tax rates, τ , and technology adoption barriers, π , for various θ_z 's for which the model is consistent with both U.S. and Japanese postwar development observations.

Table 3 reports the effect of tax rates on relative balanced growth per capita incomes, and table 4 reports the effect of technology adoption barriers on relative balanced growth per capita incomes for our model calibrated to U.S. observations for various θ_z 's. For any θ_z that is consistent with Japanese development, namely θ_z 's between .55 and .50, we find that the effect of tax rates on balanced growth income levels is far too small to account for the huge observed income disparity across countries. For the calibrated model with $\theta_z = .50$, an increase in the tax rate on income from 0 percent to 90 percent reduces balanced growth incomes by less than a factor of three. For the calibrated model with $\theta_z = .55$, the level effects are larger, but only slightly so. For $\theta_z = .55$, an increase in the tax rate from 0 percent to 90 percent reduces balanced growth incomes by a factor of 3.3.

TABLE 3
EFFECT OF TAX RATES ON RELATIVE
INCOMES FOR θ_z 'S CONSISTENT WITH
JAPANESE DEVELOPMENT

| τ | $\theta_z = .50$ | $\theta_z = .55$ |
|--------|------------------|------------------|
| .00 | 121.0 | 124.3 |
| .39 | 100.0 | 100.0 |
| .67 | 76.2 | 73.5 |
| .90 | 42.6 | 38.1 |

NOTE.—For presentation purposes, we do not list the values of the remaining parameters in either table 3 or table 4. Given a value for θ_z , values for all other parameters are identified by U.S. observations.

TABLE 4
EFFECT OF TECHNOLOGY ADOPTION
BARRIERS ON RELATIVE INCOMES
FOR θ_z 'S CONSISTENT WITH
JAPANESE DEVELOPMENT

| π | $\theta_z = .50$ | $\theta_z = .55$ |
|-------|------------------|------------------|
| 1.0 | 100.0 | 100.0 |
| 1.2 | 76.6 | 71.5 |
| 1.5 | 55.2 | 47.5 |
| 2.0 | 36.3 | 28.0 |
| 4.0 | 13.1 | 7.8 |
| 8.0 | 4.8 | 2.2 |

What these numbers imply is that if tax rates were to explain the huge observed income disparity across countries, they would have to be nearly 100 percent in poor countries and nearly zero in rich ones. This is counterfactual and leads us to conclude that differences in tax rates cannot be the key to understanding the problem of development.

While differences in tax rates cannot explain the huge observed income disparity, differences in technology adoption barriers may. For values of θ_z that are consistent with U.S. balanced growth observations and the postwar development of Japan, in particular for $\theta_z = .55$, the model generates disparities in income of the magnitude observed in the data for a plausible disparity in technology adoption barriers. For a given value of θ_z , the factor difference in relative balanced growth income levels associated with technology adoption barriers, π , is $\pi^{-\theta_z/(1-\theta_k-\theta_z)}$. Because this factor difference increases with θ_z 's, .55 is the value of θ_z among all those values consistent with U.S. balanced growth observations and the postwar development of Japan that generates the largest disparity in income levels for any disparity in technology adoption barriers. For this value of θ_z , a country with technology barriers twice the size of those in the United States will be roughly one-fourth as rich as the United States, another with technology barriers four times the size of those in the United States will be one-fourteenth as rich, and another with technology adoption barriers eight times the size of those in the United States will be one forty-fifth as rich.

For countries such as the United Kingdom, Colombia, Paraguay, and Pakistan, whose incomes relative to those of the United States stayed more or less constant over the 1950–88 period, the model with $\theta_z = .55$ has the following implications for the size of their relative technology adoption barriers. For the United Kingdom, which maintained an income level relative to that of the United States

of roughly 60 percent over the 1950–88 period, the model implies technology adoption barriers that were 1.3 times larger than those in the United States. For Colombia, which maintained a relative income of roughly 22 percent over the 1950–88 period, the model implies technology adoption barriers 2.3 times larger than those in the United States. For Paraguay, which maintained a relative income of roughly 16 percent over the 1950–88 period, the model implies technology adoption barriers 2.8 times larger than those in the United States. And for Pakistan, which stayed at roughly one-tenth the U.S. level over the 1950–88 period, the model implies technology adoption barriers 3.5 times larger than those in the United States.

V. Postwar Recoveries and Development Miracles

In this section we consider the development experiences of four countries that have realized large postwar increases in income relative to that of the United States and interpret these experiences in terms of the size of the technology adoption barriers.¹⁰ Specifically, for a given country, we determine the value, or values, of π for which the model matches the country's development experience over the 1950–88 period. In interpreting these experiences, we allow relative technology adoption barriers in a country to change between subperiods if such changes are suggested by the data. The same procedure that was applied to postwar Japan to find its value of π is used here. The development experiences we interpret are the postwar recoveries of France and West Germany and the postwar development miracles of South Korea and Taiwan.

A. France

The plot of France's path of per capita income over the 1950–88 period is depicted in figure 3. As figure 3 makes clear, a marked change in France's relative economic performance began around 1979. We interpret this as a change in the relative technology adoption barriers. The value of π for which the model matches France's 1950 and 1978 income levels is 1.01, and the value of π for which the model matches France's 1980 and 1988 income levels is 1.25. Under this interpretation, during 1950–78, France was essentially converging to the U.S. income level. During 1980–88, however, France was converging to an income level that was roughly two-thirds of the U.S. level.

¹⁰ These experiments were suggested to us by V. V. Chari.

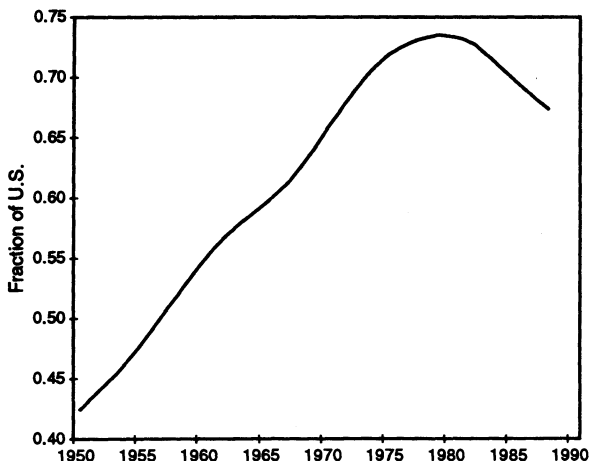


FIG. 3.—France, 1950–88

B. West Germany

Figure 4 shows the path of per capita income in West Germany over the 1950–88 period. West Germany's path suggests that a change in relative technology adoption barriers occurred around 1965. The value of π that matches 1950 and 1964 West German income levels is 0.88, and the value of π that matches 1966 and 1988 West German income levels is 1.12. Our interpretation of West Germany's postwar recovery is that an increase in its relative technology adoption barriers changed West Germany's convergence path from a relative balanced growth income level of 1.21 over the 1950–64 period to a relative balanced growth income level of 0.81 over the 1966–88 period.

C. South Korea

South Korea's postwar development experience is shown in figure 5. South Korea's path suggests a change in relative technology adoption barriers around 1963. The value of π for which the model matches South Korea's 1953 and 1962 income levels is 3.5, and the value of π for which the model matches South Korea's 1964 and 1988 income levels is 1.44. If no subsequent changes in relative technology adoption barriers were to occur, a South Korean would eventually attain an income level that was 51 percent of the level of an American.

D. Taiwan

Taiwan's postwar development experience, shown in figure 6, is similar to South Korea's. Around 1965 there appears to have been a

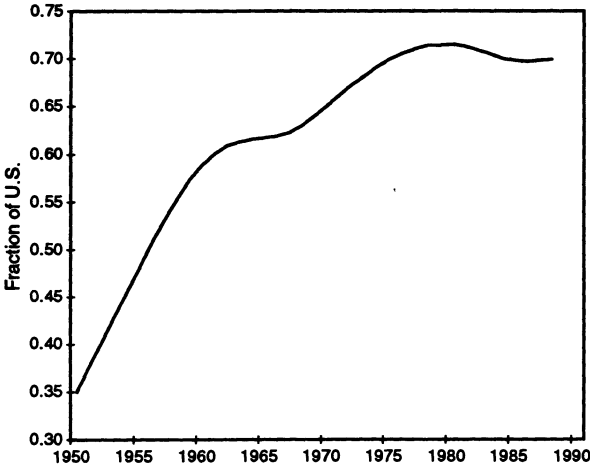


FIG. 4.—West Germany, 1950–88

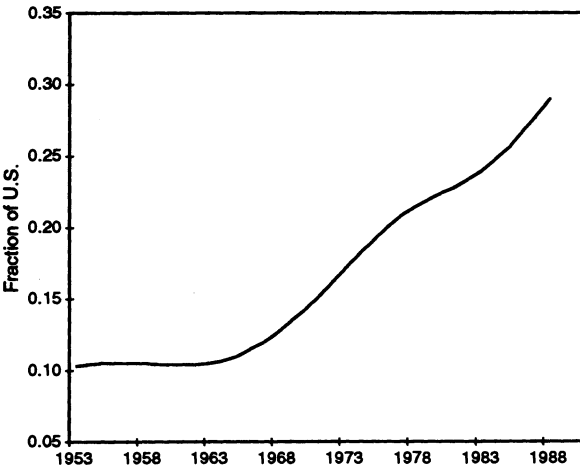


FIG. 5.—South Korea, 1953–88

change in regimes that changed the relative technology adoption barriers. The value of π for which the model matches Taiwan's 1950 and 1964 income levels is 2.42, and the value of π for which the model matches Taiwan's 1966 and 1988 income levels is 1.30. If this value of π over the 1966–88 period were to continue indefinitely, a Taiwanese would eventually attain an income level that was 62 percent of the level of an American.

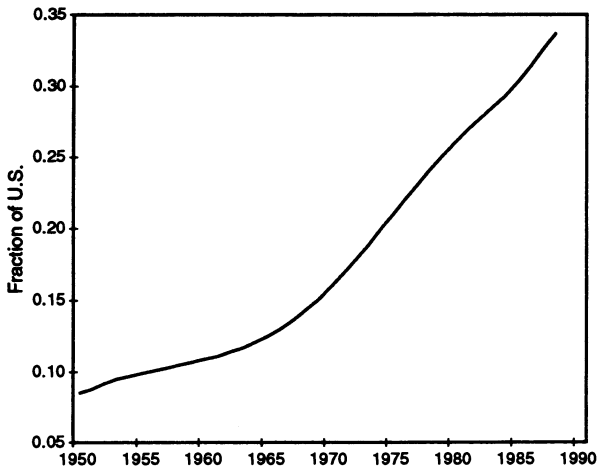


FIG. 6.—Taiwan, 1950–88

The interpretation afforded by the model of each of these four countries' development experience seems quite reasonable. The model is consistent with the development miracle of Japan and the rapid postwar development experiences of France, West Germany, South Korea, and Taiwan.

VI. Concluding Remarks

The problem in economic development is to account for both the great disparity in the wealth of nations and the development experiences of nations, including development miracles. Lucas (1993, p. 252) emphasizes that a theory of economic development must be consistent with a development miracle occurring in South Korea, but not in the Philippines, which appeared to be a very similar economy in 1960. Our theory is that the development miracle of South Korea is the result of reductions in technology adoption barriers in that country, and the absence of such a miracle in the Philippines is the result of no reductions in technology adoption barriers there. Like Lucas (1993, p. 270), we conclude that there must be a large unmeasured investment in the business sector, an investment he views as *learning on the job* and we view as *technology adoption investment*.¹¹ We find that for our model to be consistent with both the observed income disparity and development miracles, this investment must be about 40 percent of measured output.

¹¹ For interesting growth models that emphasize learning by doing with economy-wide spillovers, see Stokey (1988) and Young (1991).

Microeconomic evidence exists to suggest that considerable unmeasured investment occurs in the business sector. For example, profiles of earnings show large increases in earnings with age and tenure (see, e.g., Murphy and Welch 1991; Topel 1991). Another example is that productivity at the firm level shows large increases with firm-specific experience (see Rapping 1965; Irwin and Klenow 1993). Still another is the large investment made by entrepreneurs when they start businesses (see Dahmen 1970). We would also include trade school training, including forgone wages, as part of our unmeasured technology adoption investment. We emphasize that a better accounting of this unmeasured investment may find that its share is significantly smaller than the 40 percent of measured gross national product required by our theory. If so, this would lead to a rejection of our candidate for a theory of economic development.

Under the assumption that our theory passes this test (and we would be surprised if it did not), the crucial test is to obtain direct measures of the magnitudes of the barriers to technology adoption across countries and to see whether differences in these barriers account for differences in the wealth of nations. If barriers to technology adoption prove to be the key to economic development, then the next step is to understand why barriers vary across countries and across time in a given country.¹² Recent papers (Boldrin and Scheinkman 1988; Backus, Kehoe, and Kehoe 1991) have begun to study the role trade could play in the development process, but our conjecture is that greater trade openness contributes to development because it weakens the forces of resistance to technology adoption. The final step is to design sustainable arrangements (see Chari and Kehoe 1990) with the property that resistance to technology adoption is weak and stays weak.

Appendix

Construction of Figure 1

Of the 121 countries in the world with 1969 populations exceeding 1 million, we deduced from the Summers and Heston (1991) data set that 55 of these countries had achieved the 10 percent level by 1960 and 55 had not. The other 11 countries are Albania, Bulgaria, Cuba, Czechoslovakia, Libya, Mongolia, Namibia, North Korea, Romania, the Soviet Union, and the People's Democratic Republic of Yemen. Of the 55 countries that in 1960 had at least 10 percent of 1985 U.S. per capita GDP, all but Guatemala achieved the 20 percent level by 1985. Using the Maddison (1991) data, we deduced when

¹² Some early work in this area already exists. The paper by Krusell and Ríos-Rull (1992) is one example.

15 of the 16 currently rich countries achieved this doubling; using Summers and Heston (1991), we deduced when another 18 achieved this development. These are the 33 countries plotted in figure 1. The remaining 22 countries achieved the 10 percent level prior to 1950, the first year covered in the Summers and Heston data set.

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