

May 1991

## TECHNOLOGY ADOPTION AND GROWTH

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### ABSTRACT

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Technology change is modeled as the result of decisions of individuals and groups of individuals to adopt more advanced technologies. The structure is calibrated to the U.S. and postwar Japan growth experiences. Using this calibrated structure we explore how large the disparity in the effective tax rates on the returns to adopting technologies must be to account for the huge observed disparity in per capita income across countries. We find that this disparity is not implausibly large.

The views expressed herein are those of the authors and not necessarily those of the Federal Reserve Bank of Minneapolis, the University of Minnesota, the Federal Reserve System or the U.S. Department of Justice.

One need only look at a copy of the World Development Report or the survey by Summers and Heston [1988] to see how incredibly diverse per capita income levels are across countries. Such diversity has not always been a characteristic of the data, however. By Rosenberg and Birdzell's account [1990], income levels in the 18th century were fairly uniform across countries. The current diversity clearly then reflects a tendency for countries to develop at different rates and at different times.

The countries that were first to industrialize and thus break from the rest of the world tended to be located in Western Europe. These countries were later followed by the U.S. and Canada. Most recently, several countries centered about the Pacific Rim have made the leap. Many of the countries in this latter group have in the process experienced rates of growth that are spectacular relative to historical standards. Some countries, most notably those of sub-Saharan Africa, have yet to make the transition.

That there is greater diversity in income levels today than three centuries ago is clear. However, it would, we believe, be misleading to identify this occurrence as a spreading out of the distribution of per capita income levels. Within the set of non-African countries, the recent trend has been for income levels to move towards the mean.<sup>1</sup> If spreading out of the distribution were a characteristic of the data, then it should be the case that within the set of non-African countries per capita income levels move away from the mean as well.

Why some countries have been able to make the leap while others have not, and why amongst those countries having made the transition performances differ, are, we think, the central issues that confront the field of

economic growth, and the ones in which our current efforts are intended to resolve. We believe that a theory, if it is to have any hope of accounting for these observations, must have as its central focus technological change. Our view differs from neoclassical growth theory, however, in that we believe this change to occur only when individuals, or groups of individuals, make specific decisions to adopt new technologies. For us then, the question of why differences in growth rates and income levels exist across countries is really a question of why all countries do not adopt the same technologies at the same time.

While some period of time may elapse before individuals in one country become aware of a technological discovery in another country, we do not believe this to be the reason these differences exist. Most industry studies suggest that the adoption of a new technology requires investment in capital, with a substantial fraction taking the form of investment in intangible capital. In adopting a computer, for example, a firm must not only make the necessary investment in hardware and software, but it must train its personnel in the use of the new system. This training of personnel represents a substantial diversion of resources away from productive activities.

Instead, what matters in determining whether a particular technology will be adopted is the return that the individual, or group of individuals, making the adopting decision expects to earn on its investment. There is, we think, a large body of evidence that indicates that the institutional arrangements within a country can substantially reduce this return. The ways in which these institutional arrangements can reduce this return are not limited to official government taxes on capital. Olson [1982] emphasizes the role of redistributive coalitions and Krueger [1974]

emphasizes the role of rent seeking activity. We believe that these difference in institutional "taxes" across countries explain the observed diversity in per capita income levels.

There are many instances where relatively permanent changes in the institutional arrangements within a country have been associated with noticeable changes in that country's income level relative to the rest of the world and sustained, but not permanent, changes in its growth rate. Before 1980, black peasant farmers in Zimbabwe were forbidden to bring their crops to markets. With the end of white minority rule in 1980 this all changed. The new government took further steps to allow farmers to realize a higher return on their investments by beginning a program where agricultural specialists were sent out to demonstrate productivity increasing techniques. As a result of these changes, output of cotton, peanuts, and corn by Zimbabwe's black peasant farmers has more than tripled over a 10-year period. These farmers now account for over 60% of the country's corn production and 50% of the country's cotton production whereas only 10 years ago, these farmers accounted for only 5% of the country's total production of these commodities (Henry 1990a).

The experience of Zimbabwe is consistent with the finding of L.G. Reynolds [1983] who traced the development of 41 "Third World Countries" over the 1850-1980 period. In all but four countries, Reynolds found that the period in which each country first experienced a sustained increase in its level of per capita income directly followed a "significant political event". In most all cases, this "significant political event" involved the transfer of ruling power to a more progressive, growth orientated regime.

The recent experience of Japan is again illustrative of the productivity gains that can be realized if a country's institutional

arrangements improve so as to allow individuals adopting new technologies to keep more of the return on their investment. There does not seem to be any macroeconomic policy to which one can point that would seem capable of explaining Japan's post World War II experience. We dismiss the argument that the destruction of plant and machinery associated with Japan's defeat explains that country's success. If this were the cause, why then was the experience of East Germany so poor relative to West Germany over this same period? What the loss in that war did accomplish though was to remove Japan's institutional arrangements. In their place, institutional arrangements closely resembling those of the U.S. were substituted. It is in this sense that the war served as a catalyst for growth.

This account seems far more consistent with Japan's actual experience than the account implied by the neoclassical growth model. Japan's decade of "golden growth" was the 1960's. This is in contradiction to the predictions of the neoclassical growth theory that Japan's growth rates should have been highest in the years directly following the war. In terms of Japan's institutional arrangements, change continued to occur well after the war's end. One important change occurred in 1960 when labor unions, which had enjoyed considerable strength during the 1950's due to U.S. encouragement, collided head on with management. The result of this confrontation was that labor unions in Japan became passive, acquiescent, and conservative.

While Japan's growth rate of per capita income over the second half of the postwar period has been substantially lower than its growth rate over the first half of that period, its average annual rate of growth of 6.06% between 1950 and 1985 is still spectacular relative to historical standards. That such large productivity gains were realized by Japan, and some other

countries as well, is surely a result of these countries' relative positions in the world at the time of the change in their institutions. A poorer country has the potential to realize large increases in productivity once the institutional arrangements of that country change so as to allow individuals to keep more of the returns on their investments, and these new institutional arrangements are expected by individuals to survive into the future. This is because poorer countries are most likely to adopt technologies that already have been successfully adopted in richer countries. Consequently, poorer countries will have available to them more information of what to do for successful adoption. For this reason, a poorer country with the identical institutional arrangements as a richer one need not invest as much as the richer country to realize a given increase in productivity.

Solow (1956, footnote 7) recognized that aggregation over firms results in an aggregate production function that exhibits constant returns to scale provided the firm ultimately faces diminishing returns. This for Solow justified beginning at the aggregate level. We believe that we can learn a great deal by going back a level. Consequently, we start at the disaggregate level. The firm technology we consider builds upon the span-of-control model introduced by Lucas [1978]. A firm is run by a manager, or coalition of managers, who make investments in intangible technology capital. Intangible capital is combined with tangible capital and labor inputs to produce output. For a given stock of intangible capital, there are diminishing returns with respect to tangible capital and labor inputs. The return earned by a firm on its investment in capital depends upon the institutional arrangements associated with the country in which the firm is located and the firm's current technology (as reflected by

its present stock of intangible capital) relative to the world technology.

Our hope is that such a theory can account for the experiences of most countries. Obviously, the length of this paper does not allow for such an analysis. We do, however, in the tradition of Solow [1970] and more recently Lucas [1988], calibrate the model to U.S. steady state observations. In addition, we calibrate the model to the experience of Japan over the 1950-1985 period. Using the calibrated model, we analyze the level effects associated with these institutional arrangements and compare their size with the observed differences in per capita income levels across countries.

This paper is organized as follows. Section II develops the model. Section III calibrates the model to the U.S. steady state observations and the postwar experience of Japan. Section IV takes the calibrated model and analyzes the effects of these institutional taxes on steady state income levels. Section V consists of some concluding remarks.

## II. Model Economy

Much of the groundwork for this theory was laid by Parente [1990]. We use the basic structure of that model, but extend it by introducing a version of the Lucas span-of-control model to the production technology so as to be able to distinguish between labor and capital inputs. This extension permits us to match the Parente model to the National Income and Product Account data.

### *The Household*

The household is assumed to value a composite commodity made up of a consumption good,  $c$ , and services generated by the stock of household

durables,  $d$ . In addition to this composite commodity, the household is assumed to derive utility from a public good which we denote by  $g$ . This good is viewed in the model as being local in nature (i.e. parks, libraries, fire and police services, et al.). In order to simplify the analysis, we assume that the household's utility is additively separable in the composite commodity and the public good.

The discounted stream of utility over a household's infinite lifetime is

$$(1) \quad \sum_{t=0}^{\infty} \beta^t \cdot \left[ \frac{1}{1-\sigma} \cdot \left( c_t^\phi \cdot d_t^{1-\phi} \right)^{1-\sigma} + U(g_t) \right]$$

where  $0 < \phi < 1$ ,  $0 < \beta < 1$ ,  $\sigma > 1$ , and  $U$  is strictly increasing in  $g$ . Leisure is suppressed from the household's utility as the labor-leisure decision is not that central to growth.

The time endowment of the household in every period is one. In addition the household is endowed at date 0 with a stock of durables  $d_0$ . To simplify subsequent analysis and notation we assume that this initial stock is the same for all households. The stock of durables is assumed to depreciate at a rate of  $\delta_d$ . If  $x_{dt}$  denotes additions to a household's stock of durable goods at time  $t$ , then its stock in period  $t+1$  is

$$(2) \quad d_{t+1} = (1 - \delta_d) \cdot d_t + x_{dt}.$$

### *The Firm*

For each household there corresponds a firm that at any date that household can manage if it chooses to do so. <sup>2</sup> Each firm at date 0 has associated with it an initial technology level  $A_0$  and an initial stock of tangible capital  $K_0$ . For simplicity, we assume that  $A_0$  and  $K_0$  are the same

for all firms. A manager at date  $t$  hires labor  $N_t$  and combines it with the firm's tangible capital  $K_t$  and technology level  $A_t$ , to produce output  $Y_t$  according to the following production function

$$(3) \quad Y_t = \mu \cdot A_t \cdot h(K_t, N_t).$$

The parameter  $\mu$  indexes the managerial talent of a particular household. The function  $h$  is assumed to be increasing and concave in  $K$  and  $N$ . In this paper,  $h$  is given the following functional form

$$(4) \quad h(K, N) = K^\theta \cdot [\min(N, \bar{N})]^{1-\theta} \quad 0 < \theta < 1, \quad \bar{N} > 0.$$

The time requirement to manage a firm in any period is 1 so that a household that manages a firm in period  $t$  cannot supply labor elsewhere in the economy.

Output can be used by the household for consumption and/or investment in durables, and by the firm for investment in business tangible capital and/or to adopt a more advanced technology. A firm's stock of tangible capital is assumed to depreciate at a rate  $\delta_k$ . Let  $X_{kt}$  denote the amount of investment in tangible capital by a firm at time  $t$ . Then that firm's tangible stock of capital in period  $t+1$  is

$$(5) \quad K_{t+1} = (1 - \delta_k) \cdot K_t + X_{kt}.$$

The increase in the firm's technology level resulting from an investment of  $X_A$  units of output depends on its current level of technology relative to the level of world technology at the time of investment. The world technology at time  $t$  is denoted by  $W_t$ . The world technology is meant to represent the stock of pure or disembodied knowledge (i.e. blueprints, ideas, scientific knowledge). For the purpose of this paper,  $W$  is assumed

to be determined outside the model and to grow at the constant rate of  $\gamma_w$ .<sup>3</sup>

Thus,

$$(6) \quad W_{t+1} = W_t \cdot (1 + \gamma_w).$$

Given the world technology at time  $t$  and given a firm's current technology level  $A$ , the amount of investment needed to realize a technology level equal to  $A'$  in period  $t+1$  is

$$(7) \quad X_{At} = \int_A^{A'} \left( \frac{s}{W_t} \right)^\alpha ds \quad \alpha \geq 0.$$

Integration of (7) yields

$$(8) \quad (\alpha + 1) \cdot X_{At} = \frac{A_{t+1}^{\alpha+1} - A_t^{\alpha+1}}{W_0 \cdot (1 + \gamma_w)^{\alpha \cdot t}}.$$

Without loss of generality, we set  $W_0$  equal to 1.

The only way any firm can raise its technology level from  $A$  to  $A'$  is if that firm makes the investment  $X_A$  given by equation (7). In this sense, technology is firm specific. We treat tangible capital in the model as being firm specific as well. This implies that a firm which is not operated in some period cannot rent out its tangible capital stock or license its technology.<sup>4</sup>

Feasibility requires that at each date the number of managers and the number of workers per firm equal the size of the work force. We denote the size of the work force in period  $t$  by  $L_t$ . In this paper, we ignore population growth. Thus,  $L_t$  is assumed to equal  $L$  for all time. Because our emphasis is primarily on growth and less on the size and distribution of

firms we simply assume that there are  $M = L/(\bar{N}+1)$  households with managerial talent  $\mu = \eta > 0$  and  $L - M$  households with managerial talent  $\mu = 0$ . Given this assumption it immediately follows that in equilibrium there will be  $M$  firms in the economy each of which employs  $\bar{N}$  units of labor at each date. Given that we assume all firms begin with the same technology level  $A_0$  and tangible capital stock  $K_0$ , in equilibrium the date  $t$  product of each firm will be

$$(9) \quad Y_t = \eta \cdot A_t \cdot K_t^\theta \cdot \bar{N}^{1-\theta}.$$

From (9) it is apparent that it is impossible for  $Y$ ,  $A$ , and  $K$  to all grow at the same rate along a balanced growth path. However, if we define

$$(10) \quad Z_t = \frac{A_t^{\alpha+1}}{(1 + \gamma_w)^{\alpha \cdot t}} \quad \text{and} \quad X_{Zt} = X_{At},$$

and make the corresponding change in variables, it is possible to define a steady state solution where  $Y$ ,  $K$ ,  $X_K$ ,  $Z$ , and  $X_Z$  all grow at the same rate  $\gamma$ . Variable  $Z$  will have the interpretation of a firm's stock of intangible or technology capital.

In this  $Z$ -space, the date  $t$  product of a firm becomes

$$(11) \quad Y_t = \eta \cdot (1 + \gamma_w)^{\alpha \cdot t / (\alpha + 1)} \cdot Z_t^{1/(\alpha + 1)} \cdot K_t^\theta \cdot \bar{N}^{1-\theta}$$

and the investment technology (8) becomes

$$(12) \quad (\alpha + 1) \cdot X_{Zt} = (1 + \gamma_w)^\alpha \cdot Z_{t+1} - Z_t.$$

From (11) and (12) it follows that in order for  $Y$ ,  $K$ , and  $Z$  to all grow at a rate of  $\gamma$ , the following relation between  $\gamma$  and  $\gamma_w$  must hold:

$$(13) \quad 1 + \gamma_w = (1 + \gamma)^{(\alpha - \theta \cdot (\alpha + 1)) / \alpha}.$$

Aggregation across firms in the economy implies the following aggregate per capita production relation:

$$(14) \quad y_t = \eta \cdot \varphi \cdot (1 + \gamma_w)^{\alpha \cdot t / (\alpha + 1)} \cdot \bar{N}^{1 - \theta} \cdot k_t^\theta \cdot z_t^{1 / (\alpha + 1)}$$

where  $\varphi = (1 + \bar{N})^{\theta + 1 / (\alpha + 1) - 1}$ . Here, and in subsequent analysis, lower case letters denote per capita values of the corresponding variables.

Our interest is in the ratio of variables to output. Consequently, the values for  $\bar{N}$  and  $\eta$  are not central to our experiments. The choice of managerial ability,  $\eta$ , is clearly arbitrary. Without loss of generality, then, we select  $\eta$  so that  $\eta \cdot \varphi \cdot \bar{N}^{1 - \theta} = 1$ . With this normalization, per capita output is

$$(15) \quad y_t = (1 + \gamma_w)^{\alpha \cdot t / (\alpha + 1)} \cdot k_t^\theta \cdot z_t^{1 / (\alpha + 1)}$$

#### *Institutional Arrangements*

As this theory is intended to be one of growth and not one of institutional arrangements, we are not concerned with the exact manner by which these arrangements reduce the return that an individual, or group of individuals, adopting a new technology earns on its investment, only that these institutional arrangements reduce this return. For this reason we simply treat a country's institutional arrangements as a tax on the returns to tangible and intangible capital in the business sector. The tax on intangible business capital at time  $t$  is

$$(16) \quad \tau_z \cdot r_z \cdot z_t$$

where  $r_z$  is the steady state marginal product of intangible capital. The tax on tangible business capital at time  $t$  is

$$(17) \quad \tau_k \cdot r_k \cdot k_t$$

where  $r_k$  is the steady state marginal product net of depreciation of

tangible capital.

We use the steady state marginal product on tangible capital net of depreciation because tangible capital physically depreciates and this depreciation is taken into account for tax purposes. In contrast, intangible capital does not physically wear out. It depreciates only in the sense that over time, as the level of world technology increases, its price falls.

It is very easy to think of ways in which these taxes are redistributed or dissipated. Within the lesser developed countries of the world, a large percentage of these tax receipts tend to be pocketed by government officials. Henry [1990.b], for example, reports that in Tanzania corruption within the government is so excessive that Tanzanians refer to government spending programs as "public air" because the money supposedly marked for these projects is rarely spent on such projects. To be concrete, we assume that all such tax receipts are used to provide the local public good. Our results would not change if we were to assume some or all of these goods were used in unproductive ways. The technology for producing this good is assumed to be such that one unit of tax revenue results in one unit of the public good.

In light of this redistributational scheme and the tax revenues given by equations (16) and (17), the resource constraint for our economy is

$$(18) \quad c_t + x_{kt} + x_{dt} + x_{zt} = (1 + \gamma_w)^{\alpha \cdot t / (\alpha + 1)} \cdot k_t^\theta \cdot z_t^{1 / (\alpha + 1)} - \tau_z \cdot r_z \cdot z_t - \tau_k \cdot r_k \cdot k_t$$

and

$$(19) \quad g_t = \tau_z \cdot r_z \cdot z_t + \tau_k \cdot r_k \cdot k_t.$$

### The Competitive Equilibrium

A household at each date either manages a firm or supplies work elsewhere in the economy. We permit households to go from being managers to workers and vice versa between any two periods. However, since capital is firm specific, a firm that is not managed in a given period is assumed to lose both its tangible and intangible capital stocks. Furthermore, we assume that a firm's capital stocks can only be increased if a manager is on hand in the preceding period to make the investments. Thus, any time a firm is started up again by its manager, its output in that period is zero. Let  $m_t$  indicate whether a firm is or is not managed in period  $t$ . A value of 1 for  $m_t$  indicates that the firm is managed in period  $t$  while a value of 0 indicates that the firm is not managed in period  $t$ . The problem facing a manager-firm given the institutional arrangements of the country in which it resides is to maximize its present value

$$(20) \quad V(K_0, Z_0) = \text{maximize} \left\{ \sum_{t=0}^{\infty} m_t \cdot p_t \cdot [Y_t - w_t \cdot (N_t + 1) - X_{kt} - X_{zt} - r_k \cdot \tau_k \cdot K_t - r_z \cdot \tau_z \cdot Z_t] \right\}$$

subject to constraints (4), (11), and (12), subject to constraints  $K_{t+1} = Z_{t+1} = 0$  whenever  $m_t = 0$ , and subject to initial capital stocks  $K_0$  and  $Z_0$ . Here,  $\{p_t\}_{t=0}^{\infty}$  are the Arrow-Debreu prices of the composite commodity and  $\{w_t\}_{t=0}^{\infty}$  are the real wages. Both  $\{p_t\}_{t=0}^{\infty}$  and  $\{w_t\}_{t=0}^{\infty}$  are taken as given by the manager-firm.

To be specific and to keep the notation to a minimum, we assume that all households have the same initial wealth. Given our assumptions concerning preferences, equilibrium prices and market clearing quantities are the same whether initial wealth is distributed evenly or unevenly. Let

$V_0$  denote this initial per capital wealth. Each manager owns the firm it operates so that any manager whose firm has a sufficiently large present value must have debts at date 0 just large enough so that its initial wealth is  $V_0$ . Any households that never manages and any manager whose firm has a sufficiently small present value must have claims at date 0 just large enough so that their individual initial wealths are also  $V_0$ .

A consistency requirement is that aggregate wealth  $L \cdot V_0$  satisfy

$$(21) \quad L \cdot V_0 = \sum V(K_0, Z_0)$$

where the summation is taken over all firms in the economy.

Given the assumption of equal wealth, all households face the same problem. This problem is to maximize

$$(22) \quad \sum_{t=0}^{\infty} \beta^t \cdot \frac{1}{1-\sigma} \cdot \left( c_t^\phi \cdot d_t^{1-\phi} \right)^{1-\sigma}$$

subject to the constraint that a household is either a manager or worker at each date, subject to consumer durable constraints (2), subject to the budget constraint

$$(23) \quad \sum_{t=0}^{\infty} p_t \cdot [c_t + x_{dt} - w_t] \leq V_0,$$

and subject to initial capital stock  $d_0$ . The household, like the manager-firm, takes  $\{p_t\}_{t=0}^{\infty}$  and  $\{w_t\}_{t=0}^{\infty}$  as given.

### Steady State Analysis

We exploit the fact that the competitive equilibrium allocation solves a particular programming problem to find the competitive equilibrium. The problem is

$$(24) \quad \text{maximize} \quad \sum_{t=0}^{\infty} \left[ \beta^t \cdot \frac{1}{1-\sigma} \cdot \left( c_t^\phi \cdot d_t^{1-\phi} \right)^{1-\sigma} \right]$$

subject to

$$i. \quad c_t + x_{kt} + x_{dt} + x_{zt} = (1+\gamma_w)^{\alpha \cdot t / (\alpha+1)} \cdot k_t^\theta \cdot z_t^{1/(\alpha+1)} - \tau_z \cdot r_z \cdot z_t - \tau_k \cdot r_k \cdot k_t$$

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

$$iii. \quad d_{t+1} = (1 - \delta_d) \cdot d_t + x_{dt}$$

$$iv. \quad (1+\gamma_w)^\alpha \cdot z_{t+1} = z_t + (1+\alpha) \cdot x_{zt}$$

given  $z_0, d_0, k_0, \tau_k$ , and  $\tau_z$ .

There are two special features of the problem that result in the competitive allocation being the one which solves this program. The first is that households' preference orderings on private consumptions are independent of public consumptions. The second is that taxes on capital stocks can be treated as if they were features of the technology. The taxes paid by a firm depend only on its stocks and not the stocks of other firms.

The date  $t$  decision variables for this problem are  $c_t, k_{t+1}, d_{t+1}$ , and  $z_{t+1}$ . The amount of local public good,  $g_t$ , is not a decision variable. The amount of the public good consumed each period is simply determined by the amount of tax revenues collected in each period. Thus, the choices of  $k_{t+1}, d_{t+1}, z_{t+1}$ , and  $c_t$  are not affected by  $g_t$ .

In steady state, all variables grow at the rate of  $\gamma$ . For this reason, we find it convenient to divide each variable by  $(1 + \gamma)^t$  and redefine each appropriately. Thus, in what follows, all lower case variables represent per capita values divided by  $(1 + \gamma)^t$ . With the change in variables, the

relevant problem is

$$(25) \quad \text{maximize} \quad \sum_{t=0}^{\infty} \left[ \hat{\beta}^t \cdot \frac{1}{1-\sigma} \cdot \left( c_t^\phi \cdot d_t^{1-\phi} \right)^{1-\sigma} \right]$$

subject to

$$i. \quad c_t + x_{kt} + x_{dt} + x_{zt} = k_t^\theta \cdot z_t^{1/(\alpha+1)} - \tau_z \cdot r_z \cdot z_t - \tau_k \cdot r_k \cdot k_t$$

$$ii. \quad k_{t+1} = (1 - \hat{\delta}_k) \cdot k_t + \frac{1}{q_k} \cdot x_{kt}$$

$$iii. \quad d_{t+1} = (1 - \hat{\delta}_d) \cdot d_t + \frac{1}{q_d} \cdot x_{dt}$$

$$iv. \quad z_{t+1} = (1 - \hat{\delta}_z) \cdot z_t + \frac{1}{q_z} \cdot x_{zt}$$

where

$$(1 - \hat{\delta}_k) = \frac{1 - \delta_k}{1 + \gamma}, \quad q_k = (1 + \gamma),$$

$$(1 - \hat{\delta}_d) = \frac{1 - \delta_d}{1 + \gamma}, \quad q_d = (1 + \gamma),$$

$$(1 - \hat{\delta}_z) = \frac{1}{(1 + \gamma_w)^\alpha} \cdot \frac{1}{1 + \gamma}, \quad q_z = (1 + \gamma_w)^\alpha \cdot \frac{(1 + \gamma)}{\alpha + 1},$$

and

$$\hat{\beta} = \beta \cdot (1 + \gamma)^{1-\sigma}.$$

It is clear for this system that the prices of each of the capital goods will not all be equal. We find it convenient to redefine variables in such a way so that these prices are all equal to one. This is done by multiplying capital constraints (ii)-(iv) by their respective price  $q_j$  and

by redefining variables

$$\hat{z}_t = q_z \cdot z_t, \quad \hat{k}_t = q_k \cdot k_t, \quad \hat{d}_t = q_d \cdot d_t.$$

With this change of variables, the problem becomes

$$(26) \quad \text{maximize} \quad \sum_{t=0}^{\infty} \hat{\beta}^t \cdot \frac{\kappa}{1-\sigma} \cdot \left( c_t \cdot \hat{d}_t^{1-\phi} \right)^{1-\sigma}$$

subject to

$$i. \quad c_t + x_{kt} + x_{dt} + x_{zt} = \Omega \cdot \hat{k}_t^{\theta} \cdot \hat{z}_t^{1/(\alpha+1)} - \tau_z \cdot r_z \cdot \hat{z}_t / q_z - \tau_k \cdot r_k \cdot \hat{k}_t / q_k$$

$$ii. \quad \hat{k}_{t+1} = (1 - \hat{\delta}_k) \cdot \hat{k}_t + x_{kt}$$

$$iii. \quad \hat{d}_{t+1} = (1 - \hat{\delta}_d) \cdot \hat{d}_t + x_{dt}$$

$$iv. \quad \hat{z}_{t+1} = (1 - \hat{\delta}_z) \cdot \hat{z}_t + x_{zt}$$

where

$$\kappa = q_d^{(\sigma-1) \cdot (1-\phi)} \quad \text{and} \quad \Omega = q_k^{-\theta} \cdot q_z^{-\alpha/(\alpha+1)}.$$

In finding the steady state solution, we first substitute constraints (ii)-(iv) into constraint (i), and then substitute constraint (i) for  $c_t$  in equation (26). We then take derivatives with respect to  $k_{t+1}$ ,  $z_{t+1}$  and  $d_{t+1}$ . In taking these derivatives, we treat  $r_k$  and  $r_z$  parametrically. Next we substitute into these first order necessary conditions the marginal product of intangible capital for  $r_z$  and the marginal product of tangible capital net of depreciation of tangible capital for  $r_k$ , both of which are

functions of  $k$  and  $z$ . Lastly, we invoke the steady state condition that  $k_t = k$ ,  $d_t = d$ , and  $z_t = z$  for all time and then solve for  $k$ ,  $d$ , and  $z$ .

#### *Off-Steady State Analysis*

The system given by (26) is a well behaved, deterministic, discounted dynamic program with returns bounded from above (note  $\sigma > 1$ ). Consequently (see Stokey et al., Theorems 4.2 and 4.14, 1989), successive approximations to optimality equation, beginning with a bounded initial approximation, converge to the optimal return function. This optimal return function can be used to find an optimal policy rule which is a stationary Markov policy in the state variable  $(d,k,z)$ . Indeed, this policy rule generates the unique optimal sequence. The uniqueness of the optimal policy sequence follows from the strict concavity of the return function in  $(c,d)$ , the strict concavity of the production function in  $(k,z)$ , and the fact that the return function is strictly increasing in  $c$ .

### **III. Model Calibration**

In the tradition of Solow [1957] we calibrate the model to 1987 U.S. National Income and Product Accounts. In doing so, we use a period of length one year. Our source of these accounts is the *Economic Report of the President 1990*. In addition, we calibrate the model to the postwar experience of Japan. That experiment is based upon the assumption that the institutional arrangements of the U.S. and Japan were identical in 1950 and have not changed since. Thus, the only difference, assumed to exist between the two countries lies in their 1950 capital stocks. The calibration of the model to the experience of Japan, considers the off-steady state properties

of the system while the calibration of the model to the U.S. National Income and Product Accounts considers only the steady state properties of the model. The observations pertaining to the calibration of the model to Japan's postwar experience are taken from the Summers and Heston data set.

Some variables in our model do not correspond exactly to those measured in either the National Income and Product Accounts or the Summers and Heston survey. Most notably is the failure of U.S. National Income and Product Accounts to measure the stock of intangible capital and investment in that capital. For this reason, output in our model will differ from the numbers reported in the National Income and Product Accounts by the amount of investment in intangible capital.

In light of the specification of our economy, other adjustments to the National Income and Product Accounts are called for as well. First, we reduce GNP by the amount of housing services. Since we treat residential structures as part of household capital, such an adjustment seems appropriate. Given that final real estate services product is approximately 10 percent of GNP, measured output in our model,  $y-x_2$ , is  $.90 \cdot \text{GNP}$ . Second, we separate consumption expenditures on durables from consumption expenditures on non-durables and services and include the former in the category of investment in household capital. Third, we remove residential investment from gross private investment, and add it to the category of investment in household capital. Fourth, we assign 10 percent of government purchases to investment in tangible business capital. This we do because public investments in infrastructure increase private business productivity. The remaining fraction of government purchases is identified with household consumption of the local public good in the model.

Our economy is a closed system. Therefore, there is the question of

how to treat net exports listed in the National Income and Product Accounts. We simply choose to increase real GNP by the amount of net exports, and assume that for each expenditure category, the expenditure on net exports increases the expenditure category by the same percentage as net exports increases GNP.

After making such adjustments, the ratio of consumption to measured GNP for the U.S. in 1987 is .54, the ratio of investment in durables to measured GNP is .15, the ratio of investment in tangible capital to measured GNP is .14, and the ratio of consumption of the public good to measured GNP is .17. In addition to these statistics, the model is calibrated to the ratio of nonhousehold tangible capital to measured GNP, to the ratio of household capital to measured GNP, to the U.S. steady state growth rates of per capita consumption and output, to the real return on equity in the U.S. over the postwar period, and to business tangible capital share of output less investment in intangible business capital.

The ratio of tangible business capital to measured GNP in the U.S. is approximately 1.25. With the capital of the government, we believe a ratio of 1.75 for nonhousehold tangible capital to measured GNP is reasonable. The ratio of the stock of household capital to measured GNP for the U.S. is approximately 1.25. Using the Summers and Heston data, the growth rate of both per capita output and consumption in the U.S. is approximately 2%. The real return on equity in the U.S. over the postwar period is 6.5%.

The share parameter for tangible capital  $s_k$  for our model economy is

$$(28) \quad s_k = (r_k + \delta_k) \cdot k / (y - x_z).$$

To compute the counterpart of this statistic for the U.S. economy we proceed as follows: To estimate the numerator of (28) we subtract from  $.90 \cdot \text{GNP}$  our

estimates of payments to labor. In payments to labor we include all compensation of employees, fraction  $s_k$  of entrepreneur income, fraction  $s_k$  of surplus on government enterprises, and 50 percent of indirect business taxes. Our resulting estimated value of  $s_k$  is .25.

The preference parameters whose values are selected to match these steady state observations are the relative rate of risk aversion  $\sigma$ , the consumption share parameter  $\phi$  in the utility function, and the subjective time discount factor  $\beta$ . The condition that the marginal rate of substitution in consumption between  $c_t$  and  $c_{t+1}$  equals the marginal rate of substitution in exchange between  $c_t$  and  $c_{t+1}$ , when  $c$  and  $d$  grow at the constant rate  $\gamma$ , requires that  $(1+r) = (1+\gamma)^\sigma / \beta$  where  $r$  denotes the real rate of interest. Because we calibrate the model to  $r = .065$  and  $\gamma = .02$ , our selections of values for the subject time discount factor  $\beta$  and the relative rate of risk aversion  $\sigma$  are required to satisfy  $1.065 = (1.02)^\sigma / \beta$ . Using the utility maximizing condition that the marginal rate of substitution in consumption between  $c_t$  and  $d_{t+1}$  equals the marginal rate of substitution in exchange between  $c_t$  and  $d_{t+1}$  the consumption share parameter  $\phi$  in the utility function together with parameters,  $\beta$  and  $\delta_d$ , and the real rate of interest  $r$  are required to satisfy  $\phi \cdot (\delta_d + r) / [\beta \cdot (1+r) \cdot (1-\phi)] = c/d$  when  $c$  and  $d$  grow at the constant rate  $\gamma$ . While we do not calibrate the model to the ratio of consumption expenditures to the stock of household capital for the U.S. in 1987, we do find that the ratio of consumption to the stock of household capital corresponding to our parameterized model is quite close to this ratio for the U.S.

The technology parameters whose values are to be chosen are  $\gamma_w$ ,  $\theta$ ,  $\alpha$ ,  $\delta_k$ , and  $\delta_d$ . In addition, the tax rates,  $\tau_k$  and  $\tau_z$ , must be chosen. Since the growth rate of per capita output for the U.S. over the 1950-1985 period

was approximately 2%,  $\gamma_w$ ,  $\alpha$ , and  $\theta$  must satisfy equation (13) for a growth rate  $\gamma$  equal to .02. As long as tangible capital is paid its marginal physical product, the parameter  $\theta$  equals  $(r_k + \delta_k) \cdot k / y$ . Because we calibrate the model to  $s_k = .25$  where  $s_k = (r_k + \delta_k) \cdot k / (y - x_z)$  our selection for  $\theta$  must satisfy  $\theta \cdot (y - x_z) / y = .25$ .

The parameter  $\alpha$  has important implications for how fast a country will approach its steady state. We are not aware of any existing studies which would restrict the range of values for  $\alpha$ . Nor can the value of  $\alpha$  be tied down within the model using U.S. data alone, but by using the Japanese data as well and considering the off-steady state properties of the model, the value for  $\alpha$  can be pinned down.

For the institutional "tax" on business tangible capital,  $\tau_k$ , we select a rate of 1/3. This is approximately equal to the ratio of total revenues in 1985 from all tangible capital taxation to total tangible capital income calculated by Lucas [1989]. For the institutional "tax" on intangible capital,  $\tau_z$ , we treat it symmetrically and set it to 1/3.

Capital consumption allowance with capital consumption adjustment in 1987 was roughly 12% of total output. If this entire amount corresponded to depreciation on capital in the business sector it would imply an annual depreciation rate of roughly 9.5% on this capital stock. It is not clear, however, how much of this corresponds to depreciation on household capital and how much corresponds to depreciation on non-household capital. It is, further, unclear as to how much depreciation in the household's capital stock goes unmeasured. For these reasons, we do not believe an annual depreciation rate on tangible capital and a depreciation rate on durables of roughly 8% is unreasonable.

The computational experiments whose results are reported below involve

the following steps. First a set of parametric values for the model is chosen. Once this selection is made, the steady state solution is calculated and this solution is compared to the steady state ratios for the U.S. listed above. If a solution is not inconsistent with these statistics, we then proceed to determine whether the model, with that particular set of parametric values, can account for the postwar experience of Japan. This experience was that Japan per capita income increased from 1/6th to 3/4ths of the U.S. level in the 1950-1985 period.

We use the methods of dynamic programming to determine the optimal policy functions corresponding to the system described by (26). Once these functions are found, we trace out the optimal path for a country which begins with roughly 1/6th of its steady state income in 1950. If we find that after a 36 year period, the per capita income level for this artificial economy is not approximately 3/4ths of its steady state level, we consider a new set of parametric values, and begin the experiments again.

The parametric values that seem to provide the best fit to the U.S. steady state observations and the postwar experience of Japan are listed in Table I. Table II compares the steady state solution of the model with the observation for the U.S., while Figure 1 plots the off-steady state path traced by the model to the actual path for Japan. As both Table II and Figure 1 demonstrate, the model's fit is quite good.

#### **IV. Level Effects**

The most striking feature of the data is the tremendous diversity in per capita income levels that exists across countries. A crucial test of a theory of growth is whether it can account for this diversity. Our theme is that this diversity is the result of the differences in "taxes" imposed by a

country's institutional arrangements on the return to the investment of an individual or group of individuals adopting a more advanced technology.

To determine the level effects associated with a country's institutional arrangements, we simply calculate the steady state solution to the model for various tax rates keeping all other parameters to their values of Section III. Table III reports the steady state income levels for pairs of tax rates  $(\tau_k, \tau_z)$ . As can be seen from the table, differences in the taxes imposed by a country's institutional arrangements can result in large differences in steady state income levels. Differences in tax rates, for example, of a factor 3 can lead to differences in steady state per capita output of a factor 84.

As the table also indicates, the tax on the return to intangible capital is associated with much larger level effects than the tax on the return to tangible capital. Holding the tax rate on tangible capital fixed and changing the tax rate on intangible capital by roughly a factor 3 result in level effects of roughly a factor 25. Holding the tax rate on intangible capital fixed and changing the tax rate on tangible capital by a factor 3, however, only result in level effects of roughly a factor 3.

## V. Conclusion

It is clear that the model proposed here is not one of endogenous growth. While growth arises because of specific decisions by agents to adopt more advanced technologies, neither preference parameters nor policy parameters affect growth rates. However, we see this as a virtue of the model, and not a deficiency. If savings rates had growth rate effects then the distribution of per capita income across countries would have to spread

out over time. This we do not see in the data.

For us then, a crucial feature of a model is that the level effects generated within it be large enough to account for the huge observed disparity in per capita incomes across countries and that the implied disparity in relevant parameters generating these level effects not be inconsistent with observation. Our theme is that differences in effective tax rates on the returns to technology adoption across countries are fundamental to understanding the huge diversity in per capita incomes. Our model, calibrated to the postwar growth experiences of the U.S. and Japan can account for this tremendous diversity with, what we think, is an entirely plausible implied range of tax rates.

Plausible, however, is not quantitatively meaningful. What is desperately needed is measurement of these returns across countries. Given the success of this theory and given the vast amount of anecdotal evidence that suggests that a country's institutional arrangements affect its economic performance, our hope is that effort and research will be directed to this endeavor.

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## Footnotes

<sup>1</sup> Observations for all 130 countries in the Summers and Heston data set are available only for the years 1973 through 1985. Over this 13 year period the standard deviation of the logarithm of per capita output for the non-African countries in the data set decreases by 7%.

<sup>2</sup> For simplicity, we assume that a single manager operates a firm. For an extension to coalition management, see Prescott and Boyd (1987).

<sup>3</sup> For most countries in the world, it seems entirely appropriate to assume that their policy has negligible effects on the stock of knowledge. For those few countries whose policies do significantly affect this stock, we refer to the stylized fact pointed out by Romer [1987] that over the past several centuries the world's productivity leader has very rarely been the world's science and technology leader.

<sup>4</sup> Clearly, some of a firm's tangible capital stock such as its vehicles, and office equipment is probably not firm specific. By treating this entire capital stock as firm specific, however, we greatly simplify the notation and analysis of the model without altering the basic conclusions of the model.

TABLE I  
Model Parameters

Preference Parameters:	$\sigma = 1.120$	$\beta = 0.960$	$\phi = 0.725$
Technology Parameters:	$\alpha = 1.155$ $\theta = 0.217$	$\delta_k = 0.080$ $\delta_d = 0.080$	$\gamma_w = 0.012$
Tax Rates:		$\tau_k = .333$	$\tau_z = .333$

TABLE II  
Steady State Calibrations

	Model Economy	U.S. Economy (1987)
$c/y^a$	0.50	0.54
$g/y$	0.22	0.17
$x_k/y$	0.14	0.14
$x_d/y$	0.13	0.15
$x_z/y$	0.15	—
$k/y$	1.46	1.75
$d/y$	1.36	1.25
$z/y$	4.81	—

<sup>a</sup>y is measured output which does not include  $x_z$ .

TABLE III  
Level Effects

Steady State Relative Outputs								
	$\tau_k$	.33	.43	.53	.63	.73	.83	.93
$\tau_z$								
.33		21.9	20.6	19.0	17.0	14.5	11.3	6.51
.43		17.7	16.6	15.3	13.7	11.7	9.12	5.26
.53		13.6	12.7	11.8	10.6	9.05	7.03	4.05
.63		9.80	9.21	8.49	7.61	6.52	5.06	2.91
.73		6.30	5.92	5.46	4.90	4.19	3.25	1.87
.83		3.24	3.05	2.81	2.52	2.15	1.67	0.97
.93		0.87	0.82	0.76	0.68	0.58	0.45	0.26

# FIGURE 1

