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R&D INVESTMENT AND INTERNATIONAL PRODUCTIVITY DIFFERENCES

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ABSTRACT

This paper extends previous research on the effect of investment on labor productivity at the country level by accounting for investment in R&D, as well as for investment in fixed and human capital. Privately-funded R&D investment is found to have a significant positive effect on productivity. Moreover, this effect appears to be quite large. The estimated social (national) rate of return to private R&D investment is about seven times as large as the return to investment in equipment and structures. The elasticity of GNP with respect to the privately-funded research capital stock is about 7 %--about 1/3 as large as the physical-capital elasticity (whose estimate is substantially reduced when R&D is accounted for). These findings do not support the hypothesis that there are complete, or at least instantaneous, international R&D spillovers. The social marginal product of government-funded research capital appears to be much lower than that of private research capital.

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1. Introduction

Previous cross-country empirical studies have shown that the level and/or growth rate of a nation's productivity (output per worker) depends, to an important extent, on its investment rate--the fraction of output devoted to investment. Early econometric studies of the relationship between investment and productivity (e.g. Romer (1986), Dowrick and Nguyen (1989)) adopted the traditional, narrow, national-income-accounting definition of investment, which includes only investment in tangible assets (equipment and structures).[1] Paul Romer's paper suggested that not only was investment important, it was much <u>more</u> important than suggested by the neoclassical theory of production (based on a constant returns to scale production function with diminishing marginal productivity of capital). Cross-country correlations suggested that the social elasticity of output with respect to fixed capital (α) was close to 1, much greater than capital's share in national income (about .3).

In a subsequent paper, Mankiw, David Romer, and Weil (1990), argued that Paul Romer's estimate of α was seriously biased upward by his failure to account for one type of investment in intangible assets, investment in education, or in human capital.[2] When

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[1] De Long and Summers (1991) have argued that investment in equipment may contribute much more to productivity growth than investment in structures.

[2] Failure to account for human capital biases α upward even if the two types of investment are uncorrelated. The bias is magnified if this correlation is positive, which is true in practice.

investment in education was controlled for (using a proxy based on the secondary school enrollment rate), the elasticities of output with respect to physical and human capital were both estimated to be about 1/3. In other words, intangible investment is also important--perhaps no less important than fixed investment--and must be accounted for to correctly assess the role of fixed investment.[3]

In this paper, we argue that to better understand international differences in productivity, it is necessary to account for another type of investment in intangible assets--investment in research and development (R&D), which contributes to the process of "intellectual capital" (or "research capital") formation. There have been many studies of the effect of R&D investment on productivity at the firm and industry level, and these have generally indicated that the effects of at least some types of R&D (especially privately-funded and basic research) are positive and significant, both statistically and economically. But the impact of R&D investment on productivity has not, to our knowledge, been carefully examined at the national level. Moreover, as Griliches (1991) has shown, due to the existence of "R&D spillovers," estimates of the effects of R&D investment on productivity are likely to depend on (and increase with respect to) the level of aggregation of the data; macro effects cannot be inferred directly from micro estimates.

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[3] In a recent paper based on a different methodology, however, Benhabib and Spiegel (1991) fail to find empirical support for the hypothesis that investment in education increases a nation's productivity.

Table 1 presents some very aggregate data on the magnitude of R&D investment relative to both GNP and to fixed investment in 1970 and 1980. In developed countries (as defined by UNESCO), about 2.3% of GNP is devoted to R&D. The R&D investment share is only about 0.4% in developing countries. The GNP-weighted average for the entire world is about 1.9% In contrast, the share of world output devoted to fixed investment is 22%, so aggregate R&D investment is only 8-9% as large as aggregate fixed investment.[4] Moreover, 40 to 50% of the R&D is government-funded, so the ratio of private R&D to private fixed investment is even smaller.

Despite its modest relative size, R&D investment merits serious attention for at least two reasons. First (notwithstanding the impression conveyed by Table 1), R&D investment--especially nondefense R&D[5]--has been increasing faster than fixed investment, and may continue to do so. (See Graph 1 and Table 2.) For example, between 1972 and 1988 or 1989, Japan's fixed investment intensity declined but her R&D

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[4] In the manufacturing sector, the locus of most industrial R&D investment, the ratio of R&D to fixed investment is considerably higher. Hall (1992), for example, reports that this ratio is about 1/3 for U.S. manufacturing firms.

[5] Unfortunately, systematic country-level nondefense R&D data are available beginning only in 1971. Even the available data are not without difficulties. Nondefense R&D is defined as total R&D minus government-funded defense R&D. It is assumed that all privately-funded R&D is nondefense R&D. Lichtenberg (1988, 1990) presents evidence that is inconsistent with this assumption: in the U.S. at least, the rules of the defense procurement game induce firms to spend substantial amounts of their own funds on defense R&D.

intensity increased more than 50%. Second, previous studies suggest that the mean social rate of return to R&D investment is much larger than the corresponding return to tangible investment. This discrepancy in social returns is presumably partly due to the substantially greater risk, and partly due to the (greater) spillovers, associated with R&D investment. The number of R&D "bucks" is much smaller, but the mean "bang per buck" may be much greater.

The remainder of this paper is organized as follows. In the next section we generalize the production function specified in previous cross-country productivity studies to include the stock of research capital, as well as fixed and human capital. From this we derive two estimable reduced-form equations, whose coefficients are functions of the output elasticities. In the first equation, the level of productivity is a linear function of the logarithms of the rates of investment in the three types of capital. This equation yields consistent estimates of the output elasticities if initial productivity is randomly distributed around steady-state productivity. In the second equation, the growth rate of labor productivity is a linear function of the logarithms of the investment rates and the logarithm of initial productivity. This equation may yield consistent estimates of production function parameters even if initial productivity is not randomly distributed.

Section 3 addresses the important issue of R&D spillovers. If international R&D spillovers were complete and instantaneous--if country B realized the same benefits, at the same time, from country A's research as country A did--then we would not expect to observe a positive correlation between a country's productivity and its own R&D

investment. However it seems very unlikely to us--and exisiting evidence does not support the view--that spillovers are complete, or, even if complete, that they are instantaneous. We show that if spillovers are incomplete--benefits to innovators (permanently) exceed those to imitators--own R&D investment has a positive impact on productivity; the coefficient on R&D is an estimate of the excess benefit to the innovator. We then show that even if spillovers are ultimately complete (eventually, all knowledge becomes public knowledge), own R&D investment should have a positive effect on productivity as long as proprietary knowledge is more valuable than public knowledge, and proprietary knowledge becomes public only gradually. In this model R&D investment generates both a finite, steady-state stock of proprietary knowledge, and unbounded growth in the stock of public knowledge (the latter may be indistinguishable from exogenous technical change).

Section 4 describes the data base. Empirical results are presented in section 5. Concluding remarks are made in section 6.

2. Alternative models of aggregate production

As noted above, first-generation cross-country studies of the effect of investment rates on productivity accounted only for investment in physical capital. They were based on a production function of the form

$$Y(t) = A(t)\, K(t)^{\alpha}\, L(t)^{\beta} \qquad (1)$$

and an accumulation equation

$$K(t) = (1 - \delta_K)\ K(t-1) + I_K(t) \qquad (2)$$

where Y = real output, A = an index of efficiency (or total-factor productivity), K = the stock of physical capital, L = labor input (e.g., total employment or hours worked), I_K = gross investment, and δ_K = the depreciation rate. Mankiw, Romer, and Weil extended this by incorporating the stock of human capital H in the production function:

$$Y(t) = A(t)\ H(t)^{\theta}\ K(t)^{\alpha}\ L(t)^{\beta} \qquad (3)$$

$$H(t) = (1 - \delta_H)\ H(t-1) + I_H(t) \qquad (4)$$

where I_H = the rate of investment in human capital and δ_H = the human capital depreciation rate.[6]

We propose a further extension: inclusion of the stock of "research capital" R, which is accumulated via investment in research and development I_R:

$$Y(t) = A(t)\ R(t)^{\gamma}\ H(t)^{\theta}\ K(t)^{\alpha}\ L(t)^{\beta} \qquad (5)$$

$$R(t) = (1 - \delta_R)\ R(t-1) + I_R(t). \qquad (6)$$

The primary objectives of these studies is to obtain reliable estimates of the elasticities of output with respect to physical, human, and/or research capital, which are assumed to be invariant across countries and over time. Since we lack data on K, H, and R for most, if not all, countries, these parameters cannot be estimated by direct estimation of (logarithmic transformations of) the production function.

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[6] A production function with a stock of human capital, separate from the quantity of labor input, might seem rather artificial. As we see below, the advantage of this specification is that it yields a reduced form equation in which (the level or growth rate of) output per worker depends upon the rate of investment in human capital, for which reasonable proxies exist.

One can, however, derive from the production function relationships between (the level or growth rate of) output per worker and rates of investment in physical, human, and research capital, which are observable. Under certain assumptions, these reduced-form relationships permit identification and estimation of the structural parameters (output elasticities).

Our econometric approach is similar to the one developed by Mankiw, Romer, and Weil (1990), which is based on the Solow growth model. We review this methodology using the first production function, the one without human and research capital. Then we will generalize the analysis to incorporate both types of intangible investment.

MRW specified the production function as follows:

$$Y(t) = K(t)^{\alpha} (B(t) L(t))^{1-\alpha} \qquad (7)$$

where B(t) is an index of technology. L and B are assumed to grow exogenously at rates n and g, respectively:

$$L(t) = L(0) e^{nt}$$

$$B(t) = B(0) e^{gt}.$$ [7]

The quantity of effective labor, BL, grows at rate n+g. They define the following: $s_K \equiv I_K/Y$ = the fraction (assumed constant) of output devoted to fixed investment; $k' \equiv K/BL$ = capital per unit of effective labor; and $y' \equiv Y/BL$ = output per unit of effective labor. They

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[7] MRW assume that technological progress is labor-augmenting rather than total-factor-augmenting. But the two models appear to be observationally equivalent. Comparing eqs. (1) and (12), we see that $A = B^{1-\alpha}$, and that if B grows at the constant rate g, A grows at the constant rate $(1-\alpha)g$.

show that the economy converges to a steady-state value of k', and that steady-state income per capita y^* is determined by the investment rate and other parameters as follows:

$$\ln [y^*(t)] = \ln B(0) + gt + [\alpha /(1 - \alpha)] \ln (s_K) - [\alpha/(1 - \alpha)] \ln (n + g + \delta_K) \qquad (8)$$

where $y(t) \equiv Y(t) / L(t)$. MRW assume that g, α, and δ_K are invariant across countries (and that $g=.02$ and that $\delta_K=.03$), and that B(0) varies but is unobservable; it is incorporated into the disturbance term. The observable sources of cross-country variation in steady-state income per worker are variation in s_K and in n:

$$\ln y^*_i = \text{constant} + [\alpha /(1 - \alpha)] \ln (s_{Ki}) - [\alpha/(1 - \alpha)] \ln (n_i + .05) + u_i \qquad (9)$$

Log productivity at time t is a weighted average of log productivity at time 0 ("initial productivity") and of $\ln y^*$:

$$\ln y(t) = (1 - e^{-\mu t}) \ln y^* + e^{-\mu t} \ln y(0) \qquad (10)$$

The weights depend on t (the higher is t, the closer y(t) is to y^*) and on the convergence rate μ, and $\mu = (n + g + \delta_K) (1 - \alpha)$. Substituting (9) into (10), we obtain

$$\ln y(t)_i = (1 - e^{-\mu t}) [\alpha /(1 - \alpha)] \ln (s_{Ki}) - (1 - e^{-\mu t}) [\alpha/(1 - \alpha)] \ln (n_i + .05) + e^{-\mu t} \ln y(0)_i + u_i \qquad (11)$$

This may also be interpreted as an equation determining productivity <u>growth</u>: subtracting y(0) from both sides, we obtain

$$\ln y(t)_i - \ln y(0)_i = (1 - e^{-\mu t}) [\alpha /(1 - \alpha)] \ln (s_{Ki}) - (1 - e^{-\mu t}) [\alpha/(1 - \alpha)] \ln (n_i + .05) - (1 - e^{-\mu t}) \ln y(0)_i + u_i \qquad (12)$$

If we are willing to assume that initial productivity is randomly distributed around steady-state productivity, then we can derive a simpler specification for the estimation of α. Suppose that

$$\ln y(0) = \ln y^* + \epsilon \qquad (13)$$

and that $\text{cov}(\ln y^*, \epsilon) = 0$. Substituting (13) into (10),

$$\ln y(t) = \ln y^* + e^{-\mu t}\epsilon$$
$$= \ln y^* + v \qquad (14)$$

where $v \equiv e^{-\mu t}\epsilon$ is uncorrelated with $\ln y^*$. Substituting (9) into (14),

$$\ln y(t)_i = \text{constant} + [\alpha/(1-\alpha)] \ln (s_{Ki})$$
$$- [\alpha/(1-\alpha)] \ln (n_i + .05) + w_i \qquad (15)$$

where $w \equiv u + v$.

Estimates of the parameter α may be obtained from both eq. (12) and eq. (15). If the two equations yield similar estimates of α, we should perhaps accept the assumption of random initial productivity. If the equations yield significantly different estimates, we should reject this assumption; in this case, the estimate from eq. (12) is more likely to be consistent. On the other hand, errors in measuring productivity--even "permanent" errors--will bias the estimate from eq. (12), but not the estimate from eq. (15).

For least-squares estimation of either equation (12) or (15) to yield a consistent estimate of α, s_K must be exogenous with respect to the dependent variable. In both equations, the exogeneity of s_K is open to question. One could argue that very low (subsistence) levels of income tend to cause low saving and investment rates. In this case, the estimate of α from eq. (15) is likely to be biased upward. Since initial income is controlled for in eq. (12), "feedback" from income level to savings rate would not bias the estimate from this equation. But the "accelerator" model of investment implies that high output growth causes high investment rates, suggesting that the estimate from eq. (12) could also be biased upward. Similar potential biases apply to the more general model incorporating intangible capital, to which we now return.

Accounting for intangible investment

The reduced-form equations (12) and (15) were based on the production function (1) without human and research capital, and with constant returns to scale (CRS) imposed. What happens if we replace this production function by the one with two types of intangible capital (eq. (5)), and continue to maintain the CRS assumption ($\alpha + \beta + \Theta + \pi = 1$)? We obtain generalized versions of eqs. (12) and (15) which include as regressors rates of investment in human capital and research, as well as in physical capital:

$$\begin{aligned} \ln y_i = \text{constant} &+ [\alpha /(1 - \alpha - \Theta - \pi)] \ln (s_{Ki}) \\ &+ [\Theta /(1 - \alpha - \Theta - \pi)] \ln (s_{Hi}) \\ &+ [\pi /(1 - \alpha - \Theta - \pi)] \ln (s_{Ri}) \\ &- [(\alpha + \Theta + \pi)/(1 - \alpha - \Theta - \pi)] \ln (n_i + .05) + u_i \end{aligned} \quad (16)$$

$$\begin{aligned} \ln y(t)_i - \ln y(0)_i = &\ (1 - e^{-\mu t}) \\ &\{[\alpha /(1 - \alpha - \Theta - \pi)] \ln (s_{Ki}) \\ &+ [\Theta /(1 - \alpha - \Theta - \pi)] \ln (s_{Hi}) \\ &+ [\pi /(1 - \alpha - \Theta - \pi)] \ln (s_{Ri}) \\ &- [(\alpha + \Theta + \pi)/(1 - \alpha - \Theta - \pi)] \ln (n_i + .05) \\ &- \ln y(0)_i\} + u_i \end{aligned} \quad (17)$$

where $s_H = I_H/Y$, $s_R = I_R/Y$, $\mu = (n + g + \delta_K)(1 - \alpha - \Theta - \pi)$, and we have assumed that $\delta_H = \delta_R = \delta_K = .03$.

s_R represents the ratio of total R&D investment to GNP. This total represents the sum of several different "types" of R&D. Our data permit us to classify a nation's total R&D investment in two different ways: by source of funds--private vs. government--and by whether or not the expenditure is for "fundamental" research. Previous research at the firm and industry level suggest that the rates of return to these different types of research are not equal. To allow for this possibility, we will estimate versions of eqs. (16) and (17) in which s_R is disaggregated into its components, such as s_{PR} and s_{GR} (ratios of private- and government-funded R&D investment to GNP, respectively). We will experiment with two different functional forms. The first is $\{\pi \ln [s_{PR} + (1 + \Omega) s_{GR}]\}$; under the null hypothesis that the marginal products of privately and government financed research capital stocks are equal, $\Omega = 0$.
The second is $\{\pi_P \ln (s_{PR}) + \pi_G \ln (s_{GR})\}$.

3. R&D spillovers, within and between countries

So far our treatment of R&D investment has been completely analagous to our treatment of physical investment. But it is generally believed that there are some important differences between these two types of investment. One respect in which they differ is that there are positive "spillovers" (externalities) associated with I_R, but not with I_K (or at least that I_R spillovers are much larger). Firms do not succeed in appropriating all of the returns to their R&D investments, despite the existence of a variety of means, such as patent protection and secrecy, to do so. In a recent paper, Griliches (1991) surveys empirical studies of R&D spillovers, and concludes that "taken individually, many of the studies are flawed and subject to a variety of reservations, but the overall impression remains that R&D spillovers are both prevalent and important."[8] The extreme version of the spillover hypothesis is that research capital is a pure public good, that is, that firm B benefits as much from firm A's R&D investments as firm A does.

Our estimates of the parameter π in eqs. (11) and (12) will be affected--in opposite directions--by the extent of two kinds of spillovers--within-country and between-country. As Griliches demonstrated, the coefficient of knowledge capital R is higher in the macro (country-level) than in the micro (firm-level) production function because it reflects not only the private but also the social returns to research, i.e. within-country spillovers. But between-country spillovers will tend to reduce the size of our coefficients. In the presence of intercountry R&D spillovers, the coefficients on research saving rates in eqs. (11) and (12) should be interpreted as the <u>difference</u> between the benefits a country derives from its own research and from other

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[8] Of course, for spillovers to account for the high estimated value of π, they must be confined within national borders. Otherwise, as noted above, a country's real income would be un- or weakly-related to its own R&D efforts.

countries' research.[9]

To illustrate this, consider the following simplified model in which we express output per worker in country i as a linear function of its own research capital stock and the combined research capital stock of all other countries:

$$\begin{aligned} y_i &= \pi\, x_i + \pi\, \mu\, (X - x_i) \\ &= \pi\, \mu\, X + \pi\, (1 - \mu)\, x_i \end{aligned} \tag{13}$$

where $X \equiv \Sigma_j\, x_j$. The parameter μ, $0 \leq \mu \leq 1$, indexes the completeness of spillovers:

$\mu = 0$ ==> no spillovers

$0 < \mu < 1$ ==> partial spillovers

$\mu = 1$ ==> complete spillovers.

The more complete spillovers are, the smaller the expected coefficient on x_i in eq. (13). If $\mu = 1$, eq. (13) reduces to $y_i = \pi\, \mu\, X =$ constant: country i's productivity is unrelated to the size of its own research capital stock. In the case of partial spillovers, y_i depends on x_i, and the coefficient of x_i is the <u>excess</u> benefit country i derives from its own, as opposed to foreigners', knowledge capital.

Although there is evidence consistent with the existence of R&D spillovers, the evidence suggests that these spillovers are far from complete (or instantaneous). First, a large number of econometric studies at the firm and industry level have found a strong positive

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[9] Griliches considered the effect on production function estimates of changing the level of aggregation, for a given degree of spillover. Below we consider the effect on these estimates of changing the degree of spillover, at a given level of aggregation.

relationship between the firm or industry's productivity growth and its own R&D investment behavior. As indicated above, one would be unlikely to observe this if spillovers were complete. Second, we are defining the completeness or rate of spillovers in eq. (17) as the ratio of the marginal benefit to "representative" firm j of firm i's research capital to firm i's own marginal benefit. Suppose that firm i increases research spending by $100, that its own (current) marginal benefit from this is $50, that the marginal benefit to each other firm in the industry is $2, and that there are 50 (identical) other firms. Total external benefits are twice as large as internal benefits, but average external benefits are only 4% as large. Griliches concludes from his survey of studies of R&D spillovers that the elasticity of output with respect to R at the macro level is 50% to 200% larger than the corresponding elasticity at the micro level. This should be interpreted as the ratio of total, not average, external benefits to internal benefits. The ratio of average external to internal benefits--the parameter μ in eq. (18)--is clearly much smaller: it is the 50-200% figure divided by N, the number of firms in the market (or some other measure of market structure, such as a Herfindahl index). If N = 10, for example, the implied range of the spillover parameter is 5-20%.[10]

[10] Presumably most, if not all, of the spillovers studies surveyed by Griliches are within-country studies. It is plausible that, due to the greater difficulty and cost of transmitting knowledge across borders (e.g., due to language differences), the marginal external benefit realized by the average foreign firm is smaller than the marginal external benefit realized by the average domestic firm. Thus, the overall (domestic + foreign) ratio of external to internal marginal benefit--the spillover rate--may be lower than that implied by within-

An alternative (dynamic) perspective on spillovers

Suppose that the benefits of a country's R&D investments leak out to other countries, but do so gradually. Initially, a country appropriates all of the returns to its R&D investments. Then, other countries appropriate some of the returns. As time elapses, the ratio of publicly-available to proprietary knowledge increases. In the long run, all of the knowledge becomes publicly available. Let PROP represent the stock of proprietary knowledge, and PUB the stock of publicly available knowledge. The total stock of knowledge TOT is the sum of the two: TOT $\equiv$ PROP + PUB. Suppose that the social rate of depreciation of knowledge is zero, but that the private rate of depreciation is δ_R, $0 < \delta_R < 1$:

$$TOT_t = \Sigma_i \, RD_{t-i}$$

$$PROP_t = \Sigma_i \, (1 - \delta_R)^i \, RD_{t-i}$$

$$PUB_t \equiv TOT_t - PROP_t = \Sigma_i \, [1 - (1 - \delta_R)^i] \, RD_{t-i}$$

Suppose that country i's rate of R&D investment is constant, i.e. $RD_{t-i} = RD^*$ for all i. Then the stock of proprietary knowledge converges to the finite amount

$$PROP^* = \delta_R^{-1} \, RD^*.$$

Countries with higher rates of investment in R&D will have higher steady state stocks of proprietary knowledge (even though "eventually" all knowledge becomes public knowledge). The sensitivity of $PROP^*$

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country studies.

to RD^* depends on the depreciation rate.[11] For example, if $\delta_R = .10$, a \$1 increase in RD^* will increase $PROP^*$ by \$10, while if $\delta_R = .25$, it will increase it by only \$4. The less rapidly proprietary knowledge becomes public knowledge, the more impact a country's R&D investment rate will have on its stock of proprietary knowledge (and therefore perhaps on its productivity).

Unlike PROP, the stock of publicly-available knowledge PUB does not converge to a finite steady state value. Since we have assumed that the social rate of depreciation is zero, the total stock of knowledge increases without limit if RD investment continues at the rate RD^*. Since PUB $\equiv$ TOT - PROP, PUB must diverge if PROP converges but TOT does not.

We postulate that a nation's output (conditional on its conventional capital and labor inputs) depends on the sizes of both stocks of knowledge[12]:

$$Y_i = PROP_i^{\phi 1}\, PUB^{\phi 2}$$

The stock of publicly-available knowledge is, by definition, invariant across countries, and it increases without limit over time. It therefore has essentially the same properties as (and is empirically indistinguishable from) the autonomous technical change term B(t) in

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[11] The mean age (AGE) of the R&D embodied in PROP is also inversely related to δ_R, as follows: AGE $= \delta_R^{-1}-1$.

[12] This specification does not embody the (we believe reasonable) assumption that the private marginal product of proprietary knowledge is greater than the private marginal product of public knowledge: an idea is more valuable to me if I have it alone than it is if I share it with others.

eq. (7). The rate of increase of PUB (analagous to g, the growth rate of B) depends on collective R&D investment. In addition to contributing to PUB, nation i's rate of R&D investment determines the size of its own steady-state stock of proprietary knowledge, $PROP_i$. Two implications, that on the surface might appear to be inconsistent, follow from the notion that knowledge spillovers or diffusion takes time: (1) all countries experience (unbounded) productivity growth due to growth in the stock of publicly available knowledge; and (2) relatively R&D-intensive countries have higher steady-state productivity levels due to their larger stocks of proprietary knowledge.

4. Data

Data on all variables other than R&D-related variables were taken from the Appendix of Mankiw, Romer, and Weil (1990), who in turn derived some of their data from the Real National Accounts constructed by Summers and Heston (1988). y and y_0 are real GDP divided by the working-age population (aged 15 to 64) in 1985 and 1960, respectively. s_K is the average share of real investment (including government investment) in real GDP during 1960-85. n is the average rate of growth of the working-age population during that period. s_H is the average percentage of the working-age population enrolled in secondary school.

The most inclusive sample of countries analyzed by MRW was a sample of 98 countries whose economies were not centrally planned and were not dominated by oil production. We augmented that 98-

country data set by adding data on R&D investment and its composition from UNESCO Statistical Yearbooks for as many countries as possible. We defined s_R as the average share of (nominal) R&D investment in (nominal) GNP over all available years from 1964 to 1989. At least one annual observation on the R&D/GNP ratio was available for 74 countries. For these countries, the mean number of annual observations was 5.4; the maximum was 15.[13] Since s_R is based on fewer annual data points than s_K, it is probably subject to greater measurement error. This may be largely offset, however, by the fact that R&D investment appears to be much more stable over time than fixed investment (possibly due to higher costs of adjustment associated with R&D investment).

We calculated ratios of government-funded and privately-funded R&D to GNP as follows:

$$s_{GR} = s_R \text{ (GOVSHR)}$$

$$s_{PR} = s_R \text{ (1 - GOVSHR)}$$

where GOVSHR = mean ratio of government-funded to total R&D investment. We were able to calculate GOVSHR for 57 of the countries. In these cases, GOVSHR was calculated on the basis of either one or two annual observations (the earliest and most recent available), also derived from UNESCO Statistical Yearbooks. A similar procedure was followed to calculate ratios of "fundamental

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[13] We are currently in the process of trying to fill in some of the missing data.

research"[14] and "nonfundamental research and development" to GNP: $s_{FR} = s_R$ (FUNSHR) and $s_{NR} = s_R$ (1 - FUNSHR), where FUNSHR = mean ratio of fundamental research to total R&D investment. Values of FUNSHR could be calculated for 38 countries.

Sample mean values of several key variables are reported below:

Variable	N	Mean	Std. dev.
s_R	74	0.7%	0.7%
s_K	98	17.7	7.9
s_H	98	5.4	3.5
s_R/s_K	74	3.8	3.3
GOVSHR	59	60.8	24.8
FUNSHR	38	20.5	12.3

(Unweighted) mean R&D intensity is 0.7%. This is much closer to the mean R&D intensity for developing countries shown in Table 1 (about 0.4%) than it is to the mean for developed countries (about 2.3%) because there are many more developing than developed countries. The unweighted mean ratio of R&D to fixed investment is about 4%. The coefficient of variation of s_R is higher than the CVs of s_K and s_H.

5. Empirical results

Table 3 presents estimates of output elasticities obtained via nonlinear least-squares estimation of eq. (16), which is based on the

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[14] UNESCO (1987, 5-1) defines fundamental research as "experimental or theoretical work undertaken with no immediate practical purpose in mind."

assumption of random initial productivity. In these equations, the level of output per adult in 1985 is expressed as a nonlinear function of the average shares of R&D, fixed, and human capital investment in GNP and the population growth rate during 1960-85.

In eq. (16.0), we exclude R&D from the model. The fixed and human capital elasticities are both positive, significant, and similar in magnitude to those reported by MRW (1990). In particular, α is close to capital's share in national income and Θ is roughly equal to α. In eq. (16.1), we include R&D, but do not distinguish between different types of R&D: with regard to the expression $[s_{PR} + (1 + \Omega)\, s_{GR}]$, for example, we impose the restriction $\Omega = 0$.[15] The estimated elasticity of output with respect to the research capital stock (π) is positive, large, and highly significant. The estimate of α, the physical-capital elasticity, is about one-third smaller in eq. (16.1) than it is in (16.0). Moreover, the sum of α and π in (16.1) is approximately equal to α in (16.0). This suggests that the contribution of fixed capital to output may be overestimated by failure to properly account for research capital as well as for human capital (as MRW have argued). Just as a substantial fraction (half, according to MRW) of labor income may constitute a return to human capital, a substantial part of nonlabor income may represent a return to research capital.

In eq. (16.2) we allow private and government R&D investment to have different effects on output by relaxing the restriction that $\Omega = 0$. The point estimate of Ω is very close to (not significantly different

[15] This is equivalent to imposing equality of social rates of return to private and government R&D investment.

from) -1, suggesting that the marginal product of government-funded research capital is close to zero. The estimate of π--the elasticity of output with respect to the "effective" research capital stock (the private stock plus 3% of the public stock)--is again highly significant (t = 3.0) and large (.077), relative to the share of R&D investment in GNP.[16]

An alternative functional form for distinguishing the effects of private and government R&D has similar implications. When we replace $\{\pi \ln (s_R)\}$ by $\{\pi_P \ln (s_{PR}) + \pi_G \ln (s_{GR})\}$ instead of by $\{\pi \ln (s_{PR} + (1 + \Omega) s_{GR})\}$, the estimates (standard errors) are $\pi_P = .068$ (.003) and $\pi_G = .018$ (.024).

Regression (16.2) suggests that the social rate of return to privately-funded R&D is on the order of seven times as high as the return to fixed investment. The ratio of output elasticities $\pi/\alpha \approx 1/3$ is about 7 or 8 times as large as the ratio of average investment shares s_R/s_K.

In eq. (16.3) we impose the restriction (which eq. (16.2) suggests is approximately valid) that $\Omega = -1$, i.e. that government-funded R&D investment has no effect on labor productivity. The point estimate of π declines slightly, to .073, but its t-statistic increases to 3.5.

In eq. (16.4), we classify or disaggregate R&D by an alternative (to source of funding) characteristic: whether or not the

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[16] As Table 1 indicates, GNP-weighted average R&D intensity for the world as a whole is about 2.0%. About 40% of aggregate R&D is government funded, so average "effective" R&D intensity (assuming $\Omega = -.97$) is about 1.2%.

investment is in "fundamental research." Due to the greater incidence of missing data, the sample size is about one-third smaller than in the private/government regression. Previous, firm-level studies (Griliches (1986), Lichtenberg and Siegel (1991)) have indicated that the mean rate of return to fundamental research may be much higher than the return to other R&D. The standard error of π is much greater in (16.4) than it is in the previous three regressions, but π is still marginally significant. Consistent with previous studies, eq. (16.4) suggests that there is a substantial "premium" on fundamental research: Ω is negative, albeit not significantly so. Again, the estimate of Ω is closer to -1 than it is to zero. In the final eq. (16.5), we impose the restriction $\Omega = -1$, thus maintaining the hypothesis that fundamental research is the <u>only</u> component of R&D investment that influences productivity. The point estimate of π falls to .036, but the standard error drops proportionately more, so that π is now significant at the .05 level ($t = 2.0$). Countries that devoted larger fractions of output to fundamental research between 1960 and 1985 had significantly higher output per adult in 1985.

Estimates of variants of eq. (17) are reported in Table 4. Recall that the consistency of estimates from this equation does not require the assumption of random deviations from the steady state. These are regressions of the growth of output per adult during the period 1960-85 on average shares of output devoted to R&D, fixed, and human capital investment, holding constant the initial level of output per adult.

In eq. (17.1), we do not account for R&D investment. As

MRW found in their sample of 98 countries, the estimate of the physical capital elasticity is quite high: .47. In eq. (17.2) we include both privately- and government-funded R&D investment, allowing them to have different social rates of return. The elasticity of output with respect to "weighted" R&D is positive, highly significant, and similar in magnitude to the estimate from eq. (16.2). The point estimate of Ω is again negative and close to -1, but the standard error of the estimate is much smaller in this equation. This equation implies that we may decisively reject the hypothesis that the rate of return to government-funded R&D is equal to the return to privately-funded R&D, and that we may not reject the hypothesis that the return to government R&D is zero. In eq. (17.3) we impose the latter hypothesis by setting $\Omega = -1$. The estimated elasticity of output with respect to private R&D is .066, similar to its value in eq. (16.3). As was the case in Table 3, the inclusion of private R&D substantially reduces the estimate of the physical-capital elasticity α. In this case, however, the estimate of α falls from a "higher-than-expected" value to an "expected" value.

We have seen that the estimates of the R&D-related parameters π and Ω from the "growth-rate" eqs. (17.2) and (17.3) are quite similar to the estimates from the corresponding "level" equations (16.2) and (16.3). In contrast, the estimate of α from the "growth-rate" equation is about twice as large as (and significantly different from) the estimate from the corresponding "level" equation. (The former estimate is also much closer to the average value of capital's share in national income.) This suggests that the hypothesis of "random initial productivity" may not be valid, and that the "growth-rate" equation estimates are more likely to be consistent. Although the level and growth-rate equations yield similar estimates of π and Ω, the two models do not yield similar estimates of the parameters from the alternative functional form $\{\pi_P \ln (s_{PR}) + \pi_G \ln (s_{GR})\}$. The estimates (standard errors) of these parameters from the growth-rate equation are $\pi_P = .102$ (.035) and $\pi_G = -.151$ (.045). The estimated elasticity of output with respect to government-funded R&D is negative, large, and highly significant.

The apparently low--or even negative--social rate of return to government-funded R&D should be interpreted with caution. It does not necessarily imply that government R&D does not contribute to social welfare. A substantial fraction of government-sponsored R&D is devoted to the production of intangible goods, such as national defense and health, or the reduction of "bads," such as destruction of the environment, whose value is reflected imperfectly, at best, in national accounts data. Suppose that social welfare depends on two things--national security, and everything else (or guns and butter)--and that the usual static tradeoff between the two (along the production possibilities frontier) applies. Suppose further that the production of butter, but not of guns, is included in GNP. The greater the fraction of R&D and other investment a society devotes to gun rather than butter production, the lower its measured growth rate will be. Under this view, the negative coefficient on s_{GR} merely reflects the existence of the static tradeoff between measured output (butter) and unmeasured output (guns). Even if the negative sign of this coefficient is not surprising, however, its magnitude is of interest, since it indicates the opportunity cost (in terms of conventionally-measured output) of government-funded research.

It is sometimes hypothesized that this opportunity cost is substantially reduced by pervasive spillovers from government research to the private sector. Since our estimate of the coefficient on s_{GR} should be interpreted as the opportunity cost of government R&D net of spillovers, we may conclude that, even net of these spillovers, the opportunity cost to the private sector of government research is substantial.

It might be argued that the effect of R&D investment on productivity depends more on the objective of the R&D (e.g., whether or not it is for national defense) than on the source of funding (private vs. government). Unfortunately, the availability of data on the distribution of R&D by objective is much more limited than the availability of data by source of funds. In practice, however, there appears to be a strong positive correlation across countries between the ratios of defense to nondefense R&D and government to private R&D.

We attempted to estimate the productivity-growth equation with R&D disaggregated into fundamental and nonfundamental components. Estimates of the model including the expression $\{\pi \ln (s_{FR} + (1 + \Omega) s_{NR})\}$ failed to converge. Also, the standard errors on π_F and π_N from the equation including the alternative functional form $\{\pi_F \ln (s_{FR}) + \pi_N \ln (s_{NR})\}$ were extremely large; neither parameter was significant.

6. Summary and conclusions

This paper extends previous research on the effect of investment on labor productivity at the country level by accounting for investment in R&D, as well as for investment in fixed and human capital. We examined the statistical relationship between R&D investment and both (1) the growth rate of productivity (conditional on initial productivity and other variables), and (2) the level of productivity. Privately-funded R&D investment was found to have significant positive effects on both the level and growth rate of productivity. Moreover, these effects appear to be quite large. The estimated social (national) rate of return to private R&D investment is about seven times as large as the return to investment in equipment and structures. The elasticity of GNP with respect to the privately-funded research capital stock is about 7%--about 1/3 as large as the physical-capital elasticity (whose estimate was substantially reduced when R&D was accounted for). Of course, this interpretation of our estimates is valid only if investment rates are exogenous with respect to productivity. This assumption, which previous authors in this literature have also made, is certainly open to question. If one accepts this premise, then our findings force one to reject the hypothesis that there are complete, or at least instantaneous, international R&D spillovers. The significant positive partial correlation between a nation's productivity and its own privately-funded R&D indicates that a country benefits more (at least temporarily) from its own R&D than other nations do.

All of our estimates suggested that the social marginal product of government-funded research capital is much lower than that of private research capital. Most of the estimates implied that the social marginal product of government research was insignificantly different from zero. However one version of the productivity-growth equation--the estimates from which are more likely to be consistent than those from the level equation--suggested that the marginal product of government research is negative: countries with higher government R&D spending exhibited significantly lower productivity growth. Since the productivity data we use may account badly, if at all, for the services to which much government-funded R&D is related (e.g. national security and health), the finding that government R&D reduces measured growth does not necessarily imply that it reduces social welfare. There may well be unmeasured benefits from government research, but the opportunity costs, in terms of measured growth, appear to be substantial.

Our attempts to distinguish between the social returns to fundamental research and to other R&D were hampered by limited data availability, but some of the estimates suggested that the social rate of return to fundamental research is much higher, as previous studies at the micro level have found.

BIBLIOGRAPHY

Benhabib, J., and M. Spiegel. "Growth accounting with physical and human capital accumulation." New York University, C. V. Starr Center Working Paper No. 91-66, December, 1991.

De Long, J. B., and L. Summers. "Equipment investment and economic growth." Quarterly journal of economics, Vol. CVI, No. 2, May, 1991, pp. 445-502.

Dowrick, S., and D. Nguyen. "OECD comparative economic growth 1950-85: catch up and convergence." American economic review, Vol. 79, No. 5, December, 1989, pp. 1010-30.

Griliches, Z. "Productivity, R&D, and basic research at the firm level in the 1970's." American economic review, Vol. 76, No. 1, March, 1986, pp. 141-154.

------------. "The search for R&D spillovers." NBER Working Paper No. 3768, July, 1991.

------------, and F. Lichtenberg. "R&D and productivity at the industry level: is there still a relationship?" In: Z. Griliches (Ed.), R&D, Patents, and Productivity. Chicago, IL, 1984, pp.

Hall, B. "Investment and Research and Development at the Firm Level: Does the Source of Financing Matter?" Univ. of California at Berkeley, unpub. paper, May, 1992.

Himmelberg, C., and B. Petersen. "R&D and internal finance: a panel study of small firms in high-tech industries." Federal Reserve Bank of Chicago, unpub. paper, March 23, 1990.

Lichtenberg, F. "The Private R&D Investment Response to Federal Design and Technical Competitions." American Economic Review, Vol. 78, No. 3, June, 1988, pp. 550-9.

--------------. "U.S. Government Subsidies to Private Military R&D:

The Defense Department's Independent R&D Policy." Defense Economics, Vol. 1, 1990, pp. 149-158.

-------------, and D. Siegel. "The impact of R&D investment on productivity: new evidence using linked R&D-LRD data." Economic Inquiry, Vol. 29, April, 1991, pp. 203-28.

Mankiw, N. G., D. Romer, and D. Weil. "A contribution to the empirics of economic growth." Quarterly Journal of Economics,

Mairesse, J., and M. Sassenou, M. "R&D and productivity: a survey of econometric studies at the firm level." STI review, No. 8, April, 1991, pp. 9-43 (Paris: OECD).

National Science Board. Science and engineering indicators - 1991, tenth edition. Washington, DC, 1991.

Organization for Economic Cooperation and Development. OECD science and technology indicators: resources devoted to R&D. Paris, 1984.

---. Main science and technology indicators. Paris, 1988.

Romer, P. "Crazy explanations for the productivity slowdown." In: NBER macroeconomics annual, Vol. 2, 1986, pp. 163-202.

--------. "Capital, labor, and productivity." Brookings papers on economic activity: microeconomics, 1990, pp. 337-67.

Summers, R., and A. Heston. "A new set of international comparisons of real product and price level estimates for 130 countries, 1950-1985." Review of income and wealth, Vol. 34, March, 1988, pp. 1-25.

-------------------------. "The Penn World Table (Mark 5): an expanded set of international comparisons." Quarterly journal of economics, Vol. CVI, No. 2, May, 1991, pp. 327-368.

UNESCO. Statistical yearbook. Paris, 1963-present.

United Nations. Statistical yearbook. New York, 1948-present.

Table 1

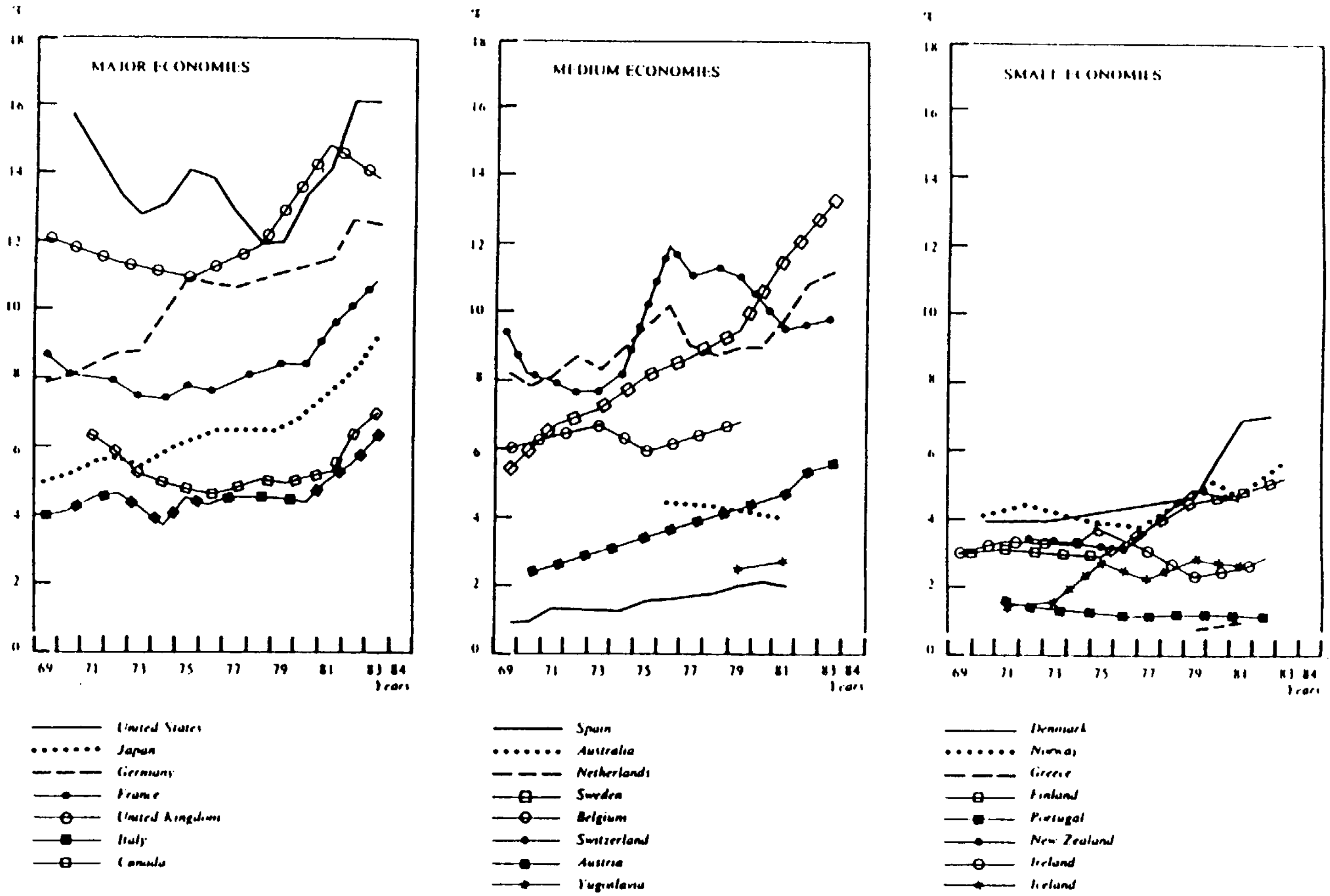
Shares of world output devoted to R&D and fixed investment, 1970 and 1980

	World Total	Developed Countries	Developing Countries
s_R (GNP-weighted average)			
1970	2.04%	2.36%	0.32%
1980	1.78	2.23	0.45
s_K (GNP-weighted average)			
1970	21.8%		
1980	22.5		
s_R / s_K			
1970	9.4%		
1980	7.9		

Source: R&D data: UNESCO 1987 Statistical Yearbook, Table 5.3.
Fixed investment data: Penn World Table 5 data base.

Graph 1

Research and development related to traditional investments*



* GERD as a percentage of Gross Fixed Capital Formation
Source: OECD/STIID Data Bank, November 1985

Table 2

Total and Nondefense R&D expenditures
as a percentage of GNP, seven industrialized countries,
selected years 1967-89

	Mean								
Year	Unwtd	Wtd	U.S.	Japan	Germany	France	U.K.	Italy	Sweden
			TOTAL R&D / GNP						
1967	1.84	2.34	2.8	1.6	2.0	2.2	2.3	0.7	1.3
1970	1.88	2.24	2.6	1.9	2.1	1.9	NA	0.9	NA
1972	1.90	2.13	2.4	1.9	2.2	1.9	2.1	0.9	NA
1978	1.84	1.98	2.1	2.0	2.2	1.8	2.2	0.8	NA
1980	1.92	2.14	2.3	2.2	2.4	1.8	NA	0.9	NA
1981	2.14	2.26	2.4	2.3	2.5	2.0	2.4	1.0	2.4
1989	2.43	2.58	2.7	3.0	2.9	2.3	2.0	1.3	2.8
			NONDEFENSE R&D / GNP						
1972	1.58	1.63	1.6	1.9	2.1	1.5	1.5	0.9	NA
1981	1.84	1.86	1.8	2.3	2.4	1.5	1.7	1.0	2.2
1989	2.11	2.10	1.9	3.0	2.8	1.8	1.6	1.2	2.5
			FIXED INVESTMENT / GNP						
1972	--	--	18	36	29	29	18	--	--
1981	--	--	18	31	23	25	14	--	--
1988	--	--	19	32	25	25	21	--	--
			GOVERNMENT-FUNDED R&D / TOTAL R&D						
1975	47%	47%	51%	29%	47%	54%	52%	NA	NA
1989	37	38	45	19	33	49	37	NA	NA

Source: Science and Engineering Indicators - 1991, Appendix Tables 4-26 to 4-28. Nondefense expenditure data are not available for years prior to 1970.

Table 3

Estimates of output elasticities obtained from nonlinear least-squares estimation of variants of eq. (16):

$$\ln y = \text{constant} + [\pi/(1-\alpha-\Theta-\pi)]\ln(X) + [\alpha/(1-\alpha-\Theta-\pi)]\ln(s_K) + [\Theta/(1-\alpha-\Theta-\pi)]\ln(s_H) - [(\alpha+\Theta+\pi)/(1-\alpha-\Theta-\pi)]\ln(n+.05) + u$$

Equation	(16.0)	(16.1)	(16.2)	(16.3)	(16.4)	(16.5)
N	53	53	53	53	38	38
X	--	s_R	$s_{PR} + (1+\Omega)s_{GR}$	s_{PR}	$s_{FR} + (1+\Omega)s_{NR}$	s_{FR}
Parameter (std. error)						
π	--	.090 (.004)	.077 (.026)	.073 (.021)	.068 (.037)	.036 (.018)
Ω	--	--	-.972 (.133)	--	-.699 (.702)	--
α	.282 (.032)	.199 (.000)	.183 (.064)	.184 (.063)	.288 (.071)	.314 (.064)
Θ	.310 (.021)	.303 (.025)	.321 (.044)	.321 (.043)	.253 (.053)	.261 (.051)

y = output per adult in 1985

s_R = mean ratio of total R&D investment to GNP, 1964-88

s_{PR} = s_R (1 - GOVSHR), where GOVSHR = mean ratio of government-funded to total R&D investment.

s_{GR} = s_R (GOVSHR)

s_{FR} = s_R (FUNSHR), where FUNSHR = mean ratio of "fundamental research investment" to total R&D investment.

$s_{NR} = s_R (1 - FUNSHR)$
s_K = mean ratio of fixed investment to GNP, 1960-85.
s_H = mean ratio of number of people enrolled in secondary school to working-age population (proxy for human capital investment rate).

Table 4
Estimates of variants of eq. (17):

$$\ln y(t) - \ln y(0) = (1 - e^{-\mu t}) \{[\alpha/(1-\alpha-\Theta-\pi)] \ln(s_K) + [\Theta/(1-\alpha-\Theta-\pi)] \ln(s_H) + [\pi/(1-\alpha-\Theta-\pi)] \ln(s_R) - [(\alpha+\Theta+\pi)/(1-\alpha-\Theta-\pi)] \ln(n+.05) - \ln y(0)\} + u$$

Equation	(17.1)	(17.2)	(17.3)
N	53	53	53
X	--	$s_{PR} + (1+\Omega)s_{GR}$	s_{PR}
RSS	4.288	3.801	3.842
Parameter <u>(std. error)</u>			
π	--	.062 (.028)	.066 (.026)
Ω	--	-.971 (.025)	--
α	.474 (.047)	.357 (.088)	.354 (.086)
Θ	.236 (.056)	.258 (.058)	.259 (.071)
μ	.017 (.001)	.021 (.005)	.021 (.005)

$y(t)$ = output per adult in 1985

$y(0)$ = output per adult in 1960

s_R = mean ratio of total R&D investment to GNP, 1964-88

s_{PR} = s_R (1 - GOVSHR), where GOVSHR = mean ratio of government-funded to total R&D investment.

s_{GR} = s_R (GOVSHR)

s_K = mean ratio of fixed investment to GNP, 1960-85.

s_H = mean ratio of number of people enrolled in secondary school to working-age population (proxy for human capital investment rate).