

TIME SERIES TESTS OF ENDOGENOUS GROWTH MODELS

by

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**Submitted to the Department of Economics
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ABSTRACT

This thesis proposes a general test of endogenous growth models based on the observation that per capita growth rates in the U.S. appear to be stationary over the last century. This test is then used to provide time series evidence against both of the major alternatives to the neoclassical growth model: the "AK"-style models and the R&D-based models. A modified version of the Romer [1990] R&D model is introduced that is not rejected by the stationarity test, but the extended model alters a key implication usually found in endogenous growth theory. Although growth in the extended model is generated endogenously through R&D undertaken by profit-maximizing agents, the long-run growth rate depends only on parameters that are usually taken to be exogenous. In particular, steady state growth depends on population growth, reflecting the tight link in R&D-based models between inventions and inventors. Empirical evidence on TFP growth and R&D in the U.S., France, Germany, and Japan provide support for the extended model.

Thesis Supervisor:

**Dr. Olivier Jean Blanchard
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and
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Introduction

In the last ten years, the endogenous growth literature has returned to a question that macroeconomists have historically found difficult to answer: What determines the long-run rate of economic growth? The recent growth literature has proposed several candidates to answer this question, but empirical work on this topic has been inconclusive. This dissertation develops a framework for testing endogenous growth models using time series evidence and proceeds to test and analyze several of the likely candidates for understanding growth.

The first chapter of the thesis examines the time series behavior of growth rates for fifteen advanced OECD economies and concludes that over the last century growth rates are, subject to some qualifications, stationary. The stationarity of growth rates appears to be inconsistent with the prediction of many recent endogenous growth models that permanent increases in investment rates, openness, human capital investment, etc. should lead to permanent increases in the growth rate. For example, in the post-War period, growth rates for these OECD countries are either stationary or exhibit a negative trend, whereas investment rates generally exhibit large positive increases. This contradicts the key result of the accumulation-based "AK" models that a permanent increase in the investment rate should lead to a permanent increase in the growth rate. Empirically, I identify bounds on the dynamic response of the growth rate to a permanent change in the investment rate. These bounds indicate that a permanent increase in the investment rate produces only a transitory effect on growth that disappears after about eight years.

The second chapter focuses on the more recent R&D-based models of endogenous growth. According to these models, the total factor productivity growth rate should be proportional to the amount of labor engaged in R&D. Empirically, however, growth rates appear to be stationary while resources devoted to R&D exhibits a unit root with large positive drift. Thus, the "stationarity restriction" suggests that both "AK" style models and the more recent

R&D-based growth models are inconsistent with the time series evidence on growth rates.

Chapter Two proceeds by proposing a modified version of the Romer [1990] R&D model that is not rejected by the stationarity test. However, the extended model alters a key implication usually found in endogenous growth theory. Although growth in the extended model is generated endogenously through R&D undertaken by profit-maximizing agents, the long-run growth rate depends only on parameters that are usually taken to be exogenous. In particular, steady state growth depends on population growth, reflecting the tight link in R&D-based models between inventions and inventors.

Chapter Three of the thesis explores the empirical implications of the augmented R&D model discussed in the previous chapter. The model to be analyzed is nonlinear and involves cointegration, but an extension of the argument in West [1988] reveals that the usual (asymptotically normal) inference will apply. The parameter estimates suggest that steady state TFP growth should be about 0.6% per year, much lower than the TFP growth rates observed in the manufacturing sector during the last forty years. This apparent puzzle is resolved by analyzing the transition path dynamics of the model: the share of labor devoted to R&D has been increasing for most of the post-War period, suggesting that the advanced OECD economies are not currently exhibiting steady state behavior. The implication is that once this share stabilizes, TFP growth rates could fall by more than a percentage point. This chapter also analyzes briefly the one episode in the post-War period during which the share of labor in R&D stopped increasing: the late 1960s to the early 1970s. The analysis suggests that the TFP slowdown is potentially consistent with the model's predictions, lending credibility to the idea that TFP growth rates are currently higher than their steady state values.

Finally, the concluding chapter examines growth in a cross-section of countries, with a particular focus on the relative price of capital. This paper is close in spirit to the DeLong and Summers [1991] paper and was written at about the same time as that paper.

Chapter 1

Time Series Tests of Endogenous Growth Models

I. Introduction

The main contribution of the endogenous growth literature has been to indicate which economic and social parameters determine the long run rate of growth within a country. Policies which affect these parameters can, at least in theory, alter the long run growth rate and potentially improve welfare. This is the primary result, for example, of models with spillovers to capital accumulation such as those found in Romer [1986, 1987].

While numerous theoretical models have been proposed as explanations of growth, the empirical work designed to distinguish among these models has been confined to two areas. The first line of research follows Baumol [1986] by focusing on the convergence hypothesis: do countries which begin with different levels of GDP per capita tend to end up at similar levels of GDP per capita? Cross sectional work in this area tends to find convergence in the data, supporting neoclassical models of growth, while time series work (such as Quah [1990] and Bernard [1991]) tends to find convergence in growth rates but not in levels. Thus, this line of research has not succeeded completely in distinguishing among endogenous growth models.

The second line of research is based on the cross sectional breakdown of growth rates conducted by Barro [1991a]. This work suggests that variables such as the investment rate, human capital investment, and government consumption help to explain the cross sectional distribution of growth rates. For instance, countries with high investment rates also tend to be countries with high growth rates. A key criticism of this type of research, however, is that it cannot control for productivity shocks or country effects. Perhaps countries have high growth rates and investment rates because they experienced a large productivity shock that increased both variables. Or perhaps some other variable (which often goes by the sufficiently vague rubric of "culture") generates high investment and high growth. Almost by definition, a cross sectional study cannot address the crucial question of whether or not a permanent increase in the

investment rate will have a permanent effect on the growth rate, but this type of question is exactly what must be addressed in order to test endogenous growth models.

Time series methods provide a natural framework for examining these issues since they are designed to distinguish between permanent and transitory movements in the data. For instance, if growth rates are affected by shocks which have permanent effects and shocks which have transitory effects, then growth rates should exhibit a unit root. Alternatively, some models of endogenous growth predict that the key force driving growth is investment. If investment rates are well approximated by a unit root process, then growth rates should be as well; or if investment rates exhibit an upward trend in some countries, we should see a similar trend in growth rates under this type of model, *ceteris paribus*.

The first part of this paper, Section II, is devoted to an examination of the time series properties of growth rates in the U.S. economy for 1880 to 1987 and in a sample of OECD countries for a slightly shorter period. The robust result of this section is that growth rates in the U.S. are stationary with no evidence of a deterministic trend or mean shift. Any model which predicts that some variable X has a permanent effect on growth will, therefore, be inconsistent with the data if X has either a unit root or a deterministic time trend. This is true unless the model also predicts that some other variable Z has a permanent effect on growth which counteracts the effect of X . A similar result holds for the sample of OECD economies, especially when one accounts appropriately for the interruption by World War II.

The second part of this paper, Section III, uses this result to test accumulation-based models of endogenous growth. A simple taxonomy of these "AK" models reveals that, broadly speaking, they have at least one of two predictions. Models in which the linear "K" term in the production function does not include all technological progress predict that growth rates should have a deterministic trend or a unit root, contrary to the results in Section II. Alternatively, all accumulation-based models share the prediction that an increase in the rate of accumulation

results in a long-run increase in the rate of growth: the rate of accumulation corresponds to X in the discussion above. In a standard "AK" model with physical capital and technology capital, I show that the rate of accumulation will be equal to the rate of investment in physical capital. For many countries in the sample, however, investment rates exhibit either a stochastic or a positive deterministic trend and therefore violate the stationarity restriction implied by Section II. This result suggests that a permanent increase in investment will have only a transitory effect on the growth rate and constitutes direct evidence against the accumulation-based models of growth. An unresolved question, though, is the horizon over which investment affects growth. If the effects persist for twenty-five or thirty years, then perhaps the AK model represents a useful approximation.

To address this question, Section IV examines a dynamic fixed-effects model of growth and investment. Because of endogeneity concerns, OLS estimates of this model will be biased, but I show how to use the OLS estimates to construct bounds on the dynamic response of the growth rate to a change in the investment rate. These bounds, which will contain the true dynamic response under plausible assumptions, indicate that the relevant horizon over which investment affects growth is at most eight years. Moreover, this result also arises when the concept of investment is restricted to producer durables, a restriction suggested by the cross-sectional research of De Long and Summers [1991] and Jones [1993b]. I view this strong evidence against the accumulation-based "AK" models of endogenous growth.

Section V concludes the paper by noting that R&D-based models of endogenous growth are potentially consistent with the time series evidence discussed in Sections III and IV. The models by Romer [1990b] and by Grossman and Helpman [1991], for example, generate the result that a subsidy or a tax on capital accumulation has no effect on steady state growth. In this respect, then, these R&D-based models perform better than the accumulation-based models. This observation should be interpreted with caution, however: Jones [1993a] explores the time series

implications of the R&D-based models and finds that these models must be modified in important ways in order to be consistent with the time series evidence.

II. Time Series Properties of Growth Rates

Numerous endogenous growth models in the literature yield the prediction that a permanent increase in some variable will have a permanent effect on the growth rate. The literature review in Grossman and Helpman [1991], for example, cites no fewer than ten potential determinants of long-run growth, including physical investment, human capital investment (as proxied for by enrollment rates and literacy rates), export shares, inward orientation, government consumption, population growth, and regulatory pressure. To the extent that these variables are not simply stationary about a constant mean, we should expect to see permanent movements in growth rates. Moreover, the permanent movements in these variables in OECD economies has generally been in the growth-increasing direction rather than in the growth-decreasing direction. For instance, one suspects that openness to international trade has generally increased over the last hundred years. Similarly, durables investment as a share of GDP has increased for most of these economies since 1950. The various models in endogenous growth theory, then, might lead us to expect to see permanent movements in growth rates, generally in an upward direction, over the last hundred years or so since World War II.

With this in mind, consider the following simple exercise.¹ An economist living in the year 1929 (who has miraculous access to historical per capita GDP data) fits a simple linear trend to the natural log of per capita GDP for the U.S. from 1880 to 1929 in an attempt to forecast per capita GDP today, say in 1987. How far off would the prediction be? We can use the prediction error from this constant growth rate path (as a percent of GDP in 1987) as a rough indicator of

¹I am indebted to David Weil (who in turn credits Larry Summers) for suggesting this lucid method of presentation.

the importance of the positive permanent movements in growth rates.

Figure 1 displays the somewhat surprising result of this exercise: the prediction is off by only about 5% of GDP, even correcting for business cycle effects!² Furthermore, the prediction *overestimates* per capita GDP rather than underestimates it, indicating that the average growth rate between 1880 and 1929 (1.81% annually) was actually slightly larger than that between 1929 and 1987 (1.75% annually). From 1950 to 1987, which corrects somewhat for the effects of the Great Depression and World War II, the average growth rate was 1.91%, but this difference is statistically insignificant (see below).

As is clear from the figure, a simple linear trend fits per capita GDP (in logs) extremely well. Growth rates for the last century in the U.S. appear to have a constant mean. This casual observation is confirmed rigorously by several empirical methods in Table 1. The first row tests for a simple trend in growth rates over the period 1880 to 1987. The coefficient on the trend is 0.006 percentage points suggesting that each year raises growth rates by less than one-hundredth of a percentage point.³ But this trend is statistically insignificant: the Newey-West [1987] corrected t-statistic of 0.23 easily fails to reject the hypothesis of no trend in growth rates.

The second row of Table 1 reports the results from an Augmented Dickey-Fuller test for a unit root in growth rates. The estimate of the AR(1) root is only 0.314, and the test statistic of -6.68 easily rejects the null hypothesis of a unit root in growth rates at the 1% significance level, which corresponds to a t-statistic of -3.51.⁴

²The data on GDP per capita is constructed from Maddison [1982, 1989] by Bernard [1991].

³Growth rates are computed as the change in the natural log of GDP per capita and then multiplied by 100. The average growth rate for the U.S. for 1880 to 1987 is 1.78%.

⁴An interesting question is whether or not the vast literature testing for a unit root in the *level* of output obviates the test in first differences. In fact, there is some evidence in Pantula [1989] and in Dickey and Pantula [1987] that this is not the case. They show that Augmented Dickey-Fuller tests are more likely to conclude incorrectly that a process is stationary when there are really two unit roots in a series than when there is only a single unit root. In theory, then, the

If the shocks that have permanent effects on growth rates occur infrequently, say every ten or fifteen years or more, then the ADF tests may have very little power. They are based on the extreme case in which permanent shocks occur every period. The third row of Table 1 considers the other extreme by testing for the presence of a single permanent change in growth rates over the entire sample period. This test for a single mean shift follows the methodology suggested by Bai, Lumsdaine, and Stock [1991]. The basic idea behind this test is to conduct a Chow test for a mean shift at each possible break point and then to adjust the critical values of the Wald statistic to reflect the sequential nature of the test. The correct critical values are provided in Table A.1 of Bai, Lumsdaine, and Stock. With 15% trimming of the sample on each side, the maximum Wald statistic for U.S. growth rates occurs at the year 1933 and takes the value 2.14. The procedure, not surprisingly, suggests that the most likely candidate for a mean shift in growth rates occurs during the Great Depression. This Wald statistic, though, is insignificant even at the 15% significance level, which corresponds to a value of 6.17. The test cannot reject the null hypothesis of no mean shifts in growth rates during the period 1880 to 1987 in favor of a single mean shift.

Finally, the last row of Table 1 omits the years of the Great Depression and World War II and tests for a difference in the mean growth rate for the periods 1880-1929 and 1950-1987. The growth rate in this last period was higher by about a tenth of a percentage point, but the t-statistic of 0.23 reveals that this difference is statistically insignificant. This last result confirms the intuition garnered from Figure 1 that growth rates for the U.S. economy since 1880 essentially fluctuate in a stationary way around a constant mean.

presence of multiple unit roots in output could conceivably explain the mixed evidence on unit roots in the level of output. Of course, as I argue in this paper, this is not in fact the case.

Results for Other Countries

The stationarity of growth rates in the United States should be somewhat disconcerting in the context of the endogenous growth results reviewed by Grossman and Helpman [1991]. This stationarity will ultimately be the source of a simple test of endogenous growth models which will be described in detail at the end of this section and applied to the "AK" style growth models in the next section. First, though, we will attempt to extend the basic stationarity result to other countries.

Table 2 reports the results of this attempt for a sample of fourteen additional advanced OECD economies.⁵ The data on per capita GDP are taken from Maddison [1982, 1989] and the starting point of 1900 is chosen as in Bernard [1991] to minimize the problems associated with border changes in these countries. I have restricted my sample to the advanced OECD economies on the basis of data availability for long periods. In addition, the process of industrialization and development is likely to be different from the process generating the sustained growth of the countries that have already industrialized. Certainly the "AK" models and the R&D-based models of endogenous growth describe this latter process, but it is not at all clear that they help us to understand the former. When using time series data to test these models, then, it is important to restrict attention to the growth experience of countries for which the models are likely to be useful.⁶

The first column of Table 2 confirms the basic stationarity result for the fourteen OECD countries during the period 1900-1987. Augmented Dickey-Fuller tests uniformly reject the null

⁵These additional countries are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, Netherlands, Norway, Sweden, and the United Kingdom.

⁶In part of his research, Quah [1990] employed a statistical concept known as the random field to test for a unit root in growth rates for a panel of 109 countries for the period 1960-1985. Constraining the point estimates to be the same, Quah rejected the null hypothesis that the growth rates of all countries contain a unit root.

hypothesis that growth rates for each of these countries contain a unit root, and the significance level is always greater than 1%. Estimates of the AR(1) root are always less than 0.37, the value obtained for Canada.

The second column of Table 2, however, reveals that simple time trend tests for the OECD growth rates are marginally significant for several countries. Growth rates in Japan, for example, exhibit a time trend with a coefficient of 0.055 percentage points per year and a Newey-West corrected t-statistic of 1.90. Although none of the other trend tests yield a higher t-statistic, the point estimates are always positive.

Results from the difference-in-mean test are reported in the third column of Table 2 and compare the mean for the period 1900-1929 with the mean from the period 1950-1987. In contrast with the results for the U.S. in Table 1, the results here indicate that several countries exhibit positive, significant mean shifts between these two periods. Similar results also appear when the Bai, Lumsdaine, and Stock [1991] test for an endogenous mean shift is employed, but these results are potentially misleading because of the Great Depression and World War II. The countries with significant differences in the means are Australia, Austria, Germany, Italy, Japan, and the U.K. With the exception of Australia, these are all countries that were severely affected by the war. One explanation for the shift in average growth rates is that after the war the marginal product of the decimated resources such as nonresidential structures and manufacturing equipment were very high. The Marshall Plan facilitated the inflow of capital and generated a strong recovery from the war in the ensuing decades. According to this theory of transition dynamics, one would expect the growth effects to decline over time as recovery took place.

The fourth and fifth columns of Table 2 support this hypothesis. Column four reveals that growth rates after the war remained stationary according to the usual ADF tests, but column five shows that many of the countries affected by World War II exhibit a negative trend in growth

rates for the period 1950-1988.^{7,8} Trend tests in Austria, France, Germany, Italy, and Japan all reject the hypothesis of no trend in favor of a negative trend at the 5% significance level or better.

The picture that emerges for the growth experience of the OECD sample is mixed. Growth rates over the period 1900-1987 clearly do not exhibit a unit root. However, there is some evidence of a positive mean shift after World War II together with a downward trend for several countries in the sample. Figure 2 illustrates this graphically by comparing U.S. and Japanese growth rates for 1900 to 1987. The U.S. growth rates are essentially fluctuations around a constant mean for the entire period. In contrast, Japanese growth rates fluctuate around a constant mean until World War II. After the war, they rise considerably and then decline in subsequent years. The suggestion in the time series pattern is that the growth rates are likely to return to a constant mean, stationary process. In this sense, growth rates for the OECD sample are similar to growth rates in the U.S. -- they are probably best viewed as stationary over the very long run. Nevertheless, the change in the stochastic properties following World War II suggest that care must be taken in interpreting empirical work based on the entire sample. For this reason (as well as in response to data availability), the remainder of the empirical work in this paper will focus on the period since 1950.

The results of this section strongly reject the implicit prediction of many endogenous growth models that growth rates should exhibit a unit root. Using time series data over a very long horizon for fifteen OECD countries, tests reveal that the growth rate of GDP per capita is stationary. This stationarity has important implications for empirical work. For instance, one

⁷The results in these two columns are calculated using data on per capita GDP from the Summers and Heston [1991] data set in order to maintain comparability with later results.

⁸Including a time trend in the ADF test reduces the power of the test, but the null hypothesis of a unit root is still rejected.

might be tempted to decompose growth and openness into permanent and transitory components to examine the extent to which permanent movements in growth are due to permanent movements in openness. The lack of a unit root in growth rates indicates that growth rates exhibit no permanent movements, so that such a decomposition is trivial. This observation imposes a strong and testable restriction on endogenous growth models: if an endogenous growth model predicts that permanent movements in some variable X have permanent effects on growth, then either

- (a) X must be stationary with no trend, or
- (b) some other variable (or variables) Z must also have permanent effects on growth that offset the movements of X . If X is integrated of order one, then Z must also be integrated of order one and X and Z must be cointegrated with a cointegrating vector that is determined by the endogenous growth model.

This restriction must hold exactly for the U.S. since we have shown that U.S. growth rates appear to exhibit a constant mean for the entire period 1880 to 1987. For the other OECD countries, it should be modified slightly to reflect the potential for a negative trend in growth rates after 1950. But otherwise, the basic spirit of the restriction remains true.

In the next section, I will use this stationarity restriction to test accumulation-based models of endogenous growth that rely on constant returns to a broadly-defined concept of capital.

III. Tests of Accumulation-Based Models of Endogenous Growth

Broadly speaking, recent endogenous growth models can be divided into two major strands: those that endogenize the growth rate via accumulation (so that a production function effectively exhibits constant returns to scale for a sufficiently general definition of capital) and those that endogenize the growth rate by focusing explicitly on technological progress (so that

capital accumulation may still run into diminishing returns as in the neoclassical Solow model). Models in the first class, which I refer to as "accumulation-based" models, include Romer [1986, 1987], Rebelo [1987, 1991], Barro [1991b], and Benhabib and Jovanovic [1991]. Models in the second class, or "R&D-based" models, include Aghion and Howitt [1990], Grossman and Helpman [1991], Romer [1990b], and Young [1991]. This section uses the stationarity test developed in Section II to test the accumulation-based models of growth. Elsewhere (in Jones [1993a]) I consider the implications of the stationarity restriction for the R&D-based models.

For the empirical work that follows, it is useful to distinguish between two types of accumulation-based "AK" models. In the first type of accumulation-based model, technology is not completely endogenized, and "A" still grows over time because of some remaining exogenous technological progress. For example, one of the models presented by Romer [1990a] assumes that production depends on physical and human capital. In this model, there is no obvious reason why the addition of human capital should eliminate all unmodelled exogenous technological change: when the 80486 computer supplants the 80386 computer, this innovation is certainly not captured by a change in physical or human capital, but rather by a change in their joint productivity. The second type of accumulation-based model is the more familiar model in which "A" is a constant and "K" includes all technological progress.⁹ As we will see shortly, the first type of "AK" model is rejected easily by the stationarity restriction. The second type is slightly more difficult to reject, but in the end the time series evidence against this model is compelling.

III.1 "AK" Models with Some Exogenous Technological Progress

Consider a simple Ramsey growth model in which the production function exhibits

⁹There is a deeper issue at work here. It is well-known (see Gordon [1992] for instance) that price deflators do a poor job of accounting for quality changes. With appropriate quality-adjusted deflators, it is arguable that capital quality differences such as the difference between the 80486 and the 80386 computers should be captured in the capital variable.

constant returns to capital as well as some remaining Hicks-neutral technological progress:

$$\begin{aligned}
 & \max_{c_t} \int_0^{\infty} e^{-\rho t} u(c_t) dt \\
 & \text{s.t.} \\
 & c_t = y_t - i_t \\
 & y_t = A_t k_t = e^{g t} k_t \\
 & \dot{k}_t = i_t - \delta k_t
 \end{aligned} \tag{1}$$

where the notation is standard: $u(\cdot)$ is a CRRA utility function, c is consumption, y is output, i is investment, k is capital, g is the rate of exogenous technological change, δ is the rate of depreciation, and ρ is the rate of time preference. Setting up the Hamiltonian and solving this model yields the familiar Ramsey rule for growth:

$$g_t = \sigma(e^{g t} - \rho - \delta) \tag{2}$$

where σ represents the intertemporal elasticity of substitution.

Equation (2) reveals that the growth rate of this economy will be proportional to the level of technology, and since this level grows exponentially, the growth rate of the economy will be growing exponentially. In terms of the stationarity test, this model predicts that the growth rate depends on a variable which is nonstationary so this model is rejected easily by the results in Section II. To the extent that the "AK" model is correct, then, the rate of exogenous technological progress must be equal to zero. The remainder of this section imposes this restriction and tests the more familiar version of the "AK" model in which "A" is constant.

III.2. "AK" Models with a Constant "A"

In order to consider the case in which the "A" parameter is constant over time, we must explicitly include technology (denoted by θ) somewhere else in the production function. A

natural way of accomplishing this is given by the following continuous time model:¹⁰

$$\begin{aligned}
 & \max_{c_t} \int_0^{\infty} e^{-\rho t} u(c_t) dt \\
 & \text{s.t.} \\
 & c_t = (1 - s_t^k - s_t^\theta) y_t, \\
 & y_t = A k_t^\alpha \theta_t^{1-\alpha} \\
 & \dot{k}_t = \phi s_t^k y_t - \delta k_t, \\
 & \dot{\theta}_t = s_t^\theta y_t - \delta \theta_t,
 \end{aligned} \tag{3}$$

where s^k and s^θ are the investment rates in capital and technology respectively, ϕ is one plus the subsidy rate that applies to capital accumulation, and the remaining variables have the interpretations given before. Production in this model exhibits constant returns to the accumulable factors, which will generate endogenous growth. The model is appealing in that the accumulation of technology is endogenized using utility maximizing agents.

Solving the problem in equation (3), it is straightforward to show that the ratio θ/k (which we will define as ψ) is constant and equal to $(1-\alpha)/(\alpha\phi)$.¹¹ Thus, although this model allows technology to accumulate endogenously, in fact capital and technology accumulate in lock step. This results from the fact that agents can invest in either the quantity of capital k or the quality of capital θ . They will undertake these investments to the point at which they are indifferent between putting an extra unit into quantity or into quality. Given the setup in equation (3), this translates into a constant ratio of θ/k . Using this fact, we can rewrite the production function in terms of a new "reduced form" production technology:

¹⁰This model can, of course, be interpreted more generally. The variable θ need not represent technology but could represent another type of accumulable resource such as human capital. The results that follow do not depend on any particular interpretation.

¹¹Since there are no adjustment costs in this model, the economy will instantaneously adjust the initial amounts of k and θ so that the θ/k ratio equals $(1-\alpha)/(\alpha\phi)$. More generally, the results in this section will hold along the balanced growth path.

$$y_t = \tilde{A} k_t, \quad \tilde{A} = A \psi^{1-\alpha} \quad (4)$$

Equation (4) looks exactly like the standard "AK" production technology in which the parameter multiplying the capital stock is a constant. In a sense, then, this model is a special case of the model considered earlier.

Solving this model for the growth rate along the balanced growth path yields:

$$\gamma_t = \sigma(\alpha\phi\tilde{A} - \rho - \delta) \quad (5)$$

The important thing to note here is that a subsidy to capital accumulation raises the steady state growth rate. Equation (6) derives the steady state investment rate:

$$s^* = \sigma\left(\alpha - \frac{\rho}{\phi\tilde{A}}\right) + (1-\sigma)\frac{\delta}{\phi\tilde{A}} \quad (6)$$

Note that an increase in the subsidy to capital accumulation can affect the steady state investment rate in either direction because the substitution effect toward investment is offset by the income effect (with a higher subsidy rate, less pre-subsidy investment is needed to produce the same level of post-subsidy investment). It is natural to assume that the subsidy will raise the steady state investment rate, and this will be true for plausible values of σ (e.g. $\sigma=1$).

Now consider the steady state relationship between the growth rate and the investment rate. We can take logs and differentiate (4) to find

$$\gamma = -\delta + \phi\tilde{A}s^* \quad (7)$$

That is, the steady state growth rate of output is an affine transformation of the investment rate for physical capital. In this model, then, the dynamics of growth rates should be similar to the dynamics of investment rates. An increase in the investment rate (for instance because of an

increase in the subsidy or a fall in the rate of time preference) will be matched by an increase in the steady state growth rate. Furthermore, if investment rates exhibit a stochastic trend (i.e. a unit root) or a deterministic trend, then growth rates should inherit this property. As we have seen, growth rates have neither a stochastic nor a deterministic trend, so the presence of one of these in investment rates would violate the stationarity restriction and serve as evidence against the model in equation (3).

At this point, it should be noted that the model in equation (3) has been written down explicitly in numerous recent growth papers, although the production function is generally written as some variant of (4). These include Romer [1986, 1987], Rebelo [1991], Barro [1991b], and Easterly [1991], among others. The formulation in (3) is perhaps more appealing intuitively than the common "AK" structure of (4) because it recognizes that technology is accumulated endogenously. In this model, agents can invest either in the quantity of capital or in the quality of that capital. The result of this model is that capital and technology move together. This feature is likely to be robust to a number of changes. For instance, with adjustment costs and embodied technology, firms would adjust their capital stock periodically, as in the Ss literature. Since technology is embodied in capital, firms would adjust their technology only when they adjust their capital, so that capital and technology once again move together. Whenever this result holds -- that is whenever the ration θ/k is approximately constant over time -- the relationship in equation (7) between growth and physical investment will be valid. Therefore, time series tests of the restriction given in equation (7) will represent a test of an entire class of models in the literature, and the rejection of this restriction would suggest that the accumulation of technology and the accumulation of capital must be modelled more carefully.

III.3. Stationarity Tests of Investment Rates

Equation (7) relates growth rates and investment rates in the accumulation-based models

of endogenous growth, and the prediction that a permanent increase in the investment rate generates a permanent increase in growth is one of the hallmarks of these models. As discussed earlier, growth rates for the OECD sample are stationary for the period 1950 to 1988, although for some countries the growth rates exhibit a downward trend. The restriction imposed by equation (7) will be violated, then, if investment rates are nonstationary or if they exhibit an upward trend.

Table 3 offers the basic empirical evidence on the time series properties of investment rates. Strictly speaking, the stochastic process for investment rates cannot be a pure unit root process. Investment rates are bounded (between zero and one) but we know that a unit root process will cross any finite bound with probability one. Nevertheless, it may be the case that in the relevant range, investment rates are well-characterized by a unit root process.¹² Based on equation (7), however, to the extent that a unit root process characterizes investment rates, we should also expect a unit root process to characterize growth rates under the model in equation (3). Therefore the ADF tests are in fact valid tests of that model.

Augmented Dickey-Fuller tests for a unit root in the total gross investment rate are reported in the first column of Table 3. For only one of the fifteen countries does the ADF test reject the null hypothesis that investment rates contain a unit root at a significance level greater than or equal to 10%. (Interestingly, this country is the U.S.). The second column of Table 3 reports the results from simple time trend tests for total investment rates. Several of the countries, including the U.S., exhibit highly significant and positive time trends in the total investment rate. Comparing this evidence with the time series properties of growth rates suggests that the stationarity restriction imposed in equation (7) is violated for many of the countries in the OECD sample.

¹²Bertola and Drazen [1990], for instance, provide an example in which government spending as a share of GDP follows a random walk with drift until it reaches a "trigger point".

There are several problems with using total gross investment when examining the dynamics of growth rates and investment rates. First, the composition of investment has shifted in recent decades away from structures and toward producer durables, a reasonable response to the destruction of nonresidential and residential structures during World War II.¹³ Since the productive life of producer durable investment is much less than that of structures, it is possible that the positive trend in the total investment rate data is an artifact of the increase in investment designed to replace worn-out capital which accompanies the shift to durables. Total *net* investment may in fact show no trend at all.¹⁴

Another important criticism of the use of total investment data is suggested by the recent research of De Long and Summers [1991] and Jones [1993b]. These authors argue that machinery investment is the crucial component of investment for explaining growth performance: in cross-country regressions, machinery investment rates are strongly correlated with growth whereas nonmachinery investment rates and growth are uncorrelated, even when other explanatory variables such as enrollment rates and initial income are held constant. This result appears to be extremely robust in the cross-section data. If machinery investment, which averages about one-third of total investment, is the central component of investment driving growth, then focusing on total investment may be misleading.

The final two columns of Table 3 report the ADF tests and time trend tests for the producer durable investment rate. Producer durable investment differs from machinery investment only by the inclusion of transportation equipment in the former. Since the cross

¹³As evidence for this, see the results on the trends in producer durable investment rates to be discussed shortly.

¹⁴The trend in investment rates for the U.S. is reduced considerably, for instance, when one looks at net investment instead of gross investment. (See, for instance, Charts 4-2 and 4-3 in the *Economic Report of the President 1990*). It should be noted, though, that the depreciation data is itself subject to criticism. For example, most depreciation in practice results from obsolescence rather than physical depletion. See Scott [1992] for this criticism.

section results for producer durables investment are very similar to the results for machinery investment, this difference should matter little in the results reported here. Using producer durables investment also addresses the concern with differences in depreciation rates since the primary difference is between structures and equipment.

The results for producer durables investment in Table 3 reinforce the earlier results and indicate that the durables component of investment actually exhibits a stronger upward trend than total investment, reflecting the shift to durables and away from structures alluded to earlier. ADF tests reject the null hypothesis of a unit root in durable investment rates for only four countries, but each of these countries exhibits a statistically significant positive deterministic trend in its durable investment rate. Also the U.S. durable investment rate, in contrast to total investment rates, shows evidence of a unit root with strong positive drift. Similarly, time trend tests find highly significant and positive trends in durable investment rates for eleven of the fourteen countries for which data are available.

Taken together, the results in Table 3 can be interpreted as fairly strong support of the view that investment rates contain either a stochastic or a deterministic trend, for most of the advanced OECD countries. Furthermore, it is difficult to think of any omitted variable Z that could offset the effect of investment, at least for the countries for which the trend in investment is upward. The "AK" model itself, for example, certainly suggests no such variable. Human capital investment and openness, two leading possibilities, both certainly trend upward in the post-War period.¹⁵ Also, energy price shocks will not suffice: the shocks in 1973 and 1979 are best viewed as one-time shocks since energy price inflation has actually been less than CPI

¹⁵Data on education in the U.S., for instance, shows an increase in education expenditure as a fraction of GNP from 4.8% in 1959 to 6.8% in 1986. Current expenditure shares might be less relevant from the standpoint of growth theory given the long lags between expenditure on education and its effect via a better educated workforce. However, the average years of education for the population aged 25 and over in the U.S. has risen from 9.3 years in 1950 to 12.6 years in 1986. (These data are taken from the *Digest of Education Statistics*, 1988).

inflation for the period 1950-1988.¹⁶ This failure of the stationarity test indicates that the model of equation (3) is rejected by the data, suggesting that the accumulation-based models do not provide a good description of the driving forces behind growth in developed countries.

The evidence from the stationarity test is compelling, but it does not take full advantage of the restriction imposed in equation (7). The unit root tests examine the time series behavior of investment and growth separately. The remainder of this paper considers the co-movement of growth and investment over time and provide additional evidence against the accumulation-based models.

III.4. Panel/Time Series Test of the AK Models

A natural procedure for testing the accumulation-based models is to test the restriction in equation (7) explicitly. Reinterpreting this equation to allow for investment and growth to interact over time so that not all of the effects occur contemporaneously, the restriction from the accumulation-based models suggests a dynamic relationship such as

$$g_t = A(L)g_{t-1} + B(L)i_t + \epsilon_t, \quad A(1) < 1 \quad (8)$$

where $A(L)$ and $B(L)$ are two lag polynomials. The restriction in equation (7) can be interpreted in this dynamic relationship as the requirement that

$$B(1) > 0 \quad (9)$$

which says that the sum of the coefficients in the polynomial $B(L)$ is positive: a permanent shock to investment will permanently raise the growth rate.

¹⁶If we were to end the sample at 1982, energy price inflation would be slightly higher than CPI inflation. However, from 1982 to 1988 energy prices fell in real terms so that for the period 1950-1988 energy price inflation is actually below CPI inflation. (See the appendix tables in the *Economic Report of the President, 1990*).

Alternatively, $B(1) \leq 0$ would constitute a violation of the accumulation-based models as characterized by equation (7), whether investment rates are stationary, trending, or integrated. If the interpretation of the ADF tests given previously is incorrect and investment rates are actually (trend) stationary, then estimating equation (8) will provide the appropriate test of the accumulation-based models. In this case, the t-test for $B(1)=0$ will have the usual distribution. However, this test is robust to the nonstationarity of investment rates as well. If investment rates are integrated of order one, it is easy to show that, asymptotically, OLS estimation of equation (8) must produce $B(1)=0$.¹⁷ In general, however, the usual inference methods will no longer apply.¹⁸ The presence of a negative trend in the growth rates of some countries, together with the positive trend in investment rates may lead to the estimation of $B(1) < 0$, but this again will clearly constitute a rejection of the accumulation-based models.

The first row of Table 4 reports the least squares estimate of $B(1)$ in equation (8). When investment is measured as total investment, the OLS estimate of $B(1)$ is -0.0128 which is insignificantly different from zero (the test statistic is -0.40).¹⁹ For producer durables

¹⁷To see why, notice that equation (8) can always be rewritten as

$$g_t = A(L)g_{t-1} + B(1)i_t + B^*(L)\Delta i_t + \epsilon_t$$

where $B^*(L)$ is a $(p-1)$ th order lag polynomial such that

$$b_k^* = -\sum_{i=k+1}^p b_i, \quad k=1, \dots, p-1$$

In this specification, the RHS includes only stationary terms except for the contemporaneous investment variable which has $B(1)$ as its coefficient. This regression of a stationary variable on a variable that is integrated of order one must yield zero. Otherwise, the error ϵ will be $I(1)$ and have unbounded variance. To minimize the variance of the error term, OLS makes it a stationary variable (asymptotically) and therefore places zero weight on the $I(1)$ variable.

¹⁸Park and Phillips [1988] show that in the special case in which the $I(1)$ variable is strictly exogenous, the OLS estimates of the $I(1)$ coefficient will be asymptotically normal. More generally, however, the OLS estimates will have a distribution that is a Brownian motion functional.

¹⁹The test statistic from the OLS regression is actually -0.37. Table 4 reports the test statistics for the null hypothesis that the sum of the lagged investment coefficients is $-b_0$, where b_0 is taken as given. As is clear from this example, this difference matters little for the results.

investment, the $B(1)$ estimate is also less than zero at -0.305 . The simple OLS results, then, provide no evidence that a permanent increase in the investment rate results in a long-term increase in the growth rate.

Because of the inclusion of the contemporary investment term in equation (8), OLS estimates of $B(1)$ will be biased, and the direction of the bias will generally be ambiguous. Classical econometrics requires an instrument for current investment in order to identify the true value of $B(1)$, but such instruments are notoriously hard to come by in the investment literature. Bosworth [1985], for instance, examines the behavior of investment and its components after the substantial reforms of the 1981 tax act and concludes that tax variables are very poor indicators of the subsequent movements in investment. However, a simple technique described below allows us to compute bounds on the true value of $B(1)$. To the extent that these bounds can be used to test the restriction imposed by equation (7), no classical instrument is needed.

To construct bounds on $B(1)$, we use economic theory and the OLS estimates of equation (8) to calculate lower and upper bounds for the coefficient on the endogenous variable. Then, N^* specifications of equation (8) can be estimated by restricting the coefficient on the endogenous variable to take on N^* equally-spaced values in the range between the lower bound and the upper bound. For each of these N^* estimates, we calculate the associated estimate of $B(1)$, and with a sufficiently fine grid (i.e. for N^* sufficiently large), the extreme values of these estimates of $B(1)$ will bound the true value. Tests can be conducted using these extreme bounds.

Even though the bias of $B(1)$ is ambiguous, the contemporaneous investment coefficient b_0 will be biased upward in the OLS regression under the plausible assumption that the covariance between the innovation ϵ and current investment is positive.²⁰ This would be the case for most reasonable interpretations of the shocks that affect growth and investment. For instance, an

²⁰A simple "partialling out" argument can be used to show this since the covariance between ϵ and the exogenous variables is assumed to be zero.

exogenous shock to productivity will simultaneously raise both the growth rate and the investment rate. In a structural VAR framework for growth and investment, this covariance assumption is equivalent to assuming that the coefficient on growth in the investment equation is positive.

Under this assumption, the OLS estimate of b_0 represents an upper bound on the true coefficient. To obtain the lower bound for b_0 recall that in simple growth models such as the Solow model or the accumulation-based models discussed earlier the contemporaneous effect of a change in investment on growth is nonnegative -- a lower bound of zero then seems plausible. These bounds imply that the true value of b_0 lies in the range $[0, .847]$ for total investment and $[0, .926]$ for durable investment, as shown in Table 4. With these bounds, Table 4 reports the values of $B(1)$ implied by equation (8) when b_0 takes on N^* evenly spaced values in these ranges, where N^* is taken to be eleven (representing 10 evenly spaced intervals). Surprisingly, the OLS estimates of $B(1)$ represent the upper bounds: the estimates of $B(1)$ for other values of b_0 are all less than the OLS estimate, indicating that the bias of the term $B(1)$ is dominated by the upward bias of b_0 . Since the OLS values of $B(1)$ are less than zero for both total investment and for durable investment, these tests confirm the basic stationarity results: the characterization of the accumulation-based models in equation (7) is rejected by the data.

IV. The Horizon Over Which Investment Affects Growth

The results in the previous section provide strong evidence that the key restriction imposed by accumulation-based models of endogenous growth does not hold: a permanent increase in the investment rate does not produce a permanent increase in the growth rate, but rather the effects on growth are transitory. However, the evidence does not tell us the horizon over which the effects on growth are important. Perhaps a permanent change in investment raises

growth for twenty-five or thirty years. In this case, although the accumulation-based models are not strictly correct, they may prove to be a useful approximation. Alternatively, it may be the case that the effects on growth are negligible after only eight or ten years. In this case we would conclude that the predictions of the accumulation-based models are not only technically incorrect but they are also misleading.

To estimate the dynamic response of growth rates to a permanent change in investment rates, we consider the following equation:

$$g_{it} = \alpha_i + \beta_i t_i + C(L) g_{it-1} + D(L) \Delta i_{it} + \epsilon_{it} \quad (10)$$

The inclusion of investment rates in first differences in this equation imposes the restriction $B(1)=0$ in equation (8): that is, the results from the stationarity restriction are incorporated in estimating the horizon over which investment changes affect the growth rate. Notice that the specification in (10) will involve only stationary variables so that the usual inference applies. Also, results are reported for the full sample of countries, although the results are not changed if the sample is restricted to those countries for which a unit root in the investment rate cannot be rejected.

Equation (10) includes both a country-specific intercept and a country-specific time trend. The time trends are included to capture any exogenous movements in growth rates that are omitted from the specification -- we do not want the downward trend in the growth rates of some countries to artificially shorten the dynamic effect of a change in investment on growth. However, since investment rates enter in first differences in this specification, the investment variables will be stationary and should be uncorrelated with the time trend. This is confirmed by the observation that the results that follow are easily robust to the exclusion of these trends.

Table 5 employs OLS estimates of equation (10) and reports the dynamic response of growth rates to a permanent one percentage-point increase in the investment rate, for both total

investment and durable investment. Figure 3 graphs these dynamic responses together with one standard error bands calculated numerically using the delta method. Recall that, as in the estimate of equation (8), the dynamic responses calculated using OLS will be biased in an ambiguous direction. However, it is useful to consider these results before turning to a more appropriate estimation technique.

For both total and durable investment, most of the impact of the investment shock on growth occurs contemporaneously in the OLS results. In fact, this somewhat reasonable interpretation is potentially misleading because of the upward bias associated with the contemporaneous dynamic response. The key point of the OLS results is that the positive impact on growth of a one percentage point permanent increase in the investment rate is negligible after about six years out. Furthermore, the standard error bands converge quickly as the horizon lengthens so that we can say with confidence that the positive effects on growth disappear after about six years or so.

Table 5 also reports the cumulative effect on output per capita of a one percentage point increase in the investment rate. For total investment, the long-run effect (which occurs almost entirely after six years) is to raise output per capita by about 1.06 percent; for durable investment, the effect on output is about 1.19 percent. To check the plausibility of these numbers, consider the familiar Solow model with the returns to capital less than unity:

$$\begin{aligned} y &= k^\alpha, \quad \alpha < 1 \\ \dot{k} &= sy - (n+g+\delta)k \end{aligned} \tag{11}$$

where the notation is the same as in the previous section, except that n and g are population growth and exogenous productivity growth. In this model, it is straightforward to show that

$$\frac{\partial \ln y^*}{\partial s} = \frac{\alpha}{1-\alpha} \frac{1}{s} \quad (12)$$

where the partial derivative is used to denote the fact that we are holding technological change constant. To calibrate this model, let's assume that $s = .25$, the average value of the investment rate from our OECD sample. For $\alpha = .25$, equation (12) indicates that a one percentage point increase in the investment rate will raise the steady state level of output per capita by 1.33 percent; for $\alpha = .33$, the long-run effect is 2.00 percent. The estimates in Table 5 from the OLS results are then plausible, but perhaps slightly low.²¹

Because of the inclusion of the contemporaneous investment term in equation (10), the same problems that we faced in estimating equation (8) apply. The dynamic responses calculated using OLS will again be biased, and the direction of the bias is ambiguous except for the contemporaneous response. However, since we are only interested in estimating the horizon over which permanent changes in investment affect the growth rate, the technique of bounds identification employed earlier is once again useful. As before, we will take the bounds on the contemporaneous effect to be zero and the OLS estimate (which is biased upward by the arguments given earlier).²² The results in Figure 3 and Table 5 report these bounds as [0, .802] and [0, 1.020] for total investment and durable investment, respectively. Given these bounds, we estimate the dynamic response of growth to an investment change N^* times by constraining the contemporaneous effect to take on evenly-spaced values within the bounds. The maximum

²¹This underestimate would be expected, particularly for the total investment rate, to the extent that depreciation is not removed. For example, as discussed earlier, the total gross investment rate for the U.S. contains a time trend (due to the shift away from structures and toward durables) even though total net investment rates do not. The fact that the estimate for producer durables investment is closer to the prediction from the Solow model supports this claim.

²²An alternative (and more restrictive in this case) lower bound could be calculated by choosing the dynamic response that generates a cumulative effect on output equal to zero.

horizon over which investment affects growth in this setup will then represent an upper bound on the true horizon since the true contemporaneous response lies within the coefficient bounds. The extreme bounds of the dynamic responses will contain the true dynamic response.²³

The dynamic response bounds calculated using this technique will be robust to several forms of misspecification. For example, the technique accounts for all sources of endogeneity that cause the covariance between the contemporaneous investment change and the disturbance to be positive (assuming the lags are still uncorrelated with the disturbance). Furthermore, to the extent that omitted variables are uncorrelated with lagged investment rates, the dynamic responses will again be unaffected. Finally, as we will see, the dynamic response bounds after about five years or so are extremely robust to changes in the contemporaneous effect suggesting that they are likely to be robust to omitted variable bias.

Figure 4 plots the dynamic responses for each of the $N^*=11$ values of the contemporaneous response. The bounds for the short term responses (0-2 years) vary considerably reflecting our uncertainty about the contemporaneous effect. But even after only three years, the dynamic responses are clustered within a small range. The figure shows that after about seven years for total investment (five years for durable investment) permanent increases in the investment rate have only negligible effects on growth.

²³By ignoring the second structural equation of the structural VAR -- the investment equation -- we are examining a counterfactually flat path for investment rates when we look at the dynamic response of growth rates to a permanent one percentage point increase in the investment rate. For the purpose of testing a theory, such a counterfactual constraint may be plausible: we want to know what the structural model implies about exactly this counterfactual sequence of investment rates. More generally though, ignoring the dynamics of investment is problematic. Given the assumptions we have made thusfar, we are unable to identify the second structural equation together with the first equation using only the bounds identification technique since we have an endogeneity problem in each equation. The bounds technique should be viewed as an identification scheme when the model is one identifying assumption short. However, in Appendix A, I show how a set of additional assumptions can be used to achieve bounds identification in this case. These assumptions are less restrictive than have been used elsewhere (for example by Blanchard and Quah [1989]) but are correspondingly less powerful in that we obtain bounds rather than a single dynamic response.

Table 5 reports the maximum dynamic response for each period after the initial shock. Note that these differ from the OLS dynamic responses, but only slightly (once again, the upward contemporaneous bias seems to dominate the dynamic responses). The results in the table confirm the cursory observations made from the figure: the dynamic response of growth to a permanent increase in the investment rate is negligible (less than two hundredths of a percentage point) after eight years for total investment and after only five years for durable investment. The difference in horizon for the two investment variables is not surprising. Recall that the positive trends in durable investment are much stronger than those in total investment. Since growth rates are stationary, the impact of durable investment on growth will plausibly be estimated to be smaller than that for total investment in the time series dimension.

These results uniformly indicate that the horizon over which a permanent shock to investment has effects on growth is less than eight years. Together with the stationarity results, this relatively short horizon is a sharp criticism of the accumulation-based models of endogenous growth. Not only does it appear that a permanent increase in the investment rate has only a transitory effect on the growth rate, but it appears that the horizon over which that effect occurs is sufficiently short to make the predictions of the accumulation-based models misleading.

The results also refine the evidence presented in the cross-section studies of De Long and Summers [1991] and Jones [1993b]. These authors find that machinery investment (which differs from durable investment via the exclusion of transportation equipment) is the key component of investment in explaining the cross-section distribution of growth rates and hypothesize that subsidies to machinery investment are likely to generate increases in long-term (twenty-five year) growth rates. The time series results in this paper suggest that permanent increases in durable investment have effects on the growth rate of advanced OECD countries such as the U.S. and Japan for only short to medium term horizons. The discrepancy between the cross-section and the time series results is accounted for by the positive trend in durable investment rates over the

last twenty-five years in these countries: every time investment rates increase by one percentage point, the economy experiences a transitory growth effect lasting for five to eight years. A positive trend in investment rates for twenty-five years, then, will easily raise the average growth rate over this horizon, but such an increase will not be permanent.^{24,25}

V. Conclusions

The first part of this paper documents in detail the observation that the growth rate of GDP per capita is stationary for the period 1900-1987 in fifteen OECD countries. This observation leads to a straightforward but important restriction on endogenous growth models. That is, if an endogenous growth model predicts that permanent movements in some variable X have permanent effects on growth, then either

- (a) X must be stationary with no trend, or
- (b) some other variable (or variables) Z must also have permanent effects on growth that offset the movements of X . If X is integrated of order one, then Z must also be integrated of order one and X and Z must be cointegrated with a cointegrating vector that is determined by the endogenous growth model.

The second part of the paper uses this restriction to test a class of endogenous growth models based on constant returns to a broad concept of capital. A version of the "AK" model

²⁴One possible way to test this hypothesis is to include changes in the investment rate in the DeLong-Summers regression. Tentative experiments with this strategy did not significantly alter the DeLong-Summers result, which may not be surprising given the endogeneity problems with the investment rate and the potential problem of country-specific "fixed effects" associated with the cross-section regression.

²⁵Auerbach, Hasset, and Oliner [1992] consider the effect of shocks to the investment rate on the coefficient in the DeLong and Summers regression and show that the point estimates are consistent with the standard Solow model.

is constructed in which technology is completely endogenized in a simple manner consistent with many papers in the growth literature. In this model, utility maximization implies that the accumulation of capital and technology are linked one-for-one so that an increase in the investment rate for capital, e.g. through an investment tax credit, results in a matching increase in the growth rate. We find empirically that investment rates are well-characterized as possessing either a stochastic or a deterministic trend, whereas from the first part of the paper we know this is not true of growth rates. Therefore, this evidence violates the stationarity restriction and constitutes a fairly strong rejection of this class of endogenous growth models.

Further evidence against these models is provided by panel/time series regressions for growth and investment. The main conclusion from this evidence is that in the Summers and Heston data since 1950 for the fifteen OECD countries, there is no evidence that changes in the investment rate are associated with long-run changes in the growth rate. This evidence is counter to the restrictions implied by models which endogenize growth and technological progress using linearity in the production function. And these results should give pause to arguments that subsidies to investment are needed to restore productivity growth: the horizon over which such an action has effects on the growth rate appears to be less than eight years.

The time series results in this paper are, however, consistent with another class of endogenous growth models, the R&D-based models that have been developed in Romer [1990b] and Grossman and Helpman [1991]. These models are similar to the original Solow model in that technology and capital accumulation do not evolve together. Rather, the fundamental driving force in the economy is technological development. These models share the prediction that a subsidy or tax on capital accumulation has a level effect but no long-run effect on steady state growth. In this respect, these models out-perform the accumulation-based models.

However, this observation must be interpreted carefully. Jones [1993a] explores the R&D-based models of endogenous growth and finds that important modifications of these models

are needed to render them consistent with the time series evidence on R&D and the stationarity of growth rates. Such modifications may be worthwhile, though, in light of the results in this paper: the growth performance of the advanced OECD economies and the accumulation-based models of endogenous growth appear to be incompatible.

Appendix A

This appendix discusses the more general application of the bounds identification technique to a bivariate vector autoregression. To set up the basic model, consider the specification

$$z_t = A(L)\epsilon_t, \quad z_t = (y_t \ x_t)' \quad (*)$$

In this structural model, we impose the following standard assumptions:

- A1. Equation (*) represents the correct structural model, where z_t and ϵ_t are each 2x1 vectors.
- A2. $A(L)$ is invertible so that the ϵ_t structural disturbances are fundamental and can be recovered using only z_t and its past history.
- A3. $E\epsilon_t\epsilon_t' = I$ and $E\epsilon_t\epsilon_{t+j}' = 0$ for all nonzero j .

Assumptions A1 and A2 are the most important assumptions in this setup, and these assumptions have been subject to recent criticism. For example, if the true structural model involves more than two shocks, the dynamic responses calculated using some estimated $A(L)$ based on A1 will be incorrect. Quah [1992] and Lippi and Reichlin [1990] discuss cases in which A2 may be violated, but Blanchard and Quah [1992] show that such violations can sometimes be unimportant from the standpoint of calculating the dynamic responses. If assumptions A1 and A2 are maintained, assumption A3 is not overly restrictive. This assumption says that the two structural shocks are uncorrelated at all leads and lags.²⁶

It is well-known that these assumptions A1-A3 are insufficient to identify the structural

²⁶Were they not, we could suppose the two shocks are linear combinations of two shocks that are in fact uncorrelated at all leads and lags. But then it would be natural to call the new shocks the structural shocks.

coefficients $A(\cdot)$ and the structural disturbances ϵ_t . This has led to several proposed methods for identifying the structural parameters when conventional instrumental variables are unavailable. The early VAR literature, for example, proposed restricting A_0 to be triangular. Recently, more sophisticated restrictions have been proposed (e.g. by Blanchard and Quah [1989] and the references cited there), but these restrictions generally require a structural assumption concerning the $A(L)$ polynomial that may or may not be true. The method of bounds identification may be a useful alternative or adjunct to these techniques. Instead of making an additional and perhaps implausible assumption on the structural polynomial $A(L)$, we can compute bounds on the true dynamic responses. This method is especially useful when the researcher cares only about the medium-to-long run properties of the dynamic responses.

Bounds identification proceeds by writing the structural model in its standard autoregressive form (using A2 to invert the polynomial):

$$\begin{aligned} y_t &= B(L)y_{t-1} + C(L)x_t + \epsilon_{1t} \\ x_t &= D(L)y_t + E(L)x_{t-1} + \epsilon_{2t} \end{aligned}$$

This system of equations has two endogenous variables but only one identifying assumption (that the covariance between the disturbances is zero). To identify bounds on the dynamic responses, we use OLS results together with economic theory to construct bounds on the coefficients on the endogenous variables c_0 and d_0 . For example, when the two variables are growth and investment rates, the positive bias in the OLS regressions can be used to construct upper bounds and zero can be plausibly chosen for the lower bounds. For each value of d in the d_0 bounds $[d_{lo}, d_{hi}]$, we can construct an instrument $x_t - d^*y_t$ for use in estimating the first equation. At the true (but unknown) value $d=d_0$, this instrument will be orthogonal to ϵ_{1t} and will produce the unbiased estimates of the parameters in the first equation. Conditioning on this value of d_0 , we can use OLS to estimate the second equation. If we calculate dynamic responses for each value in the

bounds for d_0 , then the true dynamic response will lie inside the bounds of the computed dynamic responses, and these dynamic response bounds can be used in place of the true dynamic response to test economic theory.

This bivariate bounds identification technique generates bounds on the dynamic responses of the y 's and x 's to structural disturbances, and in this respect the bivariate method may sometimes be superior to the single-equation technique discussed in the paper. However, the two-equation method is similarly more sensitive to misspecification. Omitted variable bias in this case is much more likely to produce misleading dynamic responses since the key identifying assumption of orthogonality of the structural shocks will no longer be valid. In contrast, the single equation technique is less sensitive to omitted variable bias: if the omitted variable is orthogonal to lagged values of x and y then the dynamic responses will remain unbiased (assuming the initial bounds still contain the true endogenous coefficient).

The problems with omitted variable bias are potentially serious for the two equation system of growth and investment considered previously, which is another way of saying that there may be more than two important sources of disturbances driving growth and investment. For this reason, I focused on the single-equation results in the main text. Nevertheless, Appendix Figures 1 and 2 display the dynamic response bounds for growth rates and investment rates corresponding to each of the two "structural" shocks as a simple application of the bivariate bounds identification technique. Interestingly, despite a wide range of responses of the investment rates to each of the shocks, the responses of the growth rates are actually *more* clustered than were the single equation bounds. Despite misgivings about omitted variable bias, the two equation dynamic responses provide additional support for the conclusion in the paper that permanent shocks to investment have only negligible effects on growth rates after about eight years.

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Table 1
Time Series Properties of U.S. Growth Rates
1880-1987

	Coefficient	Test Statistic
1. Time Trend	0.006	0.23
2. Augmented Dickey Fuller Test	0.314	-6.68
3. Endogenous Mean Shift	1.633 (1933)	2.14
4. Difference in Means: 1880-1929 vs 1950-1987	0.096	0.11

NOTES:

1. The Time Trend test reports the estimate of β from the regression

$$g_t = \alpha + \beta t + \epsilon_t$$

The test statistic is the t-statistic corresponding to the Newey-West [1987] corrected standard errors and tests $\beta=0$.

2. The ADF Test reports the estimate of ρ from the regression

$$g_t = \mu + \rho g_{t-1} + B(L)\Delta g_{t-1} + \epsilon_t$$

where the lag length of $B(L)$ is chosen using the Schwarz information criteria. The test statistic tests the null hypothesis of $\rho=1$. Critical values from Fuller [1976] for the 1% significance level are given below:

T=25	-3.75
T=50	-3.58
T=100	-3.51

3. The Mean Shift test is taken from Bai, Lumsdaine, and Stock [1991]. The following equation is estimated

$$g_t = \alpha + \beta I_{[t > T^*]} + \epsilon_t$$

where I is an indicator variable that takes the value one for $t > T^*$. This equation is estimated for values of T^* in (1896,1970) to reflect the 15% trimming recommended by Bai, Lumsdaine, and Stock. The reported test statistic is the maximum Wald statistic testing $\beta=0$. The critical value corresponding to the 15% significance level is 6.17. The coefficient and value of T^* corresponding to the max Wald statistic are also reported.

4. The Difference in Means for 1880-1929 versus 1950-1987 is reported together with the unadjusted t-statistic testing the hypothesis that the difference is nonzero.

Table 2
Time Series Properties of Select OECD Growth Rates

Country	ADF Test 1900-1987	Time Trend 1900-1987	Difference in Means	ADF Test 1950-1988	Time Trend 1950-1988
Australia	0.29 (-6.46)***	0.028 (1.61)	1.834 (2.85)***	-0.57 (-5.74)***	-0.010 (-0.15)
Austria	0.07 (-8.59)***	0.052 (1.62)	2.974 (2.71)**	0.26 (-4.61)***	-0.110 (-2.53)**
Belgium	0.23 (-7.26)***	0.035 (1.34)	1.740 (1.44)	0.13 (-5.16)***	-0.032 (-0.68)
Canada	0.37 (-6.25)***	0.015 (0.54)	0.617 (0.56)	-0.24 (-7.56)***	0.020 (0.38)
Denmark	0.04 (-8.83)***	0.016 (0.93)	0.772 (0.93)	0.04 (-6.08)***	-0.029 (-0.41)
Finland	0.23 (-7.27)***	0.033 (1.24)	1.823 (1.48)	0.19 (-6.45)***	-0.036 (-0.63)
France	0.24 (-7.18)***	0.036 (1.19)	1.472 (1.06)	0.53 (-3.37)**	-0.087 (-2.38)**
Germany	0.02 (-9.05)***	0.033 (1.16)	2.242 (1.79)*	0.43 (-3.88)***	-0.153 (-3.26)***
Italy	0.27 (-6.93)***	0.031 (1.31)	2.166 (2.17)**	0.19 (-4.97)***	-0.095 (-2.63)**
Japan	0.12 (-8.10)***	0.055 (1.90)*	3.989 (3.90)***	0.51 (-3.58)**	-0.182 (-3.07)***
Netherlands	0.19 (-7.57)***	0.026 (1.16)	1.003 (1.05)	0.25 (-4.70)***	-0.075 (-1.40)
Norway	-0.00 (-9.20)***	0.028 (1.75)	1.282 (1.42)	0.17 (-5.21)***	0.025 (0.73)
Sweden	0.22 (-7.39)***	0.020 (0.94)	1.190 (1.48)	0.24 (-4.71)***	-0.033 (-1.00)
United Kingdom	0.24 (-7.19)***	0.025 (1.38)	1.639 (1.88)*	-0.27 (-5.62)***	0.002 (0.06)

NOTES: Test statistics are reported in parentheses. See the notes to Table 1, except note that the Difference in Means in this table refers to 1900-1929 versus 1950-1987. Significance levels are denoted by (*) for 10%, (**) for 5%, and (***) for 1%.

Table 3
Time Series Properties of Select OECD Investment Rates
1950 - 1988

Country	Total Investment		Producer Durables Investment	
	ADF Test	Time Trend	ADF Test	Time Trend
Australia	0.559 (-2.27)	-0.083 (-1.50)	0.805 (-1.71)	0.030 (1.60)
Austria	0.748 (-1.72)	0.279 (4.46)***	0.420 (-3.59)*	0.071 (3.82)***
Belgium	0.794 (-2.06)	0.034 (0.41)	...	...
Canada	0.531 (-2.95)	0.083 (1.91)*	0.810 (-1.71)	0.077 (3.85)***
Denmark	0.882 (-1.41)	-0.018 (-0.11)	0.651 (-2.66)	0.096 (5.55)***
Finland	0.618 (-2.57)	-0.068 (-0.69)	0.677 (-2.84)	0.042 (1.22)
France	0.916 (-1.17)	0.166 (1.68)	0.902 (-1.28)	0.113 (5.69)***
Germany	0.769 (-2.27)	-0.146 (-2.12)**	0.659 (-3.48)*	0.086 (6.18)***
Italy	0.797 (-2.53)	-0.095 (-0.85)	0.374 (-4.30)**	0.037 (3.69)***
Japan	0.899 (-1.41)	0.426 (2.84)***	0.820 (-1.56)	0.159 (7.76)***
Netherlands	0.823 (-2.21)	-0.140 (-1.36)	0.854 (-1.69)	0.008 (0.21)
Norway	0.573 (-3.02)	-0.036 (-0.64)	0.666 (-2.73)	-0.155 (-2.62)**
Sweden	0.819 (-1.82)	-0.033 (-0.43)	0.443 (-3.61)**	0.052 (6.08)***
United Kingdom	0.723 (-2.62)	0.158 (2.71)**	0.605 (-2.73)	0.066 (5.48)***
United States	0.028 (-5.74)***	0.068 (2.18)**	0.712 (-2.43)	0.080 (5.90)***

NOTES: Data on total investment are taken from Summers and Heston [1991]. Data on producer durable investment is unpublished data provided by Robert Summers. The ADF Tests in this table include a time trend in the regression.

Table 4
Dynamic Regression Test of Accumulation-Based Models

Total Investment			Producer Durable Investment		
b_0	B(1)	Test Statistic	b_0	B(1)	Test Statistic
0.847	-0.0128	-0.40	0.926	-0.305	-2.63
0.763	-0.0288	-0.91	0.833	-0.312	-2.69
0.678	-0.0448	-1.40	0.741	-0.318	-2.74
0.593	-0.0608	-1.87	0.648	-0.325	-2.80
0.508	-0.0768	-2.31	0.556	-0.332	-2.85
0.424	-0.0927	-2.73	0.463	-0.339	-2.90
0.339	-0.1087	-3.11	0.370	-0.346	-2.95
0.254	-0.1247	-3.46	0.278	-0.353	-3.00
0.170	-0.1407	-3.78	0.185	-0.360	-3.05
0.085	-0.1567	-4.06	0.093	-0.367	-3.09
0.000	-0.1727	-4.32	0.000	-0.373	-3.14

NOTES: This table is based on the regression

$$g_{it} - b_0 i_{it} = \alpha_i + A(L)g_{it-1} + \tilde{B}(L)i_{it-1} + \epsilon_{it}, \quad B(L) = b_0 + \tilde{B}(L)$$

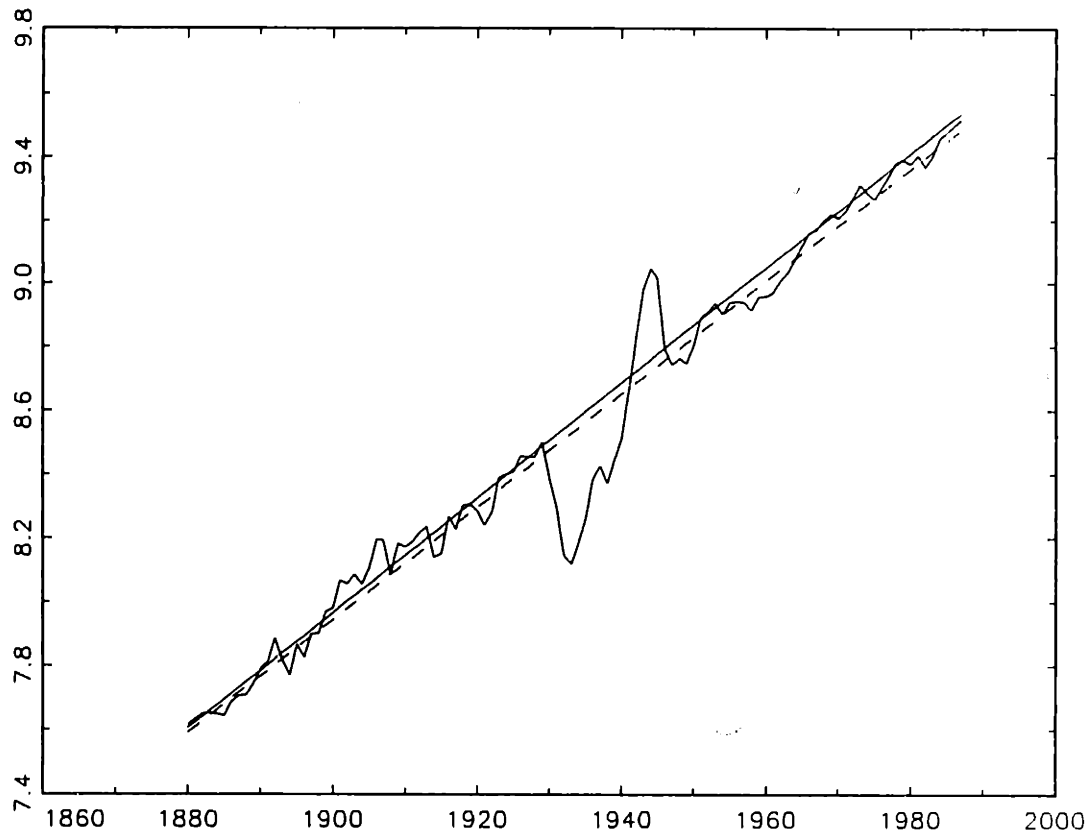
The coefficient b_0 is chosen at equal intervals in the range between zero and the OLS estimate .926. The table reports the sum of the coefficients B(1) as well as the t-statistic that this sum is equal to zero. When investment rates are $I(1)$, this t-statistic will have a nonstandard distribution (see text).

Table 5
Dynamic Response of Growth Rates to a 1% Point
Permanent Increase in the Investment Rate

Period (Year)	Total Investment			Producer Durables Investment		
	OLS Dynamic Response	OLS Cumulative Response	Maximum Bounds D.R.	OLS Dynamic Response	OLS Cumulative Response	Maximum Bounds D.R.
0	.802	.802	.802	1.020	1.020	1.020
1	-.013	.789	-.013	.167	1.186	.167
2	.030	.819	.030	-.222	0.965	-.222
3	.055	.874	.055	.263	1.228	.263
4	.081	.955	.089	-.012	1.216	-.012
5	.133	1.088	.237	-.015	1.201	-.011
6	.008	1.096	.075	-.026	1.175	-.012
7	-.008	1.088	.012	.009	1.184	.020
8	-.014	1.074	-.014	.005	1.189	.005
9	-.007	1.067	-.007	.001	1.190	.001
10	-.009	1.058	-.009	-.002	1.188	-.002
11	-.000	1.058	-.000	-.000	1.187	.000
12	.001	1.059	.004	.000	1.188	.001
13	.002	1.061	.011	.000	1.188	.000
14	.001	1.061	.006	-.000	1.188	-.000
15	.001	1.062	.003	-.000	1.188	-.000
16	-.000	1.062	-.000	-.000	1.188	.000
17	-.000	1.062	-.000	.000	1.188	.000
18	-.000	1.061	-.000	.000	1.188	.000
19	-.000	1.061	-.000	-.000	1.188	-.000
20	-.000	1.061	-.000	-.000	1.188	-.000

NOTES: The dynamic responses are calculated using regressions of growth rates on a country effect, a country-specific time trend, lagged growth rates, and current and lagged changes in the investment rates. The bounds identification technique described in the text is used to compute the maximum bounds dynamic responses. Growth and investment rate data are calculated using the Summers and Heston [1991] data for 1950-1988 as well as unpublished data provided by Robert Summers.

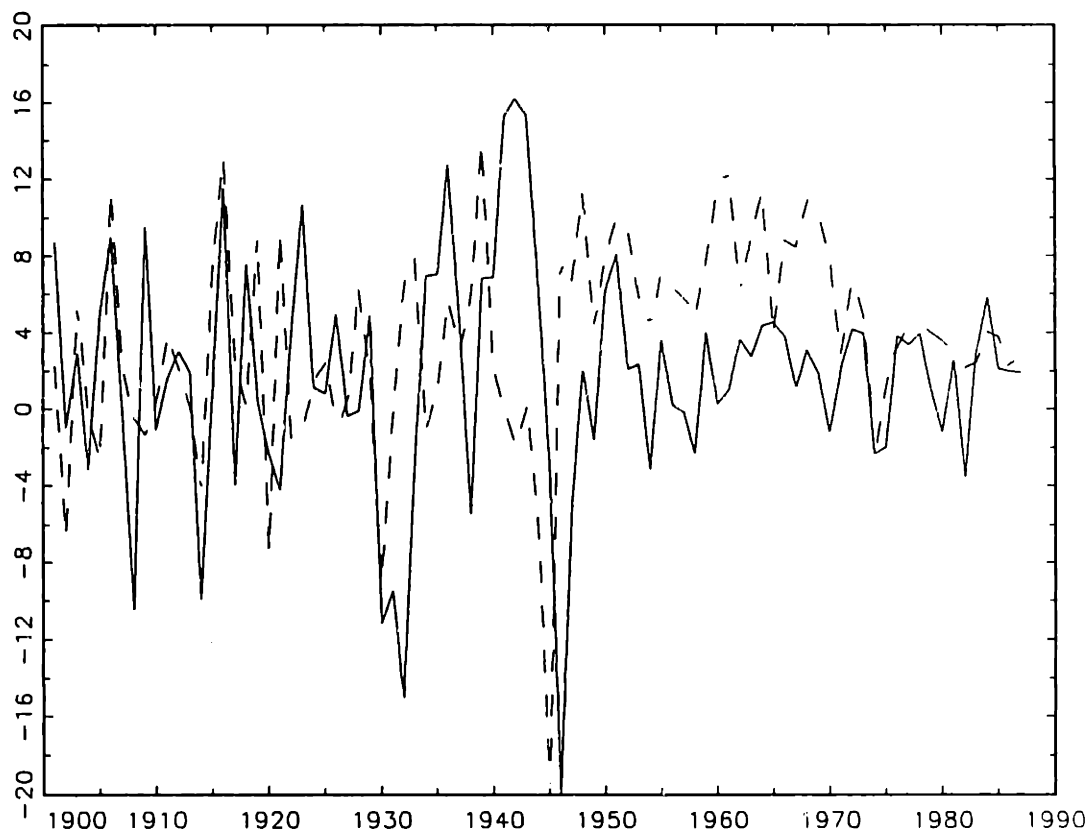
Figure 1
Per Capita GDP in the U.S.
1880 - 1987
(Natural Logarithm)



Source: The data are from Maddison [1982, 1989] as adjusted by Bernard [1991]. The solid trend line represents the time trend calculated using only data from 1880 to 1929. The dashed line is the trend for the entire sample.

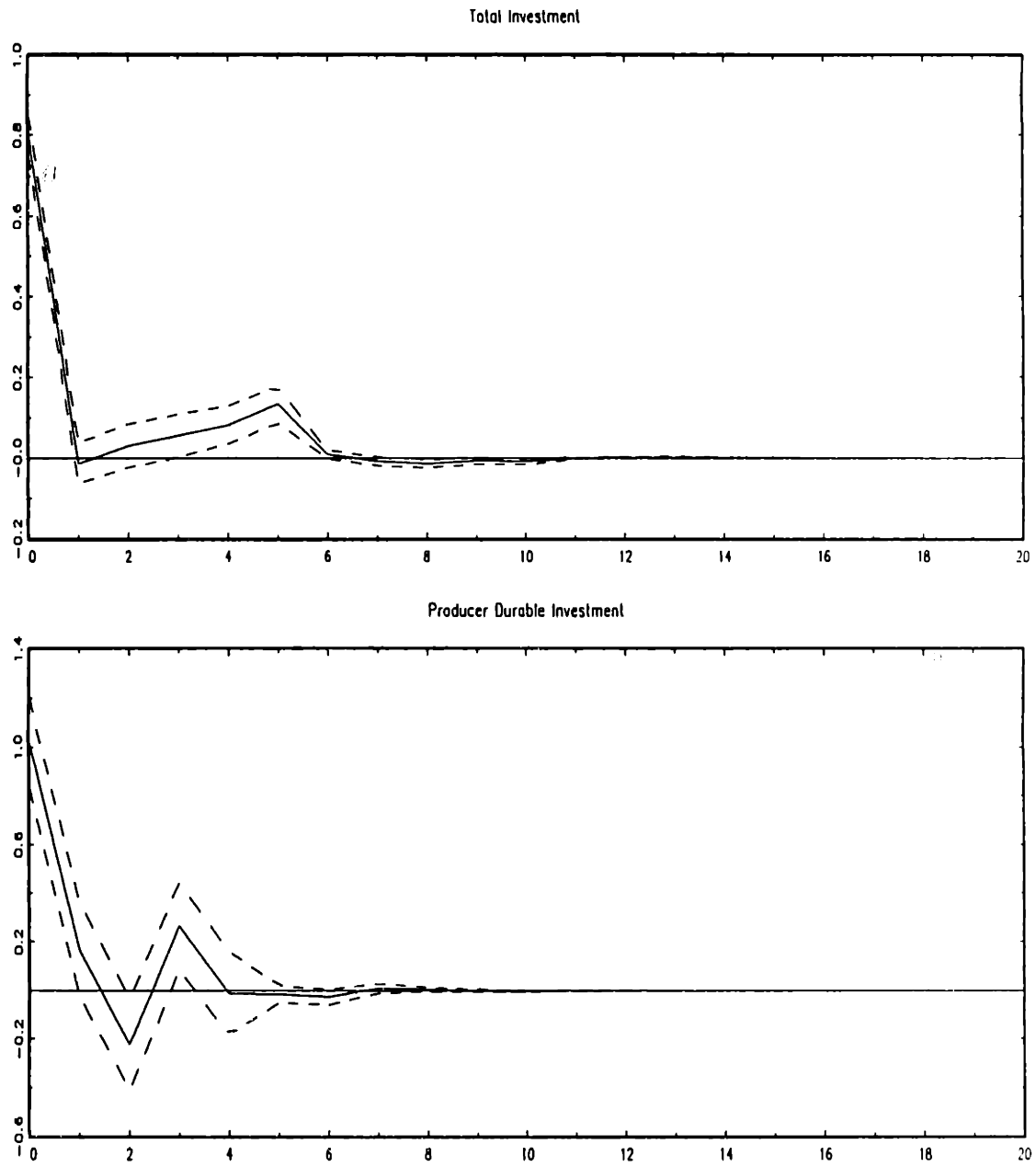
Figure 2

**Growth Rates for the U.S. (solid) and Japan (dashed)
1900 - 1987**



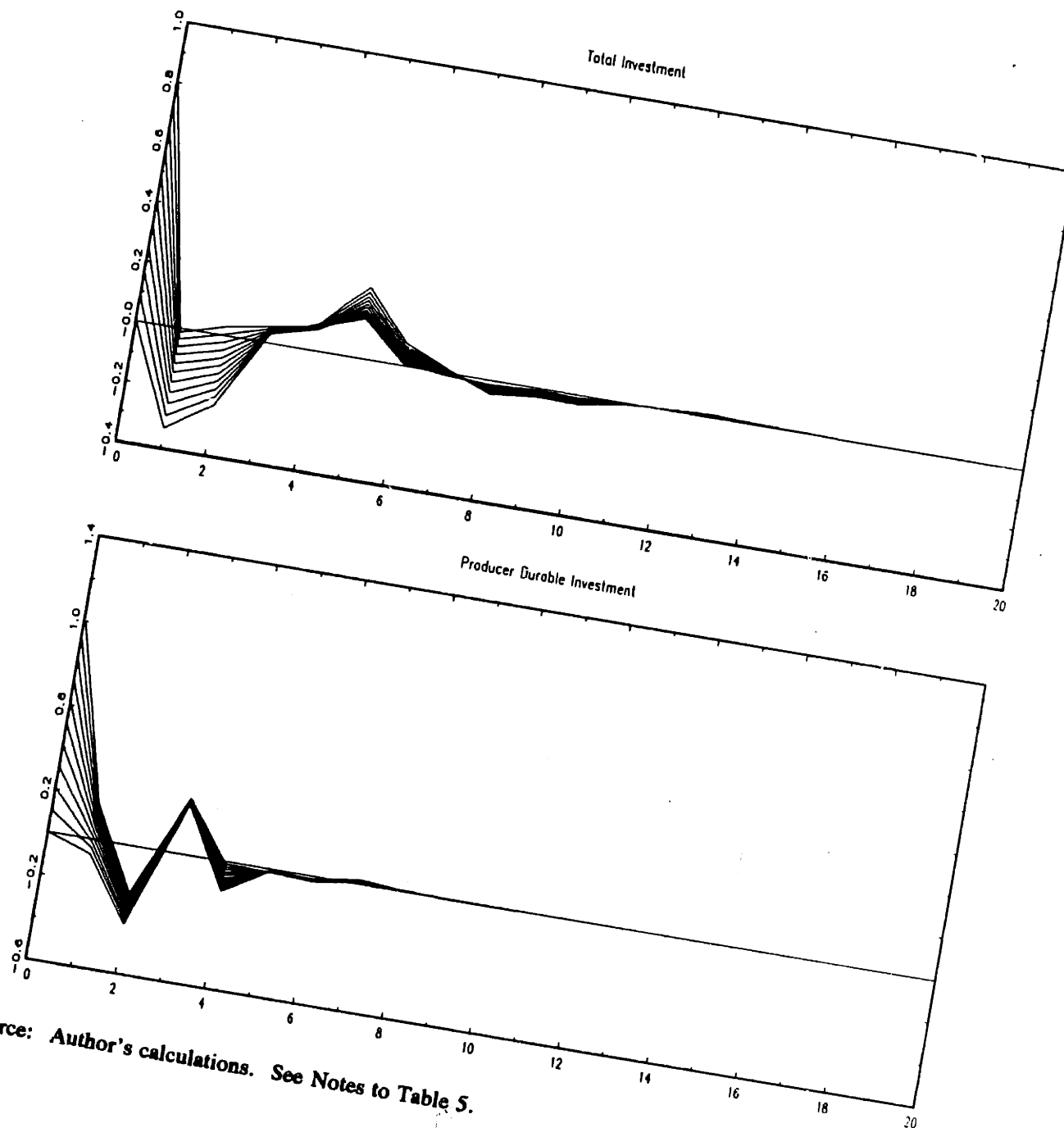
Source: The data are from Maddison [1982, 1989] as adjusted by Bernard [1991].

Figure 3
Dynamic Response of Growth Rates to a Permanent
1% Point Increase in the Investment Rate



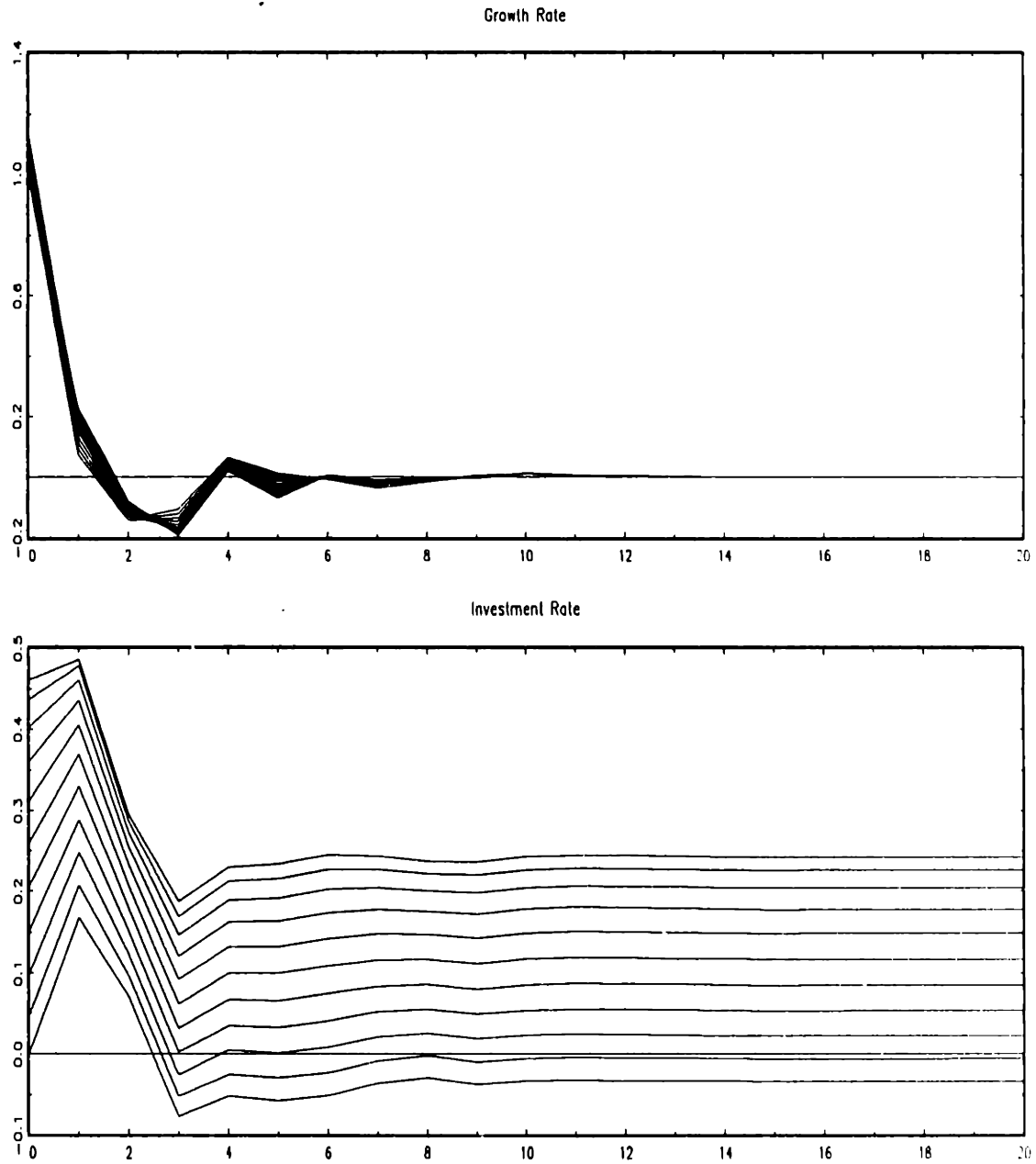
Source: Author's calculations. Dotted lines represent one standard error deviations computed using the delta method. See Notes to Table 5.

Figure 4
OLS Bounds:
Dynamic Response of Growth Rates to a Permanent
1% Point Increase in the Investment Rate

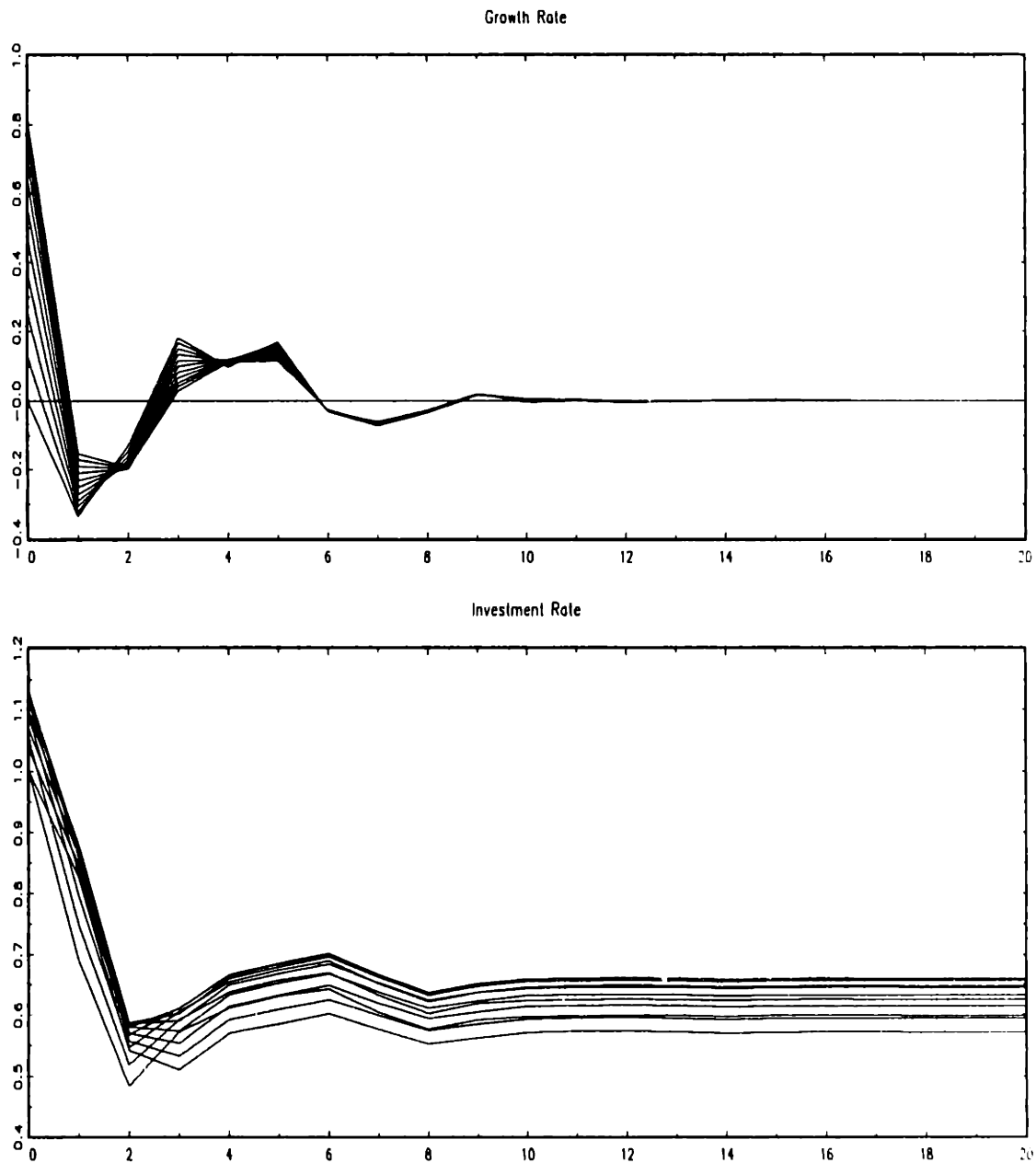


Source: Author's calculations. See Notes to Table 5.

Appendix Figure 1
Bounds Identification
Dynamic Response of Growth and Investment
Shock #1



Appendix Figure 2
Bounds Identification
Dynamic Response of Growth and Investment
Shock #2



Chapter 2

R&D-Based Models of Endogenous Growth

I. Introduction

The endogenous growth literature has produced two main alternatives to the standard Solow model, in which steady state growth is determined exogenously. The first alternative, pioneered by Romer [1986], generates endogenous growth through linearity in capital accumulation (the so-called "AK" models). Such models have been employed by numerous authors because of the simplicity with which they generate the result that policy can dictate the magnitude of long-run growth. The second alternative is the class of R&D-based growth models developed by Romer [1990], Aghion & Howitt [1992], and Grossman & Helpman [1991a,b,c]. In these models, growth is driven by technological change that results from the R&D efforts of profit-maximizing agents.

Jones [1993] proposed a general time series test of endogenous growth models and used this test to provide evidence against the "AK" style growth models. This paper continues that research by turning to the second class of models. Interestingly, the R&D-based models are readily shown to be inconsistent with time series evidence on growth rates. Together with the evidence in Jones [1993], this evidence constitutes an important criticism of the endogenous growth literature to date: neither class of models appears to be consistent with time series evidence. The remainder of this paper is then devoted to constructing a modified R&D-based model that is consistent with the stationarity of per capita growth rates. The modified model is noteworthy because, in contrast to the recent endogenous growth literature, it delivers Solow-like implications for long-run growth: even though growth arises endogenously within the model, the long-run growth rate depends only on parameters that are usually taken to be exogenous to policy manipulation.

Section II of the paper reviews the stationarity restriction and highlights an important problem with the recent R&D-based growth models of Romer [1990], Grossman and Helpman

[1991a,b,c], and Aghion and Howitt [1992] (which I will refer to in shorthand as the Romer/GH/AH models). These models share the prediction of "scale effects": a permanent increase in the level of resources devoted to R&D should permanently raise the growth rate. Section III then provides both time series and cross sectional evidence on the quantity of resources devoted to R&D. Various measures such as the number of scientists and engineers engaged in R&D for several OECD economies all exhibit a strong upward trend over time -- unit root tests suggest that the trend is stochastic so that these measures of R&D are integrated of order one. Combined with the stationarity restriction, these observations constitute direct evidence against the scale effects associated with the R&D-based models of Romer/GH/AH.

Section III proposes a simple modification of the Romer/GH/AH R&D-based models. The resulting model is consistent with the stationarity of per capita GDP growth and the nonstationarity of the level of resources devoted to R&D. The price of this consistency is the return to Solow-like predictions for long-term growth. Long-run per capita growth depends only on parameters that are usually taken to be exogenous and is therefore independent of policy changes such as subsidies to R&D or subsidies to capital accumulation. However, as in the Romer/GH/AH models (and in contrast to the Solow model), growth in the extended model arises endogenously through R&D. The steady state growth rate depends on the growth rate of inventions which in turn depends on the (exogenous) rate of population growth, reflecting an intuitive link between innovations and scientists: inventions require inventors. These results suggest a refinement of the term "endogenous growth." Growth in the model is endogenous in the sense that technological progress, which generates long-run growth, results from R&D undertaken by profit-maximizing agents. However, long-run growth is not endogenous, as it was in the "AK" models and in the Romer/GH/AH models, in the sense that policy changes have long-run growth effects.

Section IV discusses the welfare implications of the model as well as several possible

criticisms, and Section V concludes.

II. The R&D Equation

The models by Romer, Grossman and Helpman, and Aghion and Howitt focus on technological progress as the ultimate determinant of per capita growth. In these models, technological progress results from the search for new innovations, a search which is undertaken by profit-maximizing individuals. The discovery of a new innovation raises the productivity of other inputs such as capital and labor in the production of final goods, and such discoveries are ultimately the source of long-term growth.

The substance of these models can be summarized rather simply by the following two equations:

$$Y = K^{1-\alpha} (AL_y)^\alpha \quad (1)$$

$$\frac{\dot{A}}{A} = \delta L_A \quad (2)$$

where Y is output, A is productivity or knowledge, and K is capital. Labor is used in either of two activities, the production of output (L_y) or the search for new innovations (L_A) so that $L_y + L_A = L$ represents total labor in the economy. Following Romer/GH/AH, L is assumed to be constant.¹

Equation (1) is a standard production function with Harrod-neutral technological progress.

¹In some of their papers, Romer/GH/AH make the distinction between skilled labor H and unskilled labor L and assume that skilled labor is used in final output and in R&D while unskilled labor is used only to produce final output. Since the total amount of skilled and unskilled labor is assumed to be constant, this makes little difference in those models and in this paper. However, the distinction will most certainly be important in future research attempting to explore the microeconomic structure behind R&D in the context of growth models.

As argued in Romer [1990], the increasing returns to scale in this production function reflects the nonrivalrous nature of knowledge: given some level of knowledge A , doubling capital and labor inputs to production is sufficient to double output; no further increase in knowledge is required. For example, once Steve Jobs discovered how to combine labor and circuit boards to produce a personal computer, millions of additional computers could be produced with no additional innovation. The blueprints for the Apple computer could be duplicated at virtually zero cost so that only additional circuit boards and computer technicians were needed to permit an entire factory to produce Apple computers.

In the Romer/GH/AH models, the production of final output is usually written in terms of a collection of intermediate inputs that are themselves produced using capital. In these setups, A represents either the number of intermediate inputs (as in Romer [1990]) or the quality of the fixed number of intermediate inputs (as in Grossman and Helpman [1991a]). However, the reduced form of these models invariably takes a form similar to that in equation (1).²

The R&D equation in (2) is the heart of the Romer/GH/AH models. For the moment, we will defer motivating this specification and merely note that the Romer/GH/AH models assume that growth in total factor productivity is proportional to the number of individuals engaged in R&D. Since Romer/GH/AH assume that the size of the labor force is constant, the economy will be in steady state and follow a balanced growth path when the share of labor employed in R&D is constant. Along this balanced growth path, the capital-labor ratio and per capita output grow at the same rate,³ and these growth rates will be equal to the growth rate of

²This transformation is discussed in greater detail in Section III where a decentralized R&D-based model is written down and solved more formally.

³That capital and output grow at the same rate actually requires more discussion which is given in Section III. Intuitively, though, this result arises naturally when consumers are added to the model. The maximization of the present discounted value of a standard CRRA utility function leads to the familiar result that consumption growth depends on the rate of return to saving. Because of the Cobb-Douglas form of the production function, the rate of return in this

total factor productivity as is evident when equation (1) is written in per capita terms and log-differentiated. The steady state growth rate for this economy is then given by

$$\gamma_y = \gamma_A = \gamma = \delta s^* L \quad (3)$$

where s^* is the steady state share of labor devoted to R&D and L represents the total (constant) amount of labor in the economy.

In the Romer/GH/AH models, the steady state share of labor devoted to R&D is solved for explicitly in terms of the parameters of the model, and, not surprisingly, one of the key results is that subsidies to the R&D sector of the economy can increase the share of labor devoted to R&D and therefore increase the balanced path growth rate.

Equation (3) also illustrates that the size of the economy is a determinant of steady state growth. If the total amount of labor in the economy is doubled, the per capita growth rate of the economy will also double. Such "scale effects" have been emphasized in a series of papers by Rivera-Batiz and Romer [1991] and Grossman and Helpman [1991a] as examples of the way in which the integration of two economies, either indirectly through trade liberalization or more directly through formal channels, can result in an increase in the steady state rate of growth, provided these economies avoid the duplication of effort in R&D and focus on different innovations. One might expect to observe such scale effects in a cross-section of countries as well as over time. Issues of technology transfer complicate the interpretation of cross-sectional evidence, but time series evidence provides a natural test of this implication.

Empirical Tests of the Romer/GH/AH Models

The prediction of scale effects by the Romer/GH/AH models lends itself naturally to a

economy is proportional to the output-capital ratio, and since the rate of return must be constant along the balanced growth path, output and capital must grow at the same rate.

test developed in Jones [1993]. In that paper, I argued that the growth rate of per capita GDP in the U.S. economy exhibits a constant mean over the period 1900-1987. Augmented Dickey-Fuller tests strongly reject the hypothesis of a stochastic trend (a unit root) in the growth rates, and simple OLS regressions fail to detect a statistically-significant trend in U.S. growth rates. Also, tests for a single endogenously-determined mean shift using the methodology of Bai, Lumsdaine, and Stock [1991] fail to reject the null of a constant mean in U.S. per capita growth rates. Moreover, in the post-WWII data, similar results obtain for a sample of fifteen advanced OECD economies, except in a few countries for which a negative deterministic trend in growth rates is evident.^{4,5}

These observations led to the proposal of a stationarity restriction that could be used to test growth models. In its strongest form, the stationarity restriction applies to the U.S. experience and can be stated as follows: if a growth model predicts that permanent changes in some variable X have permanent effects on the growth rate of the economy, then either:

- (a) X must be stationary with no trend, or
- (b) some other variable (or variables) Z must also have permanent effects on growth that offset the movements of X . If X is integrated of order one, then Z must also be integrated of order one and X and Z must be cointegrated with a cointegrating vector that is determined by the growth model.

⁴These fifteen economies are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, Netherlands, Norway, Sweden, the United Kingdom, and the United States.

⁵The countries with a negative trend in post WWII data are Austria, France, Germany, Italy, and Japan, that is primarily those countries whose capital stocks were essentially destroyed during the war. These countries actually show a small upward trend in growth rates when data from 1900-1987 is employed as a result of the negative trend after World War II. Since the average growth rates of the 1970s and 1980s for these countries are similar to the average growth rates prior to World War II, one would not want to conclude that the stochastic process for growth rates in these countries involves a positive deterministic trend; rather, it appears that a more complicated nonlinear stochastic process may be at work because of transition dynamics.

Obviously, a similar restriction will hold for the advanced OECD economies during the post-World War II period, except X may also be declining.

For the Romer/GH/AH endogenous growth models, a natural choice for X is the level of the labor force. According to equation (3), a permanent increase in the labor force should lead in the long run to a permanent increase in the steady state per capita growth rate. If we are willing to ignore the issue of transition dynamics, a straightforward test of the Romer/GH/AH models could be conducted by testing for the stationarity of the level of the labor force. I will not burden the reader with formal test results at this point. The level of the labor force clearly exhibits a strong positive trend over the period 1950-1988 and is well described as a unit root process with positive drift.

At first pass, then, the Romer/GH/AH models do not perform well according to the stationarity restriction. These models predict that the steady state growth rate should be proportional to the level of the labor force, but the level of the labor force exhibits a strong positive stochastic trend whereas growth rates are essentially flat or even declining over the period 1950-1988. This argument is strengthened by noting that it is difficult to think of any variable(s) Z that could offset this effect. For example, investment rates, human capital investment, and openness to international trade all show upward trends over this period in many of the OECD economies, as argued in Jones [1993].

The intuition behind this argument carries through in more careful analysis. In particular, the argument as it stands ignores transition dynamics. While it is difficult to imagine that transition dynamics could offset the strong increase in the labor force from 1950-1988 due to population growth and increased participation rates, this is conceptually possible. To deal with this possibility and to provide more formal testing of the Romer/GH/AH models, we now apply the idea behind the stationarity restriction to equation (2), the R&D equation. By examining the stationarity of total factor productivity growth and various measures of the amount of labor

devoted to R&D, it is possible to test equation (2) explicitly. Assuming our measures of total factor productivity growth and labor devoted to R&D correspond to \dot{A}/A and L_A , this test will be valid even along the transition path.

Figure 1 displays the number of scientists and engineers engaged in R&D for France, Germany, and Japan since 1965, and for the United States since 1950.⁶ For each country, this measure of L_A shows a very strong upward trend. Since 1965, for instance, the number of scientists and engineers engaged in R&D in the U.S. has grown from about 500,000 to almost 1 million. For Japan, the growth has been even more striking: from about 120,000 in 1965 to over 400,000 by 1987, an increase of more than 300%. Table 1 confirms these casual observations by documenting the presence of strong upward trends in L_A for each country. Augmented Dickey-Fuller tests produce point estimates clustered around one indicating the presence of a unit root in L_A .

Figure 2 completes the analysis of the R&D equation by plotting total factor productivity growth rates for France, Germany, Japan, and the U.S.⁷ Negative trends are visible for TFP growth in France and Japan, while no distinct trend is evident for TFP growth in Germany and in the U.S. The bottom half of Table 1 provides the empirical support for these observations. The point estimates of time trend coefficients for TFP growth are uniformly negative (though only significant for France and Japan), except in the case of the manufacturing sector in the U.S.

⁶Data for France, Germany, and Japan are taken from the NSF's *Science and Engineering Indicators 1989*. For the U.S. the time series is taken from the *Statistical Abstract of the United States*, various issues. These countries are chosen purely on the basis of data availability. Data for the United Kingdom was available, but only for selected years.

⁷Aggregate TFP growth data are from the OECD Department of Economic and Statistics Analytic Database and were provided by Steven Englander. Other TFP growth data used in this paper includes measures for the private business sector and the manufacturing sector of the United States taken from the Bureau of Labor Statistics [1991]. Manufacturing TFP growth data for the other countries is taken from an updated version of the OECD Intersectoral Database, as prepared by Meyer-zu-Schlochtern [1988]. The manufacturing TFP growth rates are available beginning in 1971 for France, 1961 for Germany, and 1966 for Japan.

Augmented Dickey-Fuller tests strongly reject the null hypothesis that TFP growth has a unit root, and the point estimates of the AR(1) root are never larger than 0.5. The R&D equation central to the models of Romer/GH/AH, then, violates the stationarity restriction: TFP growth is stationary or even has a negative trend while the various measures of L_A consistently exhibit a unit root with strong positive drift.

Perhaps the most straightforward way to illustrate the failure of equation (2) is to consider a simple OLS regression of the form

$$\frac{\Delta A(t)}{A(t)} = \alpha + \delta L_A(t) + \epsilon(t) \quad (4)$$

Given the results concerning the stationarity restriction, one would expect to estimate a value of δ approximately equal to zero: L_A trends upward over time while TFP growth is either flat or declining, so that the implied coefficient is either zero or negative. Table 2 confirms this intuition. A regression of the form in (4) is estimated allowing for multiple lags (up to three) of the L_A variable to reflect the fact that R&D undertaken today may not have a productivity effect for several years.¹ The sum of the coefficients on L_A and its lags is reported to illustrate the long-run response of productivity growth to a change in the amount of resources devoted to R&D. The point estimates of this sum are generally negative, consistently small in magnitude, and predominantly insignificant as suggested by the violation of the stationarity restriction.

An important alternative specification of the R&D equation that, at least on the surface, maintains the key results of the Romer/GH/AH models without imposing scale effects assumes that TFP growth depends on the share of labor devoted to R&D rather than on the quantity:

¹Pakes and Schankerman [1984], for example, find gestation lags of about one or two years between R&D spending and patent applications.

$$\frac{\dot{A}}{A} = \delta \frac{L_A}{L} = \delta s \quad (5)$$

With a specification such as (5) it is easy to see that R&D drives TFP growth and that subsidies to R&D which increase s will raise the steady state growth rate. However, this specification is unsatisfactory for a number of reasons. First, equation (5) is inconsistent with the microfoundations of the R&D models developed by Romer/GH/AH. These microfoundations imply that ideas are discovered by individuals so that the number of ideas is inherently tied to the number of persons engaged in R&D. A specification devoid of scale such as (5) has the counterfactual implication that an economy with only one unit of labor can produce as many new ideas (or at least can generate equivalent TFP growth) as an economy with 1 million units of labor.

The empirical evidence against equation (5) is also compelling. Figure 3 graphs the share of labor devoted to R&D for France, Germany, Japan, and the U.S. and suggests that equation (5) will also violate the stationarity restriction: the share of labor devoted to R&D in these countries shows a strong positive trend in the post-War period. For example, the share grows from about 0.25% in the U.S. in 1950 to nearly 0.80% by 1988, and increase of over threefold. Tables 1 and 2 confirm the violation of the stationarity restriction more rigorously and support the hypothesis that increases in the R&D share of labor do not lead to permanent increases in TFP growth rates.

Discussion

The R&D equation assumed by the models of Romer [1990], Grossman & Helpman [1991a,b], and Aghion & Howitt [1990], is robustly contradicted by the empirical evidence for the simple reason that total factor productivity growth is either flat or declining since 1960 while

various measures of R&D all exhibit strong positive trends. Before continuing, however, several concerns should be addressed. The stationarity restriction, for example, is a valid test only if there are no omitted variables that are negatively cointegrated with the number of scientists and engineers engaged in R&D. Variables such as investment and openness are unlikely to help since these variables have been trending upward by most measures during the relevant period. However, the oil shocks of the early and late 1970s are a potential explanation. Unfortunately, these shocks are probably best thought of as one-time shocks to total factor productivity growth; oil prices surely do not exhibit a negative stochastic trend over this period. It is difficult to think of a Z variable with a sufficiently strong negative trend to offset the positive scale effects emphasized by the Romer/GH/AH models.

Another concern with the empirical work presented above is that R&D is likely to affect productivity only with a lag rather than contemporaneously as is assumed in the simple R&D-based growth models. This concern is mitigated somewhat by the fact that the unit root tests and time trend tests do not rely on the cross correlation between TFP growth and L_A but rather on the univariate properties of each of these series. To the extent that these properties hold for several years before and after the sample period, these tests will be valid.⁹

Finally, the appropriateness of the country as the unit of observation deserves some discussion. To the extent that technology diffuses quickly across international boundaries, testing the R&D equation country-by-country may produce misleading results. Perhaps the correct unit

⁹The lack of R&D data for the period 1940-1945, for instance, might be troubling. The U.S. certainly devoted vast quantities of resources to R&D, and the ideas that were generated might have productivity effects only after the turmoil of World War II ended. A large, unexploited stock of ideas left over from the war should produce a high but declining TFP growth rate in post-WWII years. Together with a rising number of scientists and engineers devoted to R&D after the war, the net effect might be a flat TFP growth rate even if the Romer/GH/AH specification were true. However, since most of the analysis in this paper begins in 1960 or 1965, i.e. fifteen to twenty years *after* the war, and since the measures of L_A rise so dramatically by the 1980s, it is hard to believe this effect is driving the results.

of analysis is the entire OECD or even the world instead of an individual country. However, even if we were to accept this criticism and treat France, Germany, Japan, and the United States together as a single entity, the results would remain unchanged. The various measures of L_A have a strong positive trend for each of these countries so that a weighted sum will also exhibit a strong upward trend. It is difficult to imagine how this result would be overturned by including additional countries since the majority of world R&D is almost certainly undertaken in these four countries.

The results from this section, then, strongly call into question the assumption that R&D and total factor productivity growth are related by the R&D equation of Romer/GH/AH. The scale effects implied by this specification are not present in the time series evidence, suggesting that the qualitative results of these models are potentially misleading.

At this point, the endogenous growth literature appears inconsistent with time series evidence documenting the lack of an increase in per capita growth rates. Both the "AK"-style models and the R&D-based models are rejected by this evidence, and the latter very strongly so. These models could be salvaged by appealing to an exogenous decline in productivity -- a negative Solow residual -- but this type of ad hoc argument is intellectually unpleasant. Instead, the remainder of this paper proposes a modification to the R&D-based models that reconciles the stationarity of growth rates with the nonstationarity of resources devoted to R&D.

III. An R&D-Based Model of Growth Without Scale Effects

The R&D Equation Revisited

Consider once again the specification of the R&D equation. How does R&D affect productivity growth? Following Romer/GH/AH, define A to be the stock of knowledge or technology in an economy. Knowledge is simply the accumulation of ideas, and ideas are

developed by people. In the simplest model, then, the change in knowledge \dot{A} will be equal to the number of people attempting to discover new ideas multiplied by the rate at which R&D generates new ideas:

$$\dot{A} = \bar{\delta} L_A \quad (6)$$

Such a specification could be given microfoundations by appealing to a Poisson process governing the arrival rate $\bar{\delta}$ when the scientist searches for new ideas.

We might expect the rate at which scientists discover new ideas to be a function of the amount of knowledge in the economy. For instance, if there are increasing returns to the accumulation of knowledge, $\bar{\delta}$ would be increasing in the level of A . The discovery of calculus, the invention of the transistor, and the creation of semiconductors are all examples of major innovations that most likely raised the productivity of the scientists who followed. Alternatively, perhaps the most obvious ideas are discovered first so that the probability that a person engaged in R&D discovers a new idea is decreasing in the level of knowledge.¹⁰ Parameterizing the arrival rate $\bar{\delta}$,

$$\bar{\delta} = \delta A^\phi \quad (7)$$

In this equation, $\phi < 0$ corresponds to the case referred to in the productivity literature as "fishing out" in which the rate of innovation decreases with the level of knowledge, and $\phi > 0$ corresponds to the positive external returns case. A value of $\phi = 0$ represents the useful benchmark of constant returns to scale (zero external returns) in which the arrival rate of new ideas is independent of the stock of knowledge. Notice that these effects will be external to the individual scientist so that ϕ measures the degree of externalities across time in the R&D process.

¹⁰Alternatively, one might believe that the productivity value of new ideas is increasing in the stock of knowledge. This leads to an identical specification of the R&D equation.

Finally, consider the possibility that at a point in time the duplication and overlap of research reduces the total number of innovations produced by L_A units of labor. That is, suppose that it is not L_A but rather L_A^λ where $0 < \lambda \leq 1$ that belongs in the R&D equation. Incorporating this change into (6) and (7) yields the R&D equation:

$$\dot{A} = \delta L_A A^\phi l_A^{\lambda-1} \quad (8)$$

where $l_A = L_A$ in equilibrium, but l_A captures the externalities occurring because of duplication in the R&D process.¹¹ When $\phi = 1$ and $\lambda = 1$, this equation reduces to the R&D equation assumed in the Romer/GH/AH models.¹²

One might add other features to the basic specification of the R&D equation in (8). For instance, perhaps computers and other forms of capital play a complementary role in the discovery of knowledge in which case capital belongs in the R&D equation. Since the main results are robust to such changes, we will omit capital from the R&D equation.

In part, this discussion is meant to demonstrate that the assumption of $\phi = 1$ in the Romer/GH/AH models is arbitrary.¹³ An assumption of $\phi = 0$ might actually seem most natural since, as Romer [1990] argues, whether there are increasing or diminishing returns to R&D is in part a philosophical question. One might possibly make a plausible case for increasing returns

¹¹The incorporation of $\lambda < 1$ need not reflect externalities. For example, perhaps the addition of labor into the R&D process at a point in time requires the use of less skilled scientists. However, for the modelling purposes below, λ will be assumed to measure duplication externalities.

¹²Similar specifications have been considered elsewhere but have not been emphasized as plausible models of long-run growth. Grossman and Helpman [1991a] consider a specification analogous to (8) in which the size of the population is held fixed and note that per capita growth dies out asymptotically for the case considered below. Judd [1985] employs a specification with $\phi = 0$ to discuss the effects of patents on innovative activity.

¹³Of course, it is an important assumption from the standpoint of these models in that it generates "endogenous" growth in the traditional sense.

to R&D so that ϕ is greater than zero. However, $\phi=1$ produces a completely arbitrary degree of increasing returns and, as was shown in the previous section, is inconsistent with a broad range of time series data on R&D and total factor productivity growth. In what follows, we will impose the restriction $\phi < 1$ and show that this justifiable assumption leads to a model in which a balanced growth path is consistent with an increasing number of persons devoted to R&D.¹⁴

The Decentralized Model

Relaxing the assumption of $\phi=1$ in the Romer/GH/AH models generates a balanced growth path in the presence of an increasing labor force. To see this, rewrite equation (8) in terms of productivity growth to get:

$$\frac{\dot{A}}{A} = \delta \frac{L_A l_A^{\lambda-1}}{A^{1-\phi}} \quad (9)$$

Along the balanced growth path, total factor productivity growth is constant by definition. This will be consistent with an increasing labor force engaged in R&D provided L_A^λ and $A^{1-\phi}$ grow at the same rate, a restriction that will naturally tie down the growth rate of total factor productivity. In each of the Romer/GH/AH models, this or a similar strategy is sufficient to eliminate the scale effects. Using this simple insight, we now turn to a formal decentralized model.

Because the production function in equation (1) exhibits increasing returns to scale, the usual perfectly competitive setup cannot be used to solve for the decentralized solution. This

¹⁴An earlier version of Kremer [1992] followed Romer and focused on the R&D equation given in equation (2) that is rejected in the empirical work here (the $\phi=1$ case). That paper discusses growth over the very long run, i.e. back to 1 million B.C., but had trouble explaining growth in the twentieth century. After reading an earlier version of this paper, Kremer revised his work to focus on the case of $\phi < 1$. In light of the empirical evidence discussed earlier, it is not surprising that his revised results are consistent with twentieth century experience. More generally, the revised Kremer [1992] provides favorable evidence for the case of $\phi < 1$ including cross-sectional evidence supporting the basic link between the level of the population and the creation of knowledge.

observation motivates the different approaches taken by Romer [1990], Grossman and Helpman [1991a], and Aghion and Howitt [1990], and these models differ primarily in the way they choose to deal with increasing returns. Because of the specific nature of the Romer/GH/AH models, it is easiest to demonstrate the balanced growth path using the structure of Romer [1990], and we will follow his setup closely.¹⁵ In this model, the economy consists of three sectors. First, a final goods sector produces the consumption/capital good using labor and a collection of producer durables as inputs. Second, a collection of monopoly firms in the intermediate goods sector transforms capital into producer durables using designs discovered by the third sector, the R&D sector. In the R&D sector, individuals take advantage of the existing stock of knowledge, A , to invent new designs for producer durables and sell these designs to the intermediate sector. In this framework, the stock of knowledge corresponds to the subset of the real line denoting the producer durables for which designs have been invented. Each of the three sectors will be considered in turn.

The final goods sector produces the consumption good Y using labor L_Y and a collection of intermediate inputs x with a constant returns to scale technology:

¹⁵In the models of Grossman and Helpman [1991b] and Aghion and Howitt [1990], the specific method used here to relax the assumption that innovations increase productivity proportionally will not generate a closed form solution because of the functional form assumptions in those models. However, I conjecture that a closely-related method will work. Instead of reducing the effect of an innovation on productivity, one can let the amount of labor required to discover a new innovation grow with the level of productivity. To see the merit of this approach, consider a simple analogy. If the discovery of knowledge is thought of as climbing a ladder in which each rung is a new innovation, then the first method (the one used in this paper) corresponds to reducing a climber's vertical speed (measured in feet, not rungs, per unit of time). The second method corresponds to widening the space between each rung by ever-increasing amounts while keeping vertical speed constant. Both have the effect of making the ladder more difficult to climb. I thank Robert Barro for this insight.

$$Y = L_Y^\alpha \int_0^A x_i^{1-\alpha} di \quad (10)$$

This production technology characterizes technological change as increasing variety, in the tradition of Ethier [1982] and Dixit and Stiglitz [1977]. Invention corresponds to the discovery of a new variety of producer durable that provides an alternative way of producing the final consumer good. In this way, the fatal onset of diminishing returns is continually postponed by the creation of new inputs. It is worth noting that while this functional form is a useful theoretical device for introducing technological change in a decentralized model that yields a balanced growth path, it is by no means the only such device. Grossman and Helpman [1991a] and Aghion and Howitt [1990] provide a range of alternatives.

Since final goods production is CRS, we can without loss consider a single price-taking firm when solving for the competitive outcome. Normalizing the price of Y to unity in every period, profit maximization yields the following conditional demand functions:

$$w = \alpha \frac{Y}{L_Y} \quad (11)$$

$$p_i = (1-\alpha)L_Y^\alpha x_i^{-\alpha} \quad \forall i \quad (12)$$

where w represents the wage paid to labor in the final goods sector and p_i is the rental price of producer durable i .

The intermediate sector is composed of an infinite number of firms on the interval $[0, A]$ which have purchased a design from the R&D sector and now act as monopolists in the production of their particular variety of producer durable. Capital is rented at rate r for the period, and a firm which has purchased a design can then transform each unit of capital into η

units of the producer durable. We assume for simplicity that producer durables can be transformed costlessly back into capital at the end of the period and that no depreciation takes place. Each of the intermediate firms, then, solves the following problem every period:

$$\max_x p(x)x - r\eta x \quad (13)$$

Since these firms are monopolists, they see the downward sloping demand curve for their producer durables generated in the final goods sector. Substituting from equation (10), the monopolist's problem can be written as:

$$\max_x (1-\alpha)L_Y^\alpha x^{1-\alpha} - r\eta x \quad (14)$$

This is a standard monopoly problem with constant marginal cost and constant elasticity of demand, and it is readily solved to yield the following equations for price, quantity, and profit π :

$$\bar{p}_i = \bar{p} = \frac{r\eta}{1-\alpha}, \quad \forall i \quad (15)$$

$$\bar{x}_i = \bar{x} = \left(\frac{(1-\alpha)L_Y^\alpha}{\bar{p}} \right)^{1/\alpha}, \quad \forall i \quad (16)$$

$$\bar{\pi}_i = \bar{\pi} = \alpha \bar{p} \bar{x} = \alpha(1-\alpha) \frac{Y}{A}, \quad \forall i \quad (17)$$

These equations demonstrate that each intermediate firm sets the same price and sells the same quantity of its producer durable. Using this observation and the fact that the total stock of producer durables is related to the capital stock by

$$K = \eta \int_0^1 \bar{x} di = \eta A \bar{x} \quad (18)$$

the production function for the final goods sector can be written in the form given previously in equation (1):

$$Y = \eta^{\alpha-1} (AL_Y)^{\alpha} K^{1-\alpha} \quad (19)$$

Furthermore, these last two equations can be combined with equations (12) and (17) to yield an expression for the rental rate for capital:

$$r = (1-\alpha)^2 \frac{Y}{K} \quad (20)$$

Finally, consider the production of new designs in the R&D Sector. We assume that labor engages in R&D to search for new designs and succeeds according to the specification in equation (8). Any individual is allowed to enter the R&D sector and prospect for new designs, so that this sector makes zero profits under the free entry condition. The upstream decision by intermediate firms to produce a producer durable hinges on the difference between the cost of purchasing the patent from the R&D sector, P_A , and the monopoly rents that can be obtained in exchange. With this knowledge, the monopolistically competitive R&D sector sets the price P_A to extract the present discounted value of the intermediate sector's monopoly profit. Since all durables yield the same profit in every period, all designs, regardless of age, trade for the same price P_A at a point in time. Then, the following simple arbitrage equation must hold:

$$r = \frac{\bar{\pi}}{P_A} + \frac{\dot{P}_A}{P_A} \quad (21)$$

This equation says that the R&D sector charges a price for its designs that is just sufficient to

make the intermediate monopolists indifferent between purchasing the design to produce the durable good and not undertaking any production at all. The dividend rate π/P_A and the capital gain exactly meet the required rate of return on investment r .

Equations (9) through (21) characterize the production side of the economy. To close the model, we must also characterize the consumption/labor decisions. Following the usual convention, we will assume that these decisions can be characterized by a representative consumer maximizing an additively separable utility function subject to the standard constraints:

$$\begin{aligned} \max_{c,} \quad & \int_0^{\infty} e^{-\rho t} u(c_t) dt \\ \text{s.t.} \quad & \\ & \dot{k} = rk + w + i - c - nk \end{aligned} \tag{22}$$

where c is per capita consumption, k is per capita wealth holdings in the form of capital, and i represents income per capita resulting from the profits of the intermediate firms. In the perfect foresight equilibrium, consumers take the time paths of r , w , and i as given. Note that the budget constraint makes use of the fact that each consumer, who is endowed with a single unit of labor that is inelastically supplied, must receive the same payment w in return for supplying labor whether the labor works in the final output sector or in the R&D sector. Since anyone engaged in research can take advantage of the existing stock of designs to produce new designs, this requires

$$w = P_A \delta A^* L_A^{\lambda-1} \tag{23}$$

Assuming the utility function $u(\cdot)$ in (22) exhibits constant relative risk aversion equal to σ , the first order condition for the consumer's problem can be written as:

$$\frac{\dot{c}}{c} = \frac{1}{\sigma}(r - \rho - n) \quad (24)$$

Equilibrium and Balanced Growth in the Decentralized Model

In the perfect foresight equilibrium of the decentralized model, all agents take as given the time paths of variables that they do not control: consumers take the time paths of wages and interest rates as given; labor working in the R&D sector takes the stock of knowledge A as given; intermediate goods producers take the price of designs and the demand for producer durables as given; etc. Equilibrium is then characterized by the condition that supply equals demand for all relevant quantities.

At this point we restrict our attention to the perfect foresight equilibrium balanced growth path, also referred to as the steady state. The balanced growth path equilibrium will be defined as the perfect foresight equilibrium in which the growth rates of all variables in the model are constant. To solve for this equilibrium notice that from equation (24), a constant growth rate for per capita consumption requires a constant rate of return to capital. Then, by equation (20), the rate of return to capital will only be constant when output and capital (and therefore their per capita levels) grow at the same rate, which we will call γ . To show that per capita consumption also grows at rate γ in the steady state, consider the budget constraint in (22). The profits from firm ownership in per capita terms are equal to

$$i = \frac{1}{L} \left[\int \pi di - P_A \dot{A} \right] \quad (25)$$

where the first term reflects the profits of firms that have purchased a design and the second term nets out the purchase of new designs. Because of free entry, the R&D sector makes zero profits so that the revenue from new design sales must be equal to payments to labor employed in R&D. Using this fact, the budget constraint in (22) can be rewritten as

$$\dot{k} = \frac{1}{L} [rK + wL_Y + A\bar{\pi}] - c - nk \quad (26)$$

Each of the terms in brackets is proportional to total output Y , as is clear from equations (20), (11), and (17), and in fact these expressions sum exactly to Y so that

$$\dot{k} = y - c - nk \quad (27)$$

Dividing this expression by k , the ratio of c to k must be constant along the balanced growth path since the output-capital ratio is constant. Per capita consumption, the capital-labor ratio, and output per capita must then all grow at the same rate γ in steady state.

Finally, let us conjecture that the share of labor devoted to R&D will be constant along the balanced growth path, a reasonable assumption that will be confirmed later. In this case, the production function for the final goods sector in equation (19) can be differentiated to yield:

$$\gamma_y = \alpha \gamma_A + (1-\alpha) \gamma_k \quad (28)$$

where γ_x denotes the growth rate of variable x and lower case variables are written in per capita terms. Then, since the capital-labor ratio and output per capita grow at the same rate, (28) implies that the level of productivity also grows at this same rate. Differentiating both sides of equation (9), together with this condition, allows us to solve explicitly for the balanced path growth rates:

$$\gamma_y = \gamma_c = \gamma_k = \gamma_A = \gamma = \frac{\lambda n}{1-\phi} \quad (29)$$

Equation (29) states that the growth rate of the economy in the steady state depends only on the growth rate of the labor force and the parameters ϕ and λ , which determine the external returns (as well as the returns to scale) in the R&D sector. Notice that if we follow

Romer/GH/AH and assume $\phi = 1$, no balanced growth path exists in this economy because L is growing. Assuming $\phi < 1$ eliminates the devastating scale effects of the Romer/GH/AH model, and these scale effects are replaced by an intuitive dependence on the *growth rate* of the labor force rather than on its *level*. To see this intuition, consider the case in which $\phi = 0$ and $\lambda = 1$ so there are no externalities to R&D. In this case, the rate of innovation is independent of the stock of knowledge so that

$$\dot{A} = \delta L_A \quad (30)$$

If the labor force engaged in R&D were constant, the constant number of new innovations in each period would constitute a decreasing percentage of productivity over time. When there is very little knowledge in the economy, a new idea has a dramatic effect in percentage terms on the total amount of knowledge. However, once the economy has accumulated a large stock of knowledge, each new idea has only a small impact in percentage terms. If the number of new ideas is constant over time, then eventually the percentage increment in knowledge due to new ideas will go to zero. Growth will cease asymptotically.

Now suppose that instead of being constant, the labor force grows at some exogenous rate n . In the case of $\phi = 0$, the number of new ideas is also growing at rate n . For this to generate a balanced growth path, though, the number of new innovations must always represent a constant fraction of the stock of knowledge. But this is just another way of saying that the number of new innovations and the stock of knowledge must grow at the same rate. Since the number of new innovations is proportional to the labor engaged in R&D, the growth rate of productivity is then

inextricably tied to the growth rate of the labor force. This is the intuition behind equation (29).^{16,17}

It is also important to note what does *not* determine steady state growth in this model. Steady state growth is invariant to government tax policy, including investment tax credits and R&D subsidies. This result is immediately obvious from the derivation of equation (29). That equation hinges on taking logs and differentiating both sides of equation (9), which will necessarily be independent of a constant subsidy or tax. Therefore, such taxes and subsidies will never have growth effects in this model.

These results contrast sharply with the results of the Romer/GH/AH models in which the steady state growth rate depends endogenously on policy variables such as subsidies to R&D. This endogeneity hinges critically on the assumption that $\phi = 1$, which is strongly rejected by the time series evidence on TFP growth and R&D. Once this assumption is relaxed to generate results consistent with the time series evidence, the implications of the Romer/GH/AH models change substantially. Long run growth in the extended model depends only on population growth and the degree of external returns to R&D, parameters that are typically assumed to be

¹⁶The prediction that per capita growth depends on the growth rate of population can be found in Arrow [1962], but for a different reason. In that model, externalities to capital accumulation lead to increasing returns to scale in production, as in

$$Y = K^{\alpha+\beta} L^{1-\alpha}, \quad 0 < \alpha < 1, \quad 0 < \beta < 1$$

Romer [1986] showed that with constant population and sufficiently strong externalities so that $\alpha + \beta = 1$, growth would not cease asymptotically. As in the R&D models, however, population growth in this "AK" model will cause growth rates to increase without bound. The Arrow [1962] model has $\alpha + \beta < 1$ so that the steady state rate of per capita output growth is proportional to population growth. In this sense, the present paper relates to the Romer/GH/AH papers in the same way that Arrow [1962] relates to Romer [1986].

¹⁷This result is found in a similar setting in Nordhaus [1969]. I thank Sam Kortum for this reference.

exogenous.¹⁸

Some algebraic manipulation of the equations in the decentralized model then confirms that the share of labor devoted to the R&D sector is indeed constant along the balanced growth path and given by:

$$\begin{aligned} s^{DC} &= \frac{L_A}{L} = \frac{1}{1+\psi^{DC}}, \\ \psi^{DC} &= \frac{1}{1-\alpha} \left[\frac{\rho(1-\phi)}{\lambda n} + \sigma \right] \end{aligned} \tag{31}$$

According to this equation, the steady state share of labor devoted to R&D depends on several parameters within the model. A higher steady state growth rate $\lambda n/(1-\phi)$ is associated with a larger share of labor in R&D. A lower rate of time preference or a higher intertemporal elasticity of substitution (a lower σ) also leads to an increase in the share of labor devoted to R&D along the balanced growth path. An increase in the average number of ideas per person engaged in R&D, δ , will have no effect on the labor share of the R&D sector, but it is easy to show that a wage subsidy to labor engaged in this activity will in fact increase the share of labor devoted to R&D.¹⁹

IV. Welfare and the Social Planner Problem

To gauge the welfare properties of the decentralized solution, consider the social planner

¹⁸Kremer [1992] extends the results in this paper by allowing the level of population to be determined endogenously in a Malthusian way by the level of output.

¹⁹If ξ is the rate of the proportional wage subsidy to R&D, then the steady state share of labor in R&D will be given by

$$s^{DC} = \frac{1}{1+\psi^{DC}}, \quad \psi^{DC} = \frac{\psi^{DC}}{(1+\xi)}$$

formulation of this growth model. A representative consumer solves

$$\max_{c, L_A} \int_0^{\infty} e^{-\rho t} u(c_t) dt, \quad c = \frac{C}{L} \quad (32)$$

subject to the following constraints:

$$\dot{K} = \eta^{\alpha-1} (AL_Y)^{\alpha} K^{1-\alpha} - C \quad (33)$$

$$\dot{A} = \delta L_A^{\lambda} A^{\phi} \quad (34)$$

$$L_A + L_Y = L, \quad \frac{L}{L} = n \quad (35)$$

Setting up the usual Hamiltonian and solving this program reveals that growth in the steady state is given once again by

$$\gamma_y = \gamma_c = \gamma_k = \gamma_A = \gamma = \frac{\lambda n}{1-\phi} \quad (36)$$

Thus, growth in the decentralized model is socially optimal, despite the presence of externalities in the R&D sector and monopoly behavior in the model.

In the social planner formulation, the share of labor devoted to R&D along the balanced growth path is affected by the externalities and the imperfect competition. The socially optimal share of labor is given by

Comparing this solution to the decentralized solution in equation (31), the share of labor devoted to R&D in steady state differs from the socially optimal share for three reasons. First, the presence of an additional "- ϕ " term in the social optimum reflects the incorporation of the externalities to R&D. When these externalities are positive, too little R&D is undertaken in the

$$s^{sp} = \frac{L_A}{L} = \frac{1}{1+\psi^{sp}}, \quad (37)$$

$$\psi^{sp} = \frac{1}{\lambda} \left[\frac{\rho(1-\phi)}{\lambda n} + \sigma - \phi \right]$$

decentralized solution because agents do not take into account the increase in the value of future R&D that their discoveries impart. On the other hand, if there are diminishing returns to R&D so that ϕ is negative, there may actually be too much R&D in the decentralized equilibrium.

Second, the parameter λ enters the socially optimal share of labor in R&D reflecting the externalities at a point in time due to the duplication of research. The presence of $\lambda < 1$ will, other things equal, cause the decentralized economy to overinvest in R&D because of the negative externality.

Finally, the decentralized share of labor in R&D differs from the social optimum because of the monopoly markup over marginal cost in the sale of producer durables to the final sector, reflected by the presence of $1/(1-\alpha)$ in equation (31). This effect unambiguously causes too little labor to be devoted to R&D along the balanced growth path in the decentralized model. Note that if there are no external returns in the R&D equation so that ϕ is zero and λ is one, this is the only effect present so that R&D is too low in equilibrium. Since taxes and subsidies to R&D can affect this share, there is room in this model for tax policy to be welfare improving. Whether or not the appropriate policy is a tax or a subsidy, though, generally depends on the sign of ϕ and the magnitude of λ .

Figure 4 plots the difference between the socially optimal share of labor in R&D and the share devoted to R&D by the decentralized economy in steady state. Parameter values for this calibration exercise are $\alpha = .7$, $\rho = .03$, $n = .017$, and $\sigma = 1$. The parameter ϕ is allowed to take on values in the range $[-1, 1]$ and λ takes values in the range $(0, 1]$. The most surprising result of this exercise is that for nearly all of these parameter values the decentralized economy

underinvests in R&D. For example, even when $\phi = -1$ and $\lambda = .5$ so that there are large negative externalities to the R&D process (both at a point in time and across time), the decentralized economy underinvests in R&D. The reason is that for plausible parameter values, the monopoly effect in this model dominates the negative externalities.

This effect is documented more carefully in Figure 5 which plots the gap between s^{SP} and s^{DC} as a function of ϕ and α for λ in $\{1.00, .75, .50, .25\}$. Even if $\lambda = .5$, relatively low labor shares (below $\alpha = .6$) are required to generate overinvestment in R&D. Alternatively, values of λ of .25 or below can generate overinvestment in R&D, as shown in the last panel of Figure 5.

Together, Figures 4 and 5 suggest that the decentralized economy underinvests in R&D relative to the social optimum for plausible values of α and that this feature of the model is relatively insensitive to the parameters ϕ and λ . This perhaps surprising result suggests that the interaction between market structure and patents is possibly more important than the degree of externalities in the R&D process itself. This aspect of the model has not been explored carefully in the endogenous growth literature, but the evidence here highlights it as important for future research.

V. Conclusion

Using a simple test driven by the stationarity of per capita GDP growth rates, this paper has argued that both the recent R&D-based models of endogenous growth are inconsistent with time series evidence. The R&D models of Romer [1990], Grossman & Helpman [1991a,b], and Aghion & Howitt [1990] predict that TFP growth should be monotonically increasing in the amount of labor devoted to R&D, generating the presence of "scale effects." In fact, TFP growth is stationary or even declining in France, Germany, Japan, and the United States during the post-WWII period despite the tremendous increase in the number of scientists and engineers employed in R&D in all of these countries.

The R&D-based model of growth outlined in the second half of the paper produces a number of interesting and appealing results that are consistent with empirical observation. First, unlike the "AK" style models and the R&D models of Romer/GH/AH, this model predicts that the growth rate is determined by parameters that are exogenous and not subject to policy manipulation. Growth in the economy is tied directly to growth in productivity which in turn depends on the discovery of new designs through research and development. Since individuals are the critical input into the discovery of new designs, the growth rate of productivity and hence the growth rate of the economy depends crucially on the growth rate of the labor force, an exogenous variable. Furthermore, the growth rate of the labor force is plausibly thought of as a stationary variable with no trend, so this R&D-based growth model is consistent with the stationarity restriction.

These results should not be interpreted as arguing that cross sectional differences in growth rates are not due, at least in part, to policy differences. In this model, policy still plays an important role through the usual long-run level effects and through transition path growth effects. A country that subsidizes R&D will certainly experience an increase in per capita growth according to this model. However, the increase will last only until the transition to the new balanced growth path is complete. The importance of this transition period will depend on the parameters of the model as well as on how far the state variables are away from their balanced growth path values. In addition, the issue of technology transfer, which has been given virtually no treatment here, is suggested as a prominent feature of the growth experience of both advanced and developing countries. It is obviously incorrect to infer from these results that a country's steady state growth rate is determined by its own rate of population growth. Because of technology transfer, the world rather than the country is likely to be the most reasonable unit of observation.

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Table 1 Trends in L_A and TFP Growth				
	Time Trends		ADF Tests	
	β	N.W. t-stat	ρ	ADF t-test
<i># Scientists & Engineers in R&D, 1965-1987</i>				
France	2.726	9.69***	0.939	-0.57
Germany	4.089	22.85***	0.690	-2.73
Japan	13.326	28.82***	0.611	-1.95
United States (1950)	17.217	10.18***	0.928	-2.40
<i>R&D Labor Share 1965-1987</i>				
France	0.009	9.12***	0.893	-0.90
Germany	0.013	14.69***	0.732	-2.91
Japan	0.020	40.75***	0.437	-2.68
United States (1950)	0.010	4.15***	0.935	-2.53
<i>Aggregate TFP Growth 1960-1988 (varies)</i>				
France	-0.124	-2.09**	0.292	-3.69**
Germany	-0.075	-1.59	0.200	-4.08***
Japan	-0.204	-2.35**	0.495	-2.80*
United States (1950)	-0.055	-0.90	0.352	-3.46*
<i>Manufacturing TFP Growth 1960-1988 (varies)</i>				
France	-0.109	-1.17	0.026	-3.73**
Germany	-0.112	-1.49	0.099	-4.53***
Japan	-0.178	-1.37	0.176	-3.72**
United States (1950)	0.039	0.35	0.350	-3.33*

Notes: Time periods for TFP growth differ across countries -- see the definitions in the text. N.W. t-stats are the Newey-West [1987] autocovariance-robust t-statistics. The ADF t-test reports the test statistic for the null hypothesis that $\rho = 1$. Regressions include a trend for the first two panels but not for the second two (the growth rates). The t-statistics have the following critical values (T=25):

	No Trend	Trend
1 %	-3.75	-4.38
5 %	-3.00	-3.60
10 %	-2.62	-3.24

Significance levels are indicated by asterisks (*) in the table. The lag lengths for the ADF tests are chosen using the Schwarz information criteria.

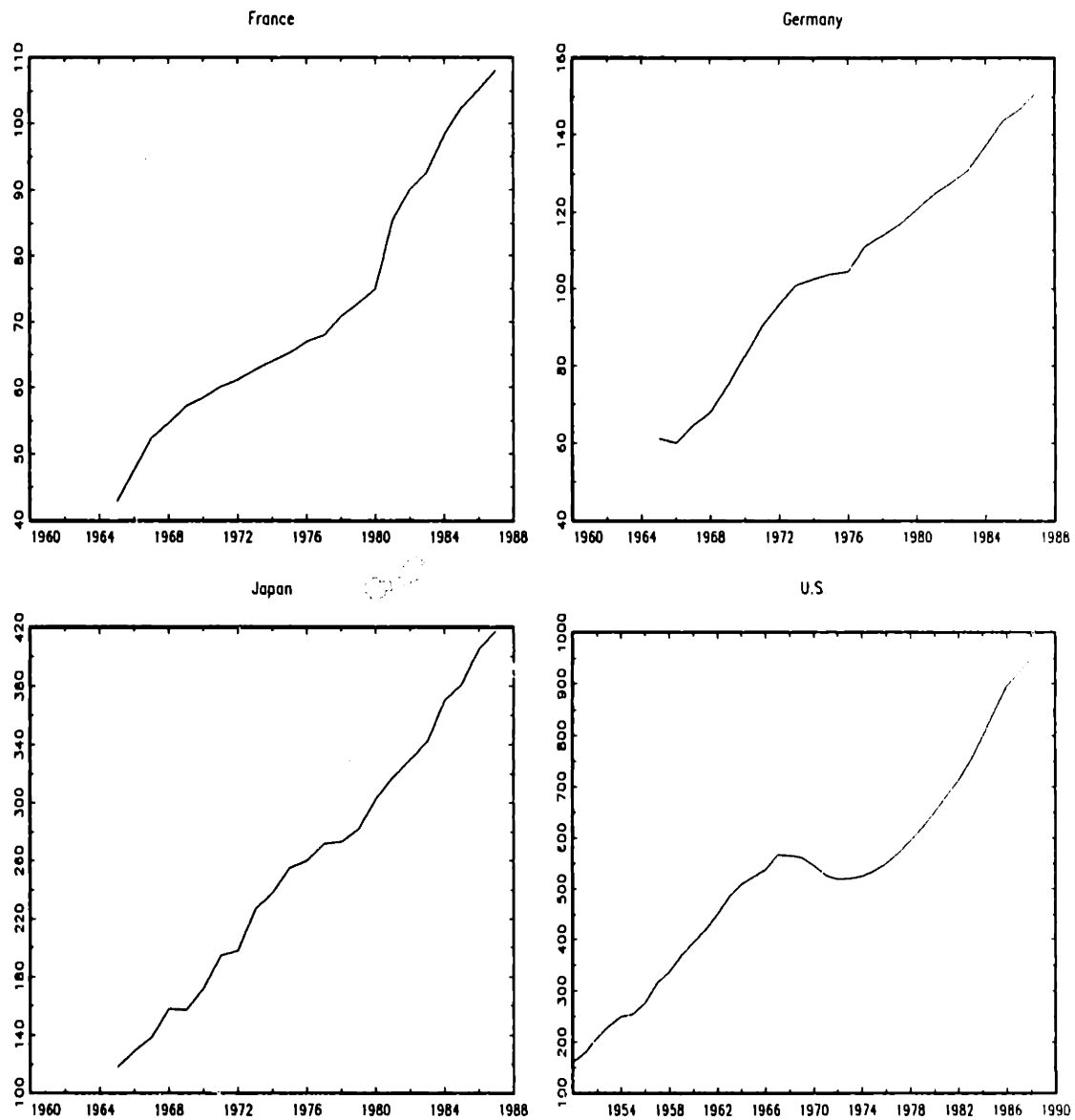
Table 2
Regression-Based Tests of the Romer/GH/AH R&D Equation

L_A Growth Variable	Aggregate TFP Growth		Manufacturing TFP Growth	
	Sum(L_A Coefficients)	t-test SUM=0	Sum(L_A Coefficients)	t-test SUM=0
<i># of Scientists & Engineers Engaged in R&D, 1965-1987</i>				
France	-0.048	-2.98	-0.050	-1.99
Germany	-0.031	-2.36	-0.047	-2.14
Japan	-0.017	-3.03	-0.014	-1.67
United States (1950)	-0.001	-0.99	0.004	1.47
<i>Total Labor Force, 1960-1988</i>				
France	-0.625	-3.16	-0.557	-1.39
Germany	-0.609	-1.97	-0.892	-1.78
Japan	-0.071	-0.55	-0.402	-1.68
United States (1950)	-0.027	-1.74	0.026	0.93
<i>R&D Labor Share (x100) 1965-1987</i>				
France	-0.013	-2.70	-0.015	-1.97
Germany	-0.010	-2.36	-0.015	-2.13
Japan	-0.012	-3.18	-0.010	-1.74
United States (1950)	-0.001	-0.40	0.006	1.43

Notes: This table is based on a regression of total factor productivity growth on a constant, L_A , and possibly one or more lags of L_A . The number of lags is chosen using the Schwarz information criteria and is generally, but not always, equal to zero. The information criteria favors the specifications with no autoregressive term over one in which lagged TFP growth is included.

Under the null hypothesis that the L_A variable is trend stationary, the t-test statistic will have the usual asymptotic normal distribution. Alternatively, if the L_A variable is $I(1)$ with drift, then only those specifications with zero lags will have t-statistics with limiting normal distributions (see West [1988]). Since an $I(0)$ variable is then regressed on an $I(1)$ variable, the sum of the L_A coefficients must in fact be zero in this case.

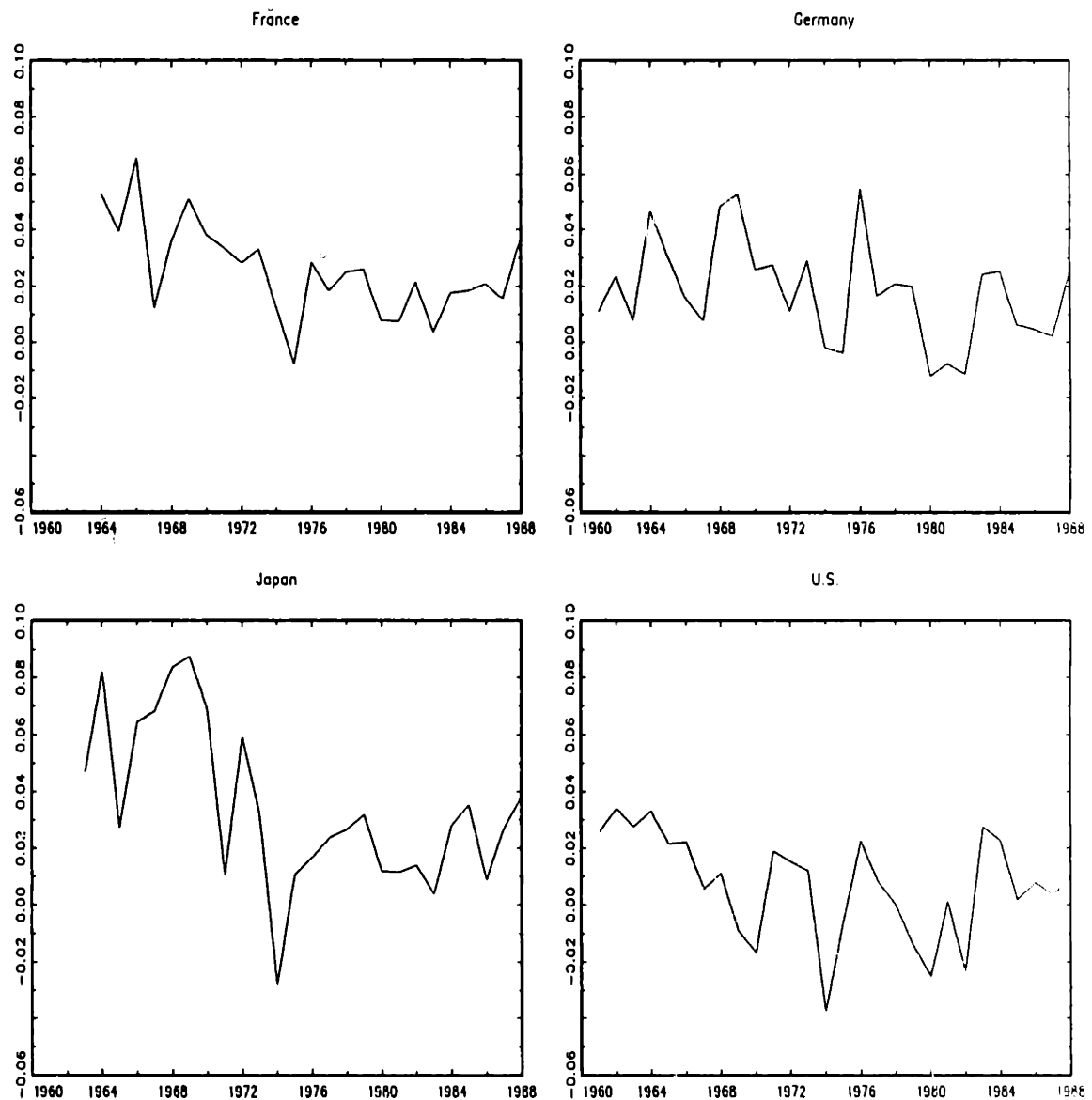
Figure 1
Scientists and Engineers Engaged in R&D (1000s)



Source: *NSF Science and Engineering Indicators 1989* and *Bureau of the Census* (various)

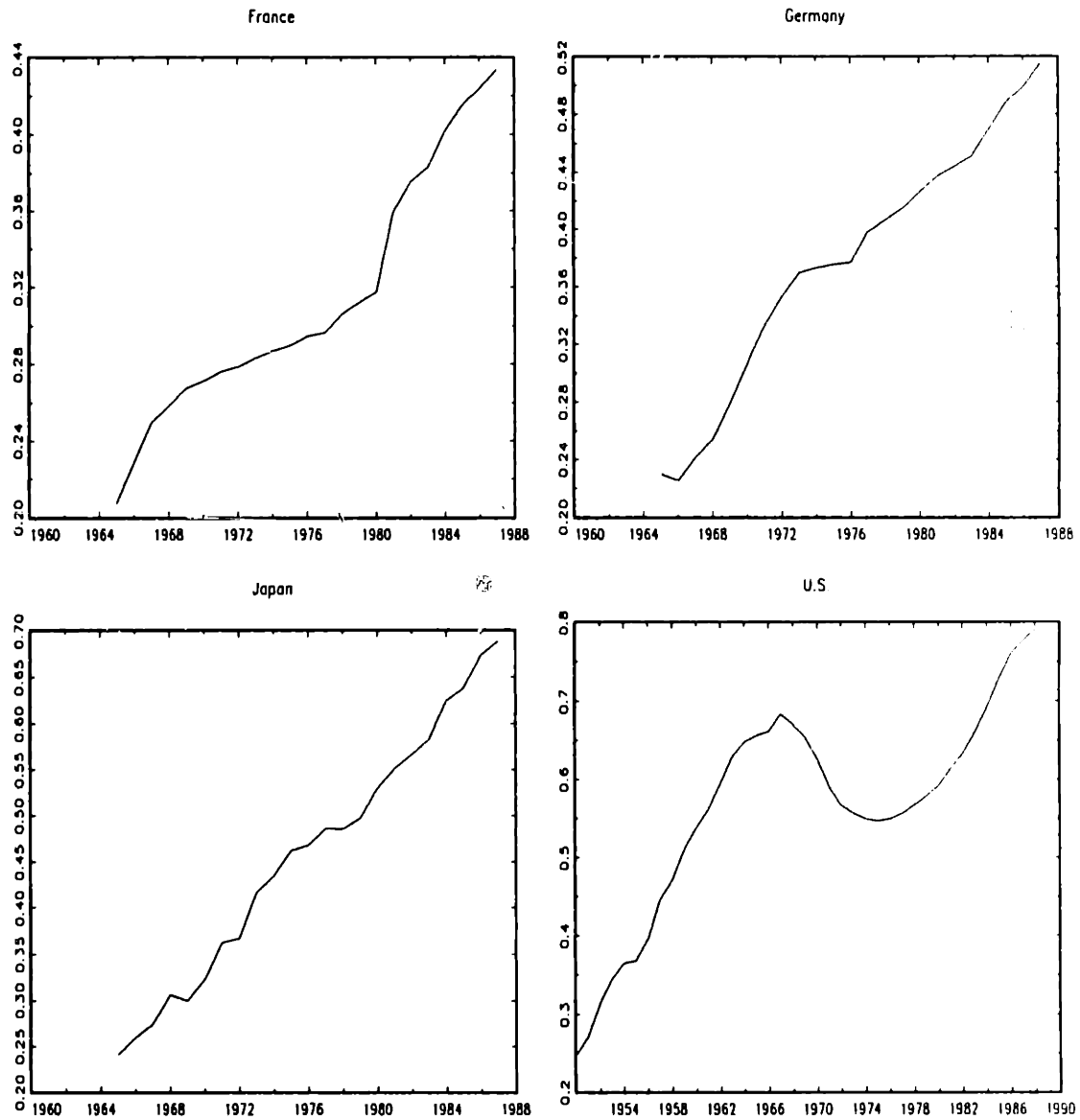
Figure 2

Aggregate Total Factor Productivity Growth



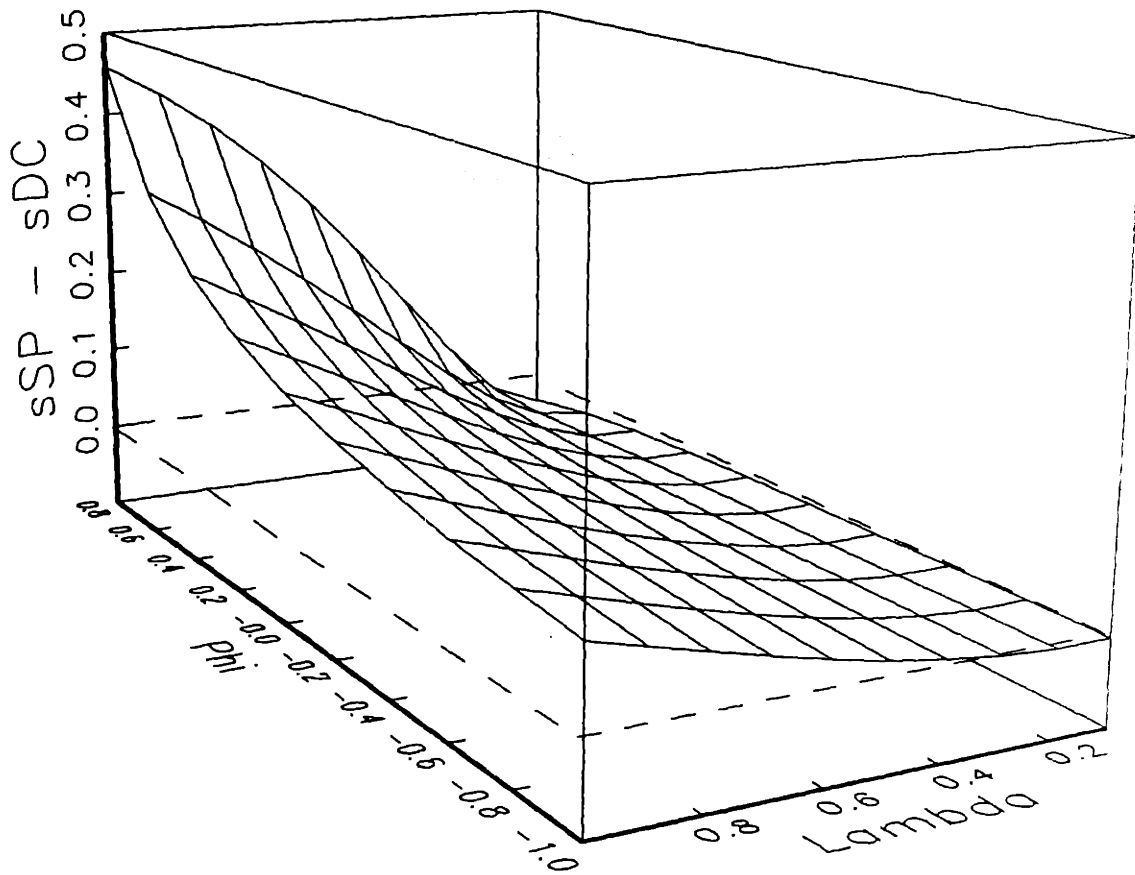
Source: OECD Department of Economics and Statistics Analytic Database. Data provided by Steven Englander.

Figure 3
Scientists and Engineers Engaged in R&D
As a Share of the Labor Force
(Percent)



Source: *NSF Science and Engineering Indicators 1989* and *Bureau of the Census* (various). Labor force data from Summers and Heston [1991].

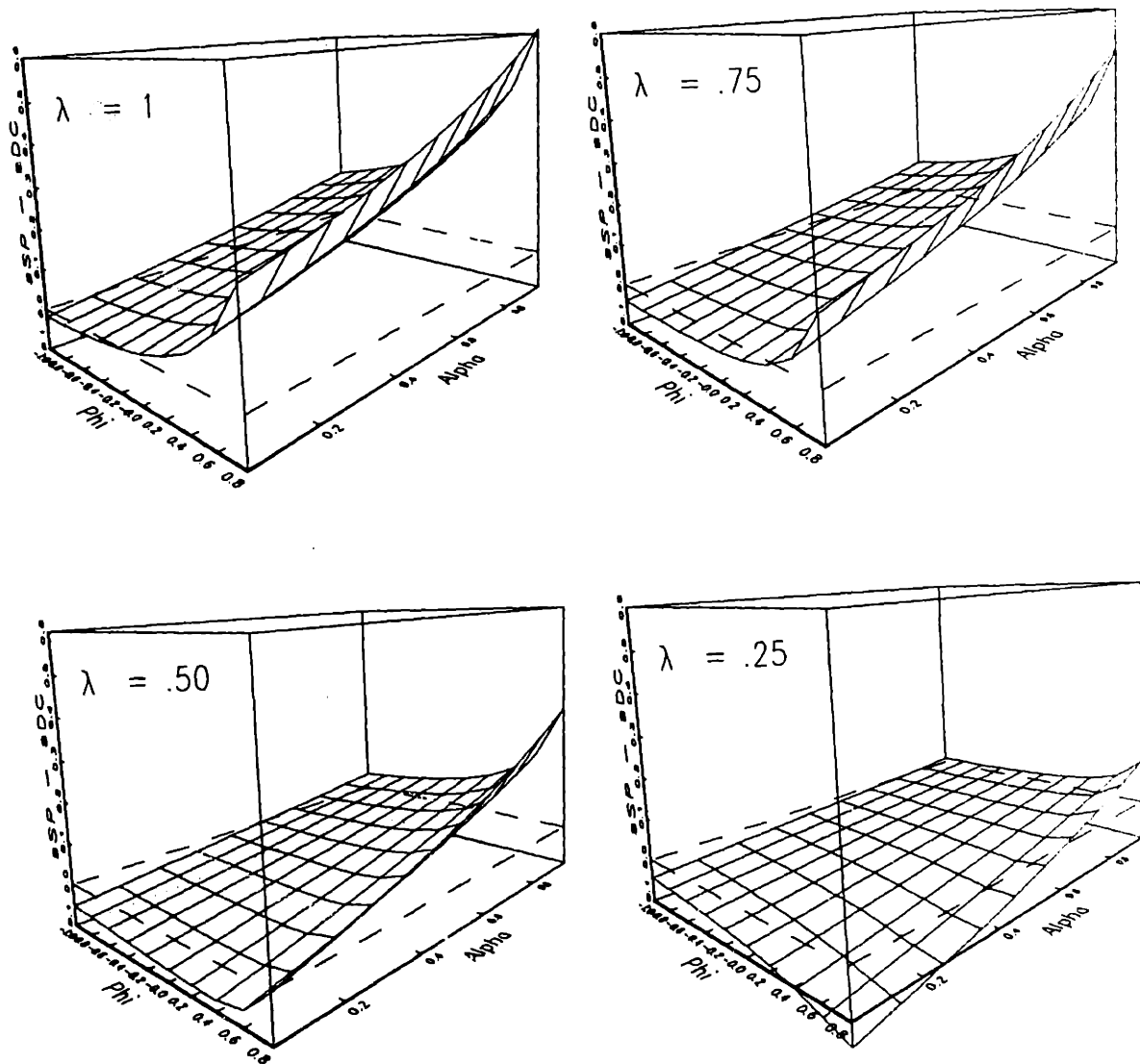
Figure 4
Difference in R&D Shares
Social Optimum versus Decentralized Economy



Source: Author's calculations.

Figure 5

**Difference in R&D Shares
Social Optimum versus Decentralized Economy**



Source: Author's calculations.

Chapter 3

Empirical Evidence on R&D-Based Growth Models

I. Introduction

In response to several recent papers criticizing the basic "AK" linear growth model, the endogenous growth literature has focused on a new class of endogenous growth models, the R&D-based models of Romer [1990], Grossman and Helpman [1991], and Aghion and Howitt [1992]. These models conjecture that it is not the accumulation of physical or even human capital that is the key to growth, but rather it is the accumulation of a good that exhibits some of the characteristics of a public good: knowledge.

Jones [1993b] examined these models empirically and found that they were easily rejected using time series evidence for advanced OECD countries. These models assume that the growth rate of knowledge, which is proportional to TFP growth in the models, is an increasing function of the level of resources devoted to R&D. Because TFP growth rates are stationary or even declining in the post-War period while the level of resources has increased dramatically, these models are inconsistent with even the most primitive empirical evidence. However Jones [1993b] also proposed an alternative model that maintained much of the intuition of the R&D-based models but is potentially consistent with the absence of large increases in TFP growth rates. In this model, the steady state growth rate of the economy depends on the growth rate of resources in R&D rather than on the level. Interestingly, the model differs in another important way from the Romer, Grossman and Helpman, and Aghion and Howitt models (which I will refer to from now on as Romer/GH/AH models). In the Romer/GH/AH framework, subsidies to R&D (and possibly to capital accumulation) can increase the steady state growth rate of the economy. In Jones [1993b], this is not the case: the steady state growth rate is invariant to the usual government policies.

This paper attempts to estimate several key parameters in the model of Jones [1993b].

Overall, the results are supportive of the model and provide several interesting insights into the R&D growth literature. Section II reviews the basic model and the parameters of interest. Section III provides several different estimates of these parameters, including the use of cointegration techniques in a nonlinear model. Interestingly, the parameter estimates suggest that steady state TFP growth should be about 0.6% per year, much lower than the TFP growth rates observed in the manufacturing sector in the last forty years. This puzzle is resolved by analyzing transition path dynamics: the share of labor devoted to R&D has been increasing for most of the post-War period, suggesting that the advanced OECD economies are not currently close to their steady states. The implication is that once this share stabilizes, TFP growth rates could fall by more than a percentage point. Section IV analyzes the one episode in the post-War period during which the share of labor devoted to R&D stopped increasing: the late 1960s to the early 1970s. The analysis suggests that the TFP slowdown is potentially consistent with the model's predictions, lending credibility to the idea that TFP growth rates are currently higher than their steady state values. Finally, Section V summarizes the results in the paper and highlights directions for future research.

II. An R&D-Based Model Without Scale Effects

An R&D-based model of economic growth that eliminates the "scale effects" prediction was discussed in detail in Jones [1993b]. The model relies on a very simple production structure summarized in the following two equations:

$$Y = K^{1-\alpha}(AL_y)^\alpha \quad (1)$$

$$\dot{A} = \delta L_A = \delta L_A^{\lambda-1} A^\phi L_A = \delta L_A^\lambda A^\phi \quad (2)$$

where Y is output, A is productivity or knowledge, and K is capital. Labor is used in either of

two activities, the production of output (L_Y) or the search for new innovations (L_A) so that $L_Y + L_A = L$ represents total labor in the economy. Also, $0 < \lambda \leq 1$ and $\phi < 1$ are assumed.

The production technology in (1) is motivated by the discussion in Romer [1990] of the nonrivalrous nature of knowledge. The insight is to notice that given a level of knowledge, only capital and labor inputs need to be doubled in order to double output, so that the production function inclusive of technology exhibits increasing returns to scale. Many casual examples support this insight. For example, with the blueprint for the latest Saturn in hand, GM can double its production of the automobile by doubling the number of factories, assembly parts, and labor hours -- GM certainly does not need to reinvent the technology for assembling the cars each time it decides to increase production.

Equation (2), which I will call the R&D equation, is the key equation in the model. The specification is motivated by the observation that people are responsible for discovering new ideas. If A represents the stock of knowledge, then \dot{A} is the increase in knowledge or the number of new ideas created in each interval of time. Thus, equation (2) says that the number of new ideas discovered during some interval depends on the number of persons searching for a new idea multiplied by the arrival rate of new ideas. The arrival rate, δ , is a function of the stock of knowledge and of the number of other researchers looking for new ideas. Thus, ϕ measures the external contribution to R&D of previously-discovered knowledge, and λ measures the degree of duplication and overlap in R&D when many researchers conduct R&D simultaneously. The parameter ϕ measures the externalities across time and the parameter λ measures the externalities across space.

The specification in (2) differs importantly from that assumed in Romer [1990] and in Grossman and Helpman [1991] and Aghion and Howitt [1992]. Those models all assumed (effectively) that ϕ is equal to one, an assumption that generates the "scale effects": with $\phi = 1$ and $\lambda = 1$, let's say, the total factor productivity growth rate should be proportional to the *level*

of the labor force, a prediction that is inconsistent with empirical evidence for advanced OECD economies in the twentieth century.

Relaxing the assumption of $\phi = 1$ eliminates the scale effects and yields the model solved in Jones [1993b]. In the social planner version of that model, a representative consumer solves

$$\max_{c_t} \int_0^{\infty} e^{-\rho t} u(c_t) dt, \quad c = \frac{C}{L} \quad (3)$$

subject to the R&D equation in (2) and to the following constraints:

$$\dot{K} = Y - C = AK^{1-\alpha}L_Y^\alpha - C \quad (4)$$

$$L_A + L_Y = L, \quad \frac{\dot{L}}{L} = n \quad (5)$$

where $u(\cdot)$ is a CRRA utility function with relative risk aversion. For a balanced growth path to exist in this model, total factor productivity growth will have to be constant. From equation (2),

$$\gamma_A = \left[\frac{\dot{A}}{A} \right]_{ss} = \delta \frac{L_A^\lambda}{A^{1-\phi}} \quad (6)$$

and this requires the ratio of R&D labor (raised to the power λ) to the stock of technology (raised to the power $1-\phi$) to be constant. Since R&D labor must grow at the same rate as the population growth rate in steady state, this equation naturally ties down the growth rate of technology. Differentiating both sides of the R&D equation along the balanced growth path gives

$$\gamma_A = \frac{\lambda n}{1-\phi} \quad (7)$$

One can set up the usual Hamiltonian for this problem and solve for the first order conditions. Along the balanced growth path, it is easy to show that all growth rates in this model

are tied down by the R&D equation:

$$\gamma_y = \gamma_c = \gamma_k = \gamma_A = \frac{\lambda n}{1-\phi} \quad (8)$$

Equation (8) states that the growth rate of the economy in the steady state depends only on the growth rate of the labor force, the parameter λ , and the parameter ϕ . Notice that if we follow Romer/GH/AH and assume $\phi=1$, no balanced growth path exists in this economy because L is growing. Assuming $\phi < 1$ eliminates the intertemporal scale effects of the Romer/GH/AH model, and these scale effects are replaced by an intuitive dependence on the *growth rate* of the labor force rather than on its *level*.

Eliminating the scale effects from the growth model has another very important effect, and that is that the growth rate of the economy cannot be affected by the usual government policies. In this model, subsidies (or taxes) to capital accumulation or to R&D do not affect the long run growth rate of the economy, as is obvious from the derivation of equation (7). Such policies have level effects rather than growth effects, as in the standard Solow model, even though growth arises endogenously within the model.

The share of labor devoted to the R&D sector can be solved for by manipulating the first order conditions and is given by:

$$s^{SP} = \frac{L_A}{L} = \frac{1}{1+\psi^{SP}}, \quad (9)$$

$$\psi^{SP} = \frac{1}{\lambda} \left[\frac{\rho(1-\phi)}{\lambda n} + \sigma - \phi \right]$$

According to this equation, the steady state share of labor devoted to R&D depends on several parameters within the model. A higher steady state growth rate $\lambda n/(1-\phi)$ is associated with a larger share of labor in R&D. A lower rate of time preference or a higher intertemporal elasticity of substitution (a lower σ) also leads to an increase in the share of labor devoted to

R&D along the balanced growth path. An increase in the average number of ideas per person engaged in R&D, δ , will have no effect on the labor share of the R&D sector, but it is easy to show that a wage subsidy to labor engaged in this activity will in fact increase the share of labor devoted to R&D.

Jones [1993b] also solves a decentralized version of this R&D model. Avoiding the details, it can be shown that steady state growth in the decentralized economy is optimal (equal to the growth rate given in equation (7)) but that the share of labor devoted to R&D is not. Specifically,

$$s^{DC} = \frac{L_A}{L} = \frac{1}{1+\psi^{DC}}, \quad (10)$$

$$\psi^{DC} = \frac{1}{1-\alpha} \left[\frac{\rho(1-\phi)}{\lambda n} + \sigma \right]$$

Comparing this solution to the social planner solution in equation (9), the share of labor devoted to R&D in steady state differs from the socially optimal share for three reasons. First, the presence of an additional " $-\phi$ " term in the social optimum reflects the incorporation of the intertemporal externalities of the R&D process. When these externalities are positive, too little R&D is undertaken in the decentralized solution because agents do not take into account the increase in the value of future R&D that their discoveries impart. On the other hand, if ϕ is negative, there may actually be too much R&D in the decentralized equilibrium.

Second, the parameter λ enters the socially optimal share of labor in R&D reflecting the externalities at a point in time due to the duplication of research. The presence of $\lambda < 1$ will, other things equal, cause the decentralized economy to overinvest in R&D because of the negative externality.

Finally, the decentralized share of labor in R&D differs from the social optimum because of the monopoly markup over marginal cost in the sale of producer durables to the final sector,

reflected by the presence of $1/(1-\alpha)$ in equation (10). This effect unambiguously causes too little labor to be devoted to R&D along the balanced growth path in the decentralized model. Note that if there are no external returns in the R&D equation so that ϕ is zero and λ is one, this is the only effect present so that R&D is too low in equilibrium. Since taxes and subsidies to R&D can affect this share, there is room in this model for tax policy to be welfare improving. Whether or not the appropriate policy is a tax or a subsidy, though, generally depends on the sign of ϕ and the magnitude of λ .

III. Estimating the External Returns to R&D

The analysis in the preceding section suggests that determining the sign and magnitude of the parameters λ and ϕ is important for a number of reasons. First, whether there are positive or negative external returns to R&D in large part determines whether or not the decentralized economy is likely to undertake too little or too much R&D relative to the social optimum. In addition, the estimation of ϕ provides a nested test of the R&D equation proposed in this paper versus various alternatives including the specification assumed by Romer/GH/AH. Finally, we are also interested in estimating the implied steady state growth rate of TFP. This steady state growth rate can be calculated as πn , where n is the exogenously given rate of population growth and π , the factor of proportionality, is given by $\pi = \alpha\lambda/(1-\phi)$.¹

Crude estimates of π and ϕ can be easily calculated using the observation that total factor productivity growth is either flat or declining for the period 1960-1988. For example, consider the case in which TFP growth exhibits no trend and λ is set equal to unity. Ignoring fluctuations (which are likely to be due to the business cycle), we can assume that TFP growth is constant.

¹Notice that TFP growth is equal to α times the growth rate of knowledge.

In this case, differentiating the R&D equation (6) with respect to time yields²

$$\frac{\dot{L}_A}{L_A} = (1-\phi) \frac{\dot{A}}{A} \quad (11)$$

so that ϕ and π are readily calculated using the (constant) TFP growth and the growth rate of L_A . Moreover, it is easy to show that if TFP growth is declining, then the estimate of ϕ computed using equation (11) will represent an upper bound on the true value of ϕ .³ The estimates of π , then, also represent upper bounds.

Table 1 reports estimates of ϕ calculated using this methodology. The somewhat surprising result in this table is that the estimates of ϕ are generally negative, suggesting that there are negative diminishing returns to R&D. The exception occurs when L_A is interpreted very broadly as the total labor force. Similarly, the estimates for π , which represents the steady state growth rate of TFP when $n=1\%$ is assumed, are generally less than 1% when L_A is measured as the number of scientists and engineers engaged in R&D but is often much greater than 1% when L_A is interpreted as the total labor force, especially for the countries other than the United States.

To understand why this result arises, notice that for the R&D-related measures of L_A , the

²The exclusion of capital from the R&D equation is based on the absence of data on capital used for R&D and the observation made earlier that R&D expenditure, which includes expenditures on capital, cannot be used to estimate ϕ . To the extent that capital and labor are used in fixed proportions in the R&D sector, omitting capital from the R&D equation is unlikely to result in any substantial bias.

³To see this, merely differentiate the R&D equation (2) with respect to time to discover that

$$\dot{\gamma}_A = \gamma_A \left[\frac{\dot{L}_A}{L_A} - (1-\phi) \frac{\dot{A}}{A} \right]$$

The left-hand side of this equation will be negative when TFP growth is declining, which requires (for positive TFP growth) that the term in braces be negative also, which quickly yields the appropriate inequality.

growth rate of L_A far exceeds the growth rate of total factor productivity. Now consider the R&D equation for $\phi=0$ and $\lambda=1$. In this case, TFP growth is proportional to the ratio L_A/A . However, if L_A is growing faster than A , then TFP growth must be increasing. To offset this effect, we must reduce the value of ϕ so that the numerator and denominator grow at the same rate. This has the effect of cranking up the growth rate of the denominator whenever ϕ is negative, which is exactly what is needed. Notice that the growth rate of the total labor force is actually less than TFP growth for France, Germany, and Japan, which accounts for the positive values of ϕ and the large values of π obtained for these countries.⁴

Nonlinear Estimation of ϕ and π

The crude estimates of ϕ and π calculated above do not make use of the full variation present in the data; they are based only on average growth rates for the entire sample period. To exploit the time series variation, consider estimating the R&D equation using nonlinear least squares in the following specification:

$$\frac{\dot{A}(t)}{A(t)} = \alpha + \delta \frac{L_A(t)^\lambda}{A(t)^{1-\phi}} + \epsilon(t). \quad (12)$$

Although nonlinear least squares can estimate the parameters of equation (12) consistently, the usual inference does not apply because of the presence of exponential trends in L_A and A : the parameter estimates are not asymptotically normal. This problem is eliminated through the approximation $e^x \approx 1+x$ where $x = \lambda \ln L_A - (1-\phi) \ln A$, which will be valid for small x . Substituting this approximation into (12) and discretizing yields

⁴The fact that the growth rate of the labor force is much less than the growth rate of the number of scientists and engineers engaged in R&D suggests that the share of labor devoted to R&D has been rising over time for these four countries. It also then implies that these economies are not on their balanced growth paths, even though TFP growth exhibits no trend for Germany and the U.S.!

$$\Delta \ln A_t = \tilde{\alpha} + \delta(\lambda \ln L_{A,t} - (1-\phi) \ln A_{t-1}) + \epsilon_t \quad (13)$$

Several remarks are now in order. First, the stationarity of productivity growth and the stationarity of the disturbance term imply a cointegrating relationship between $\ln L_A$ and $\ln A$, where the cointegrating vector is $[\lambda \quad -(1-\phi)]$. However, since cointegrating vectors are only identified up to a scaling term, λ and ϕ are not separately identified. The intuition for this result is apparent from equation (12). When $\lambda < 1$ is allowed, both λ and ϕ perform the same function of "detrending" the ratio $L_A^\lambda / A^{1-\phi}$. In the linearized approximation, there exists an infinite number of combinations of these parameters that will perform this function. In practice, then, we will estimate equation (13) imposing values of λ from the set $\{1, .75, .50, .25\}$.

Second, the parameter estimates obtained from equation (13) will typically have nonstandard limiting distributions. This is readily apparent when one notes the similarity between this specification and a standard Dickey-Fuller test for a unit root: if the exogenous term $\ln L_A$ were omitted, equation (13) would be exactly the Dickey-Fuller specification. The regressor in (13) cannot be made strictly exogenous since it is a lagged dependent variable, so the parameter estimates generally are not asymptotically normal.

Two methods allow us to circumvent this general result, both based on West [1988]. West [1988] shows in a linear model that when the regressors are all stationary except for one $I(1)$ variable, the parameter estimates will be asymptotically normal if the $I(1)$ variable has nonzero drift. The first way this applies to the estimation of (13) is a two-step cointegration method that ignores the dependent variable in the first step. Because the dependent variable is stationary, one can simply regress $\ln L_A$ on $\ln A$ to obtain the cointegrating vector, and this fits perfectly into the framework considered by West. The estimate will have a normal limiting distribution. The residuals from this regression can then be used in the second step to obtain δ since the estimate of ϕ will converge at rate $T^{3/2}$. However, in small samples, ignoring the

variation in the dependent variable may have important consequences, so that one would like asymptotic normality for the nonlinear least squares estimates of (13). This second method is possible given the following result, which extends West's argument to the nonlinear model.

Proposition 1: Consider the structural model

$$\begin{aligned}\Delta y_t &= m_t(\beta_0) + \epsilon_t, \quad \text{where} \\ m_t(\beta) &= \delta(w_t - \psi x_t), \quad \beta = (\delta \ \psi)\end{aligned}\tag{14}$$

where w_t and x_t are $I(1)$ processes with nonzero drifts μ and λ , respectively. Assume that ϵ_t is iid $(0, \sigma_\epsilon^2)$ and that ϵ_t is orthogonal to all stationary linear combinations of w_t and x_t . Define $\Upsilon_T = \text{diag}(T^{1/2}, T^{3/2})$ and define

$$B = \begin{bmatrix} \sigma_\epsilon^2 & 0 \\ 0 & \frac{1}{3} \delta^2 \lambda^2 \end{bmatrix}.\tag{15}$$

Let $\hat{\beta}$ be the nonlinear least squares estimate of β in the model in equation (). Then, if Δy_t is stationary,

$$\Upsilon_T(\hat{\beta} - \beta_0) \xrightarrow{d} N(0, \sigma_\epsilon^2 B^{-1}).\tag{16}$$

Proof. See appendix.

Note that the proposition includes the case of $x_t = y_{t-1}$ so that the nonlinear least squares estimates of the parameters in equation (13) will be asymptotically normal. The intuition for this result is straightforward. The stationarity of Δy_t and ϵ_t imply that m_t is stationary. Furthermore, $\partial m_t / \partial \beta$ consists of two terms, the first of which is proportional to m_t and is therefore stationary. The second term is $I(1)$ with nonzero drift. Since $\partial m_t / \partial \beta$ contains only a single nonstationary term, an argument similar to that in West [1988] applies. As in the linear version, however, this result is a special case. With additional trending regressors, the limiting distributions are no longer asymptotically normal, although results analogous to those in Park and Phillips [1988] should give the limiting distributions.

A final issue in the estimation of equation (13) is that we do not observe A_t but only its

growth rate. Clearly, given an estimate of A_0 for each country we could construct A_t using the growth rates, but it is easier to simply incorporate the A_0 into the parameter δ and allow δ to vary across countries in the panel estimation. Using the specification in (13), then, ϕ and π can be estimated using nonlinear least squares.⁵

Before presenting the point estimates, we will justify the approximation used to derive equation (13). Figure 1 plots actual TFP growth for the U.S. as well as the fitted values computed using three different methods corresponding to: (a) the exact NLLS model in (12), (b) the approximated NLLS model in (13), and (c) the two-step cointegration method mentioned earlier. Recall that the first method does not produce normal limiting distributions, the second does and is the method employed below, and the third method ignores the variation in the stationary dependent variable when estimating ϕ . Figure 1 shows that the exponential approximation is very good: the R^2 's in (a) and (b) for the private business sector are .242 and .241, respectively. The figure also confirms that the two-step cointegration method, while asymptotically valid, is inferior in small samples. The R^2 corresponding to this method is only .152. Therefore, Figure 1 confirms the appropriateness of using method (b).

Table 2 reports the estimates of ϕ and π from the nonlinear least squares estimation of equation (13) for the United States using the TFP growth measures taken from the Bureau of Labor Statistics [1991]. Estimates are reported for the private business sector as well as the manufacturing sector. Given the emphasis in the productivity literature on the manufacturing sector, the latter set of estimates may be more meaningful. This recommendation is consistent with the data on R&D and TFP growth. In 1988, 73% of the scientists and engineers engaged

⁵Reasonable estimates of TFP levels for 1960 suggest that the U.S. was about twice as productive as France, Germany, and Japan and that this gap closed to about 1.25 or 1.3 by the late 1980s (see Boskin and Lau [1990], for example). Using this distribution of initial TFP levels, one cannot reject the null hypothesis that the country specific δ 's are identical in the panel estimation.

in R&D were employed in the manufacturing sector, and in 1987, 76% of R&D expenditure was undertaken in the industry sector, almost all in manufacturing. Since the TFP growth performance for manufacturing has differed substantially from that for the aggregate economy, one might expect the R&D effects on productivity to show up primarily in the manufacturing sector.

The basic specification given in line (1) for the private business sector produces an estimate of $\phi = -1.282$ with a standard error of 0.320. When considering only the manufacturing sector, this external returns parameter rises to -0.144 with a standard error of 0.328. These point estimates agree nicely with the crude estimates given in Table 1 and once again suggest the presence of negative external returns to R&D. The estimates of π , together with an ad hoc value of $n = 1\%$ for population growth, imply a steady state rate of TFP growth of 0.3% for the private sector and 0.6% for the manufacturing sector, with small standard errors. Given (from Table 1) that the average TFP growth rates over this period are substantially higher at 1.21% and 2.19%, respectively, these relatively low steady state growth rates need to be explained further. We will return to this issue later.

Table 2 also reports estimates of ϕ and π when λ takes on values less than one. As speculated, reducing the value of λ increases ϕ . For example, when $\lambda = .25$, the external returns parameter rises to 0.429 for private sector TFP growth and to 0.714 for manufacturing TFP growth. The standard error for these estimates are small, so that a value of $\lambda = .25$ is consistent with positive external returns in the R&D sector. Not surprisingly, reducing the value of λ has no effect on the value of π , as should be obvious from the definition of π .

Robustness of the Empirical Results

The remainder of Table 2, together with Tables 3 and 4, illustrates the robustness of these basic results. Line (2) of Table 2 incorporates the results of Pakes and Schankerman [1984] who

found a one- to two-year lag between a dollar of R&D expenditure and the effects on patents and productivity. When $\ln L_A$ and $\ln A$ are included as two-year lags, the results are essentially unchanged. This is to be expected since it is primarily the trend in L_A that determines the magnitude of ϕ , and this trend is changed little by the introduction of lags. Line (3) takes the alternative approach of including a single one-year lag of TFP growth as an explanatory variable, thus assigning geometrically declining weights to the lags of the scaled L_A variable. Once again, the results are robust to this change. Finally, the specification in line (4) addresses a common argument that it may be incorrect to include academic research scientists in the R&D equation. When only scientists and engineers employed by the manufacturing sector for R&D purposes are counted, the results are again unchanged.

Table 3 reports similar results for the panel of advanced OECD countries (France, Germany, Japan, and the U.S.). For the basic specification using the number of scientists and engineers engaged in R&D as a measure of L_A , the results confirm those found using only U.S. data.⁶ Values of λ of about 0.75 or 0.5 are required to produce estimates of ϕ larger than zero.

Table 3 also addresses a concern that the number of scientists and engineers officially labelled as "R&D" workers may misstate the true number of persons effectively engaged in R&D. An alternative and extreme case would be that in which all labor in the country counted as R&D labor from the standpoint of the R&D equation. What is actually important here is the idea that

⁶In the basic specification with $\lambda = 1$, the estimates of the fixed effects parameters are

	Private Business Sector		Manufacturing Sector	
France	0.544	(0.139)	0.536	(0.575)
Germany	0.174	(0.176)	-0.870	(0.708)
Japan	0.221	(0.137)	0.488	(0.329)
U.S.	0.317	(0.155)	0.265	(0.395)

An F-test of the null hypothesis that the fixed effects are equal produces a statistic of 1.94 for the private business sector and 1.34 for the manufacturing sector, compared to a critical value of 2.72 at the 5% level. That is, the F-test fails to reject the null that these fixed effects are equal in both the private business sector and in the manufacturing sector.

perhaps the amount of labor devoted to R&D grows more slowly than the growth rate of scientists and engineers. The growth rate of population then represents a useful benchmark. The specifications using total labor force as a measure of L_A in line (2) of Table 3 produce values of ϕ that are typically larger than the corresponding estimates based on scientists and engineers. In these specifications, the France-Germany-Japan (F/G/J) group share a value of ϕ of about 0.668 or 0.575 for the $\lambda=1$ case, while the U.S. values are imprecisely estimated.⁷ For the specifications corresponding to aggregate TFP growth, the estimates of π for the F/G/J group imply steady state growth rates of more than 2% for TFP growth, due primarily to the slow population growth rates in these economies. Since Table 1 reports TFP growth rates of about 2% or more for these countries for the period 1960-1988, this number may not be unreasonable. What is difficult to reconcile about the total labor force results is the distinction between the F/G/J results and the U.S. results. For the U.S., π estimates of 0.12 imply a steady state TFP growth rate of less than 0.5% even when the actual population growth rate of 1.76% is used in the computation. Given the likely spillovers of technology across economies, one is reluctant to give much weight to the F/G/J results based on slow domestic population growth. Nevertheless, this more general measure of L_A appears to have much more success in generating positive external returns to R&D.

Table 4 attempts to reconcile these results by considering the following nested specification:

$$\frac{A}{A} = \alpha + \delta \frac{L^\lambda}{A^{1-\phi}} + \epsilon, \quad L = L_1^w L_2^{1-w} \quad w \in [0,1] \quad (17)$$

where L_1 represents the number of scientists and engineers engaged in R&D and L_2 is the total labor force. (The inclusion of an additional trending variable in this specification implies that the

⁷Chow tests suggest that we must estimate different parameters for the U.S. and for the France, Germany, and Japan group when using the total labor force as a measure of L_A .

parameter estimates, while consistent, will no longer be asymptotically normal. Therefore, standard errors are not reported). According to Table 4, the results for the private business sector and the manufacturing sector differ. The weight on scientists and engineers is unity for the private business sector, but drops to 0.544 for the manufacturing sector. This latter estimate implies that the growth rates of L_1 and L_2 contribute equally to TFP growth and that, at the margin, one R&D scientist is equal to about 100 persons in the labor force, a number that seems reasonable. However, given the lack of standard errors for these weights, these results are only suggestive.

Table 4 also returns to the question of whether or not a specification in which TFP growth depends only on the share of labor devoted to R&D is empirically plausible. Estimates of equation (17) in which L_2 represents the R&D labor share yield weights of 0.7 for the private business sector and 1.0 for the manufacturing sector on L_1 , the level variable. Also, the estimates of ϕ are far from unity. These results constitute additional evidence against a specification that would imply that increases in the R&D labor share can generate permanent increases in TFP growth rates.⁸

Thusfar, the results from estimating the R&D equation have been very positive. Table 5 suggests that these estimates should be interpreted somewhat cautiously. That table compares the estimates for the U.S. in Table 2 with similar estimates when a time trend is included in the R&D equation. Overall, the results are mixed. For the private business sector, the point estimates change very little when a time trend is included, suggesting that the results are extremely robust. However, the point estimates for the manufacturing sector change considerably when a time trend is included in the regression. For example, the estimate of steady state TFP growth falls from 0.6% to less than 0.2%. This sensitivity is consistent with other results in the

⁸Note that even if the weight on the R&D share were unity in equation (17), an estimate of $\phi < 1$ would nullify any long-term growth effects by the argument employed in Section IV.

productivity literature, where results are often sensitive to the inclusion of a time trend (see Griliches [1984], for example). In this context, the parameter estimates from the previous tables may best be viewed as descriptive characterizations rather than as estimates of deep structural parameters.

Does the decentralized economy invest too little or too many resources in R&D? Apart from the monopoly characteristics of patents which imply that too few resources are devoted to R&D, the answer hinges on whether or not ϕ is greater than zero and on the interpretation of λ , i.e. on whether the external returns to R&D are positive or negative. Table 6 reports s^{DC} and s^{SP} as well as their ratio for the basic parameter estimates obtained in Table 2, and several points are worth noting in this Table.

First, the decentralized economy nearly always underinvests in R&D, regardless of the parameter values taken by ϕ and λ . This point was noted in Jones [1993b], and the explanation is very straightforward: the monopoly effect in the decentralized model typically swamps the externalities effect from ϕ and λ . This is true except when λ is very small, i.e. $\lambda = .25$ or less.

Next, the table shows that the decentralized economy typically devotes about half of the optimal share of resources to R&D. For example, with $\alpha = .67$, $\lambda = 1$, and $\phi = -0.144$ (the estimates from the manufacturing sector in Table 2), s^{DC}/s^{SP} is equal to 0.41. Even for $\phi = .71$ and $\lambda = 1$, this ratio falls only to 0.32. (Notice that values of ϕ are allowed to vary even though λ is held constant at unity. This reflects the fact that imposing $\lambda < 1$ in the estimation may or may not reflect externalities to the R&D process. For example, perhaps L_A is mismeasured -- then $\lambda < 1$ could index the degree of mismeasurement instead of an actual externality).

Finally, the degree of underinvestment in R&D does appear to be somewhat sensitive to the labor share in final output. When this share is reduced from .67 to .33 (as Mankiw, Romer,

and Weil [1992] suggest, for instance), s^{DC}/s^{SP} rises to about 0.76 or more.⁹

Taken together, the results from these tables highlight several important points. First, the relatively higher estimates of ϕ for the manufacturing sector together with our prior that the external returns to R&D are probably nonnegative fits well with the focus in the productivity literature on manufacturing TFP growth when estimating elasticities. Second, it is crucial to have an estimate of λ in order to calculate the external returns in the R&D sector. A value of λ of about 0.75 or 0.5 is needed to reconcile the empirical work with the common prior that there are positive (or at the very least nonnegative) external returns to R&D in the manufacturing sector when L_A is measured conventionally as the number of scientists and engineers engaged in R&D. However, we do not need estimates of λ to conclude that the decentralized economy is likely to underinvest in R&D. This conclusion is relatively robust to the various combinations of λ and ϕ .

Finally, the results from the manufacturing sector strongly support an estimate for π of about 0.6. Taking a benchmark of 1% for population growth, this corresponds to a steady state growth rate of only 0.6% for total factor productivity. This implied steady state growth rate is much lower than the TFP growth rates observed in the last twenty-five years. From Table 1, for example, the BLS measures of TFP growth in the U.S. have been on the order of 1.21% for the private sector and 2.19% for the manufacturing sector. And the TFP growth rates for the other advanced OECD countries are even higher.

An explanation of these results that will be pursued here is that the recent experience of high but fairly constant TFP growth rates represents out of steady state behavior. For the past

⁹These last estimates may be somewhat misleading, however, because the estimates of ϕ and λ are still taken from TFP growth rates evaluated from the BLS -- i.e. with the conventional capital and labor shares.

forty years, the advanced countries have devoted increasing shares of the labor force to R&D in order to maintain high TFP growth rates, except, as we will see, during the slowdown of the early 1970s. Eventually, the share of labor devoted to R&D must stop growing, and at this point the transition to lower steady state growth will set in. This argument is formalized below.¹⁰

Transition Path Dynamics

With the exception of the slowdown during the 1970s, the advanced OECD countries have experienced TFP growth much greater than the steady state rates implied by Table 2. For the U.S. and Germany, and particularly for TFP growth in the manufacturing sector, these growth rates exhibit no apparent long-run decline. This would seem to contradict the basic prediction of the R&D equation that growth rates cannot be permanently above the steady state value.

To reconcile these observations, we consider the transition dynamics implied by the R&D equation. By focusing only on a version of the R&D equation that excludes capital, we can solve analytically for the transition dynamics of TFP growth and use the parameter estimates from Tables 2 and 3 to characterize the transition path. Define $x = L_A^{\lambda}/A^{1-\phi}$ to be the state variable. Then x will be constant along any growth path in which \dot{A}/A is constant. If s is the share of labor devoted to R&D and γ_s is the growth rate of the R&D share, then the differential equation governing the behavior of x is given by

¹⁰An alternative explanation based on the results of Jorgenson [1988] is tempting but misguided. Jorgenson disaggregates capital and labor inputs to permit differing marginal productivities and calculates an average TFP growth rate for the U.S. economy of only 0.8% for the period 1948-1979. Although this number is closer to the steady state calculations given here, any similarity is misleading. If we had used Jorgenson's TFP growth rates to estimate the steady state growth rate from the beginning, his lower estimates would have implied more negative estimates of ϕ in the R&D equation and therefore *even smaller* steady state growth rates.

$$\frac{\dot{x}}{x} = -(1-\phi)\delta(x-x_{CGP}) \quad (18)$$

where x_{CGP} is the constant growth path value of x corresponding to a constant γ_s :

$$x_{CGP} = \frac{\lambda(n+\gamma_s)}{\delta(1-\phi)} \quad (19)$$

Of course, in the steady state, γ_s cannot be positive (otherwise the share of labor devoted to R&D would eventually be greater than one). However, along a constant growth path, $\gamma_s > 0$ will simply raise the growth rate above its steady state value:

$$\left(\frac{\dot{A}}{A} \right)_{CGP} = \delta x_{CGP} = \frac{\lambda(n+\gamma_s)}{1-\phi} \quad (20)$$

Suppose the economy is on a constant growth path for some positive value of $\gamma_s = \gamma_s(0)$. Eventually, γ_s must fall to zero and the economy will transit back to the corresponding (lower) steady state growth rate. One can compute this transition path if we assume that γ_s drops immediately to zero after time $t=0$. Solving the differential equation in (26) yields¹¹

$$\frac{A(t)}{A(0)} = \frac{\lambda n}{1-\phi} \left[1 - \frac{\gamma_s(0)}{n+\gamma_s(0)} e^{-\lambda n t} \right]^{-1} \quad (21)$$

which generates an exponential decline of the growth rate as the economy transits to the new steady state. It is then easy to calculate the half-life for TFP growth, T^* , as

¹¹To solve the differential equation, apply the calculus formula for the integral of $dx/(x(ax+b))$.

$$T^* = -\frac{1}{\lambda n} \ln \left[\frac{n+\gamma_s(0)}{2n+\gamma_s(0)} \right] \quad (22)$$

$$\approx \frac{1}{\lambda(2n+\gamma_s(0))}$$

To calibrate the model, let's choose parameter values of $\phi=0$, $\lambda=1$, and $n=1\%$ which gives a steady state TFP growth rate of 0.67%.¹² Assuming a value of $\gamma_s(0)=3\%$, the initial constant growth path growth rate is 2.67%, approximately matching the values from Table 1 for the advanced OECD countries. In this case, the economy grows at a constant rate of 2.67% prior to time zero and then begins to transit to the new steady state of 0.67% annual TFP growth. The half-life of this transition path is 22.3 years (20 years using the approximation), so after about 20 years the growth rate will have fallen by one percentage point. Figure 2 plots these dynamics, first providing a twenty-year look at the initial constant growth path.

These results match up well with the behavior of the four-country sample over the last twenty-five or so years. Growth rates have been high relative to the steady states implied by Tables 2 and 3, and the labor share of R&D has been growing as well, as shown in Figure 3. For instance, subtracting population growth rates from the growth rates of L_A in Table 1 reveal differences slightly more than 3% for France, Germany, and Japan (which have population growth rates less than one percent) and less than 3% for the U.S. (which has a population growth rate of 1.76%).

The analysis of the TFP growth slowdown in Jones [1992c] indicates that TFP growth rates respond sharply to declines in L_A and that the R&D equation captures the dominant movements in TFP growth during the period 1950-1988 (see Figure 1). The transition path results of this section suggest that once the growth rate of L_A falls back into line with population

¹²Recall that TFP growth is equal to α multiplied by \dot{A}/A .

growth, TFP growth rates can be expected to decline, with a half-life of about twenty years. The fact that steady state TFP growth rates are so much lower than current growth rates indicates that this adjustment will be substantial. Of course, there are numerous factors offsetting this effect. For example, as more countries industrialize and begin to undertake more R&D, L_A increases for all countries to the extent that technology is internationally mobile. Also, the share of labor devoted to R&D in the U.S. is only about 0.8%, which suggests that we can continue to spend more resources on R&D for a long time before it becomes necessary to slow the growth of L_A .

IV. The Productivity Slowdown and Previous Empirical Work

The productivity literature, at least since Griliches [1979], has sought to provide the empirical underpinnings necessary for understanding the interaction between R&D and growth. Authors such as Griliches [1979,1980,1988,1989], Griliches and Lichtenberg [1984], Mansfield [1984], and Pakes and Schankerman [1984] have estimated equations similar in spirit to the R&D equation, and this section draws out the relationship between the model outlined earlier and the empirical results of this literature. Finally, at the end of this section we analyze the TFP slowdown in the context of the empirical results discussed earlier.

The basic approach of the productivity literature has been to estimate an "augmented production function" in which R&D capital is added to the usual Cobb-Douglas technology, i.e.

$$Y = A^\alpha L^\alpha K^\beta. \quad (23)$$

R&D capital, A , is assumed to accumulate just like physical capital according to

$$\dot{A} = R - dA \quad (24)$$

where R&D expenditure R is simply foregone output and d is the rate of depreciation of R&D capital. From a social standpoint, the productivity literature typically supports a value of d close to zero (see Griliches and Lichtenberg [1984]), so that the R&D capital accumulates according

to

$$\dot{A} = R = s^R K^\beta L^\alpha A^\theta \quad (25)$$

where s^R is the share of output devoted to R&D. With $\alpha + \beta + \theta = 1$, this model is similar to the standard Solow model with two types of capital instead of just one. Therefore, apart from exogenous technical change, per capita growth in this economy eventually dies out.

One of the major contributions of Romer [1990] was to criticize the assumption that $\alpha + \beta + \theta = 1$. Taking the level of knowledge in the economy as fixed, Romer's replication argument (given earlier) implies that doubling the amount of labor and physical capital used in production should double output. To give another example, once IBM discovered how to produce personal computers, mail-order companies could also produce personal computers using only the plans created by IBM together with capital and labor -- no new knowledge was required. According to this replication argument, $\alpha + \beta = 1$ so that $\alpha + \beta + \theta > 1$.¹³

Under this alternative assumption, it is easy to see that the basic accumulation equation for R&D capital in the productivity literature takes the form of the R&D equation when capital is included. Assuming capital and output each grow at the same rate along the balanced growth path,¹⁴ this setup implies that total factor productivity growth in steady state is given by:

$$\frac{\dot{B}}{B} = \theta \frac{\dot{A}}{A} = \frac{n}{\left[\frac{1-\theta}{\theta} \right] - \left[\frac{1-\alpha}{\alpha} \right]}. \quad (26)$$

As in the previous section, steady state TFP growth depends only on exogenous parameters of the model including population growth.

¹³It is worth noting that the productivity literature does not always assume $\alpha + \beta + \theta = 1$, but rather this seems to be a point of contention. See Griliches and Lichtenberg [1984] and Griliches [1991].

¹⁴This is true in most applications since the Euler equation for consumption growth depends on the output-capital ratio.

Comparing this setup to the one considered in Section II, two remarks are in order. First, this framework introduces a new parameter θ describing the elasticity of output with respect to R&D capital. Previously, the decentralized model implied that this elasticity was equal to the labor share in final output so that technological change was Harrod-neutral. The productivity literature instead makes this a parameter to be estimated.

According to equation (23), θ can be estimated by regressing total factor productivity growth on the growth rate of R&D capital (or, in my interpretation, the growth rate of knowledge). Equation (24) provides the mechanism for calculating the growth rate of R&D capital even when δ and ϕ are unknown (and λ is assumed to be equal to unity): adding up past R&D expenditures produces a measure of the level and the growth rate of the R&D capital stock.¹⁵ In reviewing a number of empirical papers using panel data from the manufacturing sector, Griliches [1989] cites a range of (.06,.20) for the micro estimates of θ . This range is consistent with the wider range of sectoral estimates computed by Englander et al [1988] using OECD panel data. They find estimates of θ ranging from a maximum of 0.50 for the chemical products sector down to -0.11 for the "other manufacturing" category.

Second, the framework of the productivity literature assumes unnecessarily that $\phi = \theta$ and that the share of capital in the R&D equation is equal to the share of capital in output. More generally, the R&D equation might be written

$$\dot{A} = R = \delta K_A^{1-\beta} L_A^\beta A^\phi \quad (27)$$

If we assume there is free entry into the R&D sector, then that sector makes zero profits and R&D expenditure on inputs must be equal to the value of the new ideas produced, giving the

¹⁵An important question is how to calculate the initial estimate of the R&D capital stock. Griliches [1980] assumes that prior to the earliest observation, R&D expenditure grew at a constant rate equal to the rate at which it grows during the first few years of the sample, say g . In this case, the initial R&D capital stock can be estimated as R_0/g .

relationship in (27).¹⁶

From the standpoint of our model, the restriction $\phi = \theta$ together with the empirical estimates of $\theta = .1$ or so imply $\phi > 0$ so that positive external returns to R&D would appear to be a built-in assumption. In fact, this reasoning is incorrect and it is important to understand why. Consider the basic specification of the productivity literature when capital is excluded from the R&D equation:¹⁷

$$Y = A^\theta L_Y^\alpha K^{1-\alpha}, \quad 0 < \theta \leq 1, \quad 0 < \alpha < 1 \quad (28)$$

$$\dot{A} = \delta L_A A^\phi \quad (29)$$

This setup is not comparable to the model reviewed in Section II and solved more fully in Jones [1993b]. The decentralized model solved there generates Harrod neutral technological change in the production function for final output; that is, $\theta = \alpha$. Thus, to compare the estimates in the productivity literature to the estimates given in the previous section, we must rewrite the production function in terms of Harrod-neutral technological change. In this spirit, define $B^\alpha = A^\theta$. It is easy to show that the system given by equations (28) and (29) can be rewritten as

$$Y = K^{1-\alpha} (B L_Y)^\alpha, \quad 0 < \alpha < 1 \quad (30)$$

$$\dot{B} = \theta \delta L_A B^\phi, \quad \phi = 1 - \frac{\alpha}{\theta} (1 - \theta) \quad (31)$$

Since the productivity literature maintains the assumption $\phi = \theta$ and estimates values for

¹⁶This relationship between \dot{A} and R reveals that R&D expenditure, because it includes the external effects of A^θ , cannot be used to estimate ϕ in the R&D equation.

¹⁷The exclusion of capital from the R&D equation is based on the absence of data on capital used for R&D and the observation made earlier that R&D expenditure, which includes expenditures on capital, cannot be used to estimate ϕ . To the extent that capital and labor are used in fixed proportions in the R&D sector, omitting capital from the R&D equation is unlikely to result in any substantial bias.

θ of about 0.2, the actual level of external returns to R&D relative to output can be calculated directly. Equation (31) suggests that $\phi = -1.67$ for the typical estimates in the productivity literature, implying the presence of sharply decreasing returns to R&D. Making the appropriate adjustment for the output value of knowledge is important. Without this adjustment we might have mistakenly concluded from $\phi = \theta = 0.2$ that the productivity literature estimates implied slightly positive external returns to R&D. Instead, this analysis shows that the estimates in the productivity literature are broadly consistent with those obtained above.

The TFP Growth Slowdown

Several features of the R&D equation make it impossible not to ask the question of how well the simple specification matches the TFP growth of the early-to-mid 1970s. First, a brief glance at Figure 3 reveals that the share of scientists and engineers engaged in R&D in the U.S. actually fell beginning in 1968, i.e. prior to the first effects of the TFP growth slowdown. Similar results appear if one looks at real R&D expenditure. As Griliches [1988] remarks,

[T]he observed decline in R&D in the mid-1960s could have contributed to the persistence of the productivity slowdown in the 1970s. Given the lags associated with the impact of R&D on productivity, the timing is about right. (Page 13)

However, Griliches and others generally conclude that the magnitude of the slowdown is too large to explain using the decline in R&D given the relatively small elasticity of output with respect to R&D capital, typically in the range (.06,.20). With most estimates less than 0.1, Griliches [1988, 1989] argues that the decline in the growth of R&D capital by 3 percentage points can explain only about three-tenths of a percentage point decline in TFP growth. Other common arguments are that other countries experienced larger TFP growth declines with little decline in R&D and that little of the decline in U.S. R&D occurred in company-financed R&D; most was concentrated in federally funded R&D which empirically tends to have an even smaller associated elasticity.

However, the productivity literature also finds very sharp decreasing returns to R&D (about -1.67 by my calculation) suggesting a low steady-state TFP growth rate of about .25%. In contrast, the empirical results in Table 2 imply that by relaxing the restriction that $\phi = \theta$ we can obtain external returns that are higher and more plausible and steady-state growth rates almost three times as large (about .69%). In effect, we are cranking up the elasticity, and it should not be a surprise that these estimates generate a much larger role for R&D in the TFP growth slowdown.

Table 7 reports actual and predicted average TFP growth rates by decade for the U.S. based on the results in Table 2. While the results do not match up perfectly, they uniformly predict a large slowdown in TFP growth during the 1970s. This result is displayed graphically in Figure 1, where once again the slowdown is unmistakable.

Of course, these results are only meant to be suggestive. The point is that by raising the external returns in the R&D sector to values that are closer to agreeing with our priors, the decline in L_A implies a much larger decline in productivity growth than is conventionally found in the productivity literature. Reconciling these macro results with the micro evidence would seem to be an important area for future research.

The results in Table 8 represent a tentative attempt in this direction. This table duplicates the methodology used in the productivity literature using aggregate data in order to estimate both θ and ϕ in a regression of the form

$$\ln A_t = \text{Const} + \theta N_t + \epsilon_t$$

$$\text{where } N_t = \sum_{j=0}^t (1-d)^j R_{t-j} + N_0$$

The first column of estimates reports results from both the private business sector and from the manufacturing sector, when no time trend is included in the basic regression. Particularly in the manufacturing sector, the resulting estimates of θ and ϕ are much larger than those found in the

productivity literature, suggesting that the level of aggregation may be an important -- for example, the use of aggregate data instead of firm level data may explain the good fit of the productivity growth regression plotted in Figure 1. The second column of results adds a time trend to the specification, confirming again that while the results for the private business sector are robust, the results for the manufacturing sector are sensitive to the inclusion of a time trend. Notice that the results for the manufacturing sector now agree very nicely (including the large standard errors) with results found by Griliches and others.

V. Conclusion

A modification of the R&D equation which parameterizes the degree of external returns in the R&D sector produces a model consistent with the stylized facts, and nonlinear least squares estimation using cointegration techniques confirms that the degree of external returns is substantially and significantly below unity. The modified model behaves very differently from conventional endogenous growth models. Growth in this model is endogenous in the sense that it derives from the pursuit of new technologies by rational, profit-maximizing agents. However, the long run growth rate in this model is in fact a function of exogenous parameters: the growth rate of the labor force and the degree of external returns in the R&D sector. As in the Solow model, subsidies to R&D and to capital accumulation have no long-run growth effects in this model, but rather affect growth only along the transition path to the new steady state. This result runs counter to much of the existing literature, but, as argued in this paper and in Jones [1992a,c], is perfectly consistent with the time series evidence for advanced OECD economies. Eliminating the dependence of the long-run growth rate on policy appears to be necessary to reconcile the R&D-based models of endogenous growth with the joint time series behavior of R&D and TFP growth.

The empirical results of this paper support several tentative conclusions. First, the results support the modified R&D-based model of Jones [1992b]. Parameter estimates of ϕ are significantly less than unity, and, subject to the problems in estimating λ , are potentially consistent with a prior that ϕ is zero or slightly positive. Second, the results suggest that the decentralized economy is likely to underinvest in R&D relative to the social optimum. This result appears robust to the parameter estimates because of the monopoly characteristics associated with the R&D process. Finally, empirical estimates of steady state TFP growth together with data on the share of labor devoted to R&D suggest that advanced OECD economies are not in steady state — the share of labor devoted to R&D has been growing at about 3% per year or so in these economies. The implication is that steady state levels of growth are likely to be slower than the levels currently observed, an implication that is supported by the TFP slowdown of the 1970s.

Appendix

The following lemma, based on the results in West [1988], is useful for what follows:

Lemma 1: Let x_t be a univariate I(1) process with drift λ and let v_t be a univariate stationary process with finite second moment and zero mean. Notice that v_t need not be independent of x_t . Define ω as

$$\omega^2 = \lim_{T \rightarrow \infty} V \left[T^{-1/2} \sum_{t=1}^T v_t \right] \quad (33)$$

and let B denote a Brownian motion with diffusion ω . Then

$$T^{-3/2} \sum_{t=1}^T x_t v_t \xrightarrow{d} \lambda \int_0^1 s dB(s) = N(0, \frac{1}{3} \lambda^2 \omega^2) \quad (34)$$

and

$$T^{-3} \sum_{t=1}^T x_t^2 \xrightarrow{P} \frac{1}{3} \lambda^2 \quad (35)$$

Proof: The proof follows from noting that the deterministic part of x_t dominates the stochastic part in all partial sums:

$$T^{-3/2} \sum_{t=1}^T x_t v_t = \lambda T^{-3/2} \sum_{t=1}^T t v_t + o_p(1) \quad (36)$$

and

$$T^{-3} \sum_{t=1}^T x_t^2 = \lambda^2 T^{-3} \sum_{t=1}^T t^2 + o_p(1) \quad (37)$$

The result in (34) then follows from the fact that

$$T^{-3/2} \sum_{t=1}^T t v_t \xrightarrow{d} \int_0^1 s dB(s) = N(0, \frac{1}{3} \omega^2)$$

and the result in (35) follows immediately from (37). ■

Proof of Proposition 1

Define S_T to be the sum of squared residuals minimized by NLLS:

$$S_T = \sum_{i=1}^T (y_i - m_i(\beta))^2 \quad (39)$$

Minimizing yields the following first order condition:

$$\frac{\partial S_T}{\partial \beta} \Big|_{\hat{\beta}} = -2 \sum_{i=1}^T (y_i - m_i(\hat{\beta})) \frac{\partial m_i}{\partial \beta} \Big|_{\hat{\beta}} = 0 \quad (40)$$

Following Amemiya [1985], we can linearize this first order condition around β_o to obtain

$$\frac{\partial S_T}{\partial \beta} \Big|_{\hat{\beta}} = \frac{\partial S_T}{\partial \beta} \Big|_{\beta_o} + \frac{\partial^2 S_T}{\partial \beta' \partial \beta} \Big|_{\beta^*} (\hat{\beta} - \beta_o) = 0 \quad (41)$$

for some β^* between $\hat{\beta}$ and β_o . Finally, use Υ_T to normalize the terms in (41) so that

$$\Upsilon_T^{-1} \frac{\partial S_T}{\partial \beta} \Big|_{\beta_o} = -(\Upsilon_T^{-1} \frac{\partial^2 S_T}{\partial \beta' \partial \beta} \Big|_{\beta^*} \Upsilon_T^{-1}) \Upsilon_T (\hat{\beta} - \beta_o) \quad (42)$$

Asymptotic normality of $\Upsilon_T(\hat{\beta} - \beta_o)$ is then proven in two steps, based on equation (42). First, we will show that the left-hand side of (42) is asymptotically normal using an argument similar to West [1988]. Then, we will show that the hessian term in (42) converges in probability to a fixed matrix.

1. Asymptotic Normality of $\Upsilon_T \partial S / \partial \beta$

From (40) and differentiating $m_i(\beta)$, one can show

$$\Upsilon_T^{-1} \frac{\partial S_T}{\partial \beta} \Big|_{\beta_o} = -2 \begin{bmatrix} T^{-1/2} \sum z_i \epsilon_i \\ \delta T^{-3/2} \sum x_i \epsilon_i \end{bmatrix} \quad (43)$$

Since z_i is stationary, the first element in (43) is asymptotically normal according to the usual central limit theory.

Asymptotic normality of the second element of (43) follows from the reasoning in West [1988]. Because x_i is an I(1) process with drift λ , partial sums will be dominated by the deterministic component, and Lemma 1 proves asymptotic normality.

It is easily shown that the covariance term is $o_p(1)$ because of the normalization by T^2 so that

$$\mathbf{T}_T^{-1} \frac{\partial S_T}{\partial \beta} \Big|_{\beta_0} \xrightarrow{d} N(0, 4\sigma_e^2 B) \quad (44)$$

2. Asymptotic Behavior of $\mathbf{T}_T^{-1}(\partial^2 S/\partial \beta' \partial \beta) \mathbf{T}_T^{-1}$

At this point it is convenient to assume that

$$\text{plim } \mathbf{T}_T^{-1} \left[\frac{\partial^2 S_T}{\partial \beta' \partial \beta} \Big|_{\beta_0} - \frac{\partial^2 S_T}{\partial \beta' \partial \beta} \Big|_{\beta_0} \right] \mathbf{T}_T^{-1} = 0. \quad (45)$$

This assumption can be verified for the model here since the error in $\hat{\beta}$ is of order $(T^{1/2} T^{3/2})'$. The verification, while straightforward, is tedious and is therefore omitted.

Therefore, we can restrict our attention to $\mathbf{T}_T^{-1}(\partial^2 S/\partial \beta' \partial \beta) \mathbf{T}_T^{-1}$ evaluated at β_0 instead of $\hat{\beta}$. Differentiating $\partial S_T/\partial \beta$ and normalizing yields

$$\begin{aligned} \mathbf{T}_T^{-1} \frac{\partial^2 S_T}{\partial \beta' \partial \beta} \Big|_{\beta_0} \mathbf{T}_T^{-1} &= -2 \left[\mathbf{T}_T^{-1} \sum \frac{\partial^2 m_i}{\partial \beta' \partial \beta} \epsilon_i \mathbf{T}_T^{-1} - \mathbf{T}_T^{-1} \sum \frac{\partial m_i}{\partial \beta'} \frac{\partial m_i}{\partial \beta} \mathbf{T}_T^{-1} \right] \\ &= -2(C - D) \end{aligned} \quad (46)$$

Now consider the terms C and D separately. Multiplying through, C is equal to

$$C = T^{-1/2} \begin{bmatrix} T^{-3/2} \sum x_i \epsilon_i \\ T^{-3/2} \sum x_i \epsilon_i \end{bmatrix} = T^{-1/2} O_p(1) = o_p(1)$$

so that the hessian depends only on D .

Multiplying through, D is a symmetric matrix given by

$$D = \begin{bmatrix} T^{-1} \sum z_i^2 & \delta T^{-2} \sum z_i x_i \\ \cdot & \delta^2 T^{-3} \sum x_i^2 \end{bmatrix} \quad (48)$$

and each of the elements in D can be considered separately.

The (1,1) element converges in probability to σ_z^2 under the usual law of large numbers result. The (1,2) element is equal to $\delta T^{-1/2} O_p(1)$ and therefore converges in probability to zero. Finally, the (2,2) element converges in probability to $\delta^2 \lambda^2/3$. (These are the same arguments that were used in computing the variance of $\mathbf{T}_T^{-1} \partial S/\partial \beta$). Therefore,

$$\mathbf{T}_T^{-1} \frac{\partial^2 S_T}{\partial \beta' \partial \beta} \Big|_{\beta_o} \mathbf{T}_T^{-1} \xrightarrow{P} 2B \quad (49)$$

Combine (44) and (49) with (42) and Proposition 1 is proven:

$$\mathbf{T}_T(\hat{\beta} - \beta_o) \xrightarrow{d} N(0, \sigma_e^2 B^{-1}). \blacksquare \quad (50)$$

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Table 1
Estimates of ϕ and π Using Average Growth Rates

	Average Annual L_A Growth	Average Annual TFP Growth	$\phi(\theta=1)$	Implied SS Growth Rate $\pi=\alpha/(1-\phi)$
Aggregate TFP Growth				
<i># Scientists & Engineers in R&D, 1965-1987</i>				
France	4.22 %	2.34 %	-0.245	0.55 %
Germany	4.14 %	1.63 %	-0.756	0.39 %
Japan	5.77 %	3.17 %	-0.384	0.55 %
U.S. (1960-87)	3.14 %	0.72 %	-2.009	0.23 %
U.S. (BLS TFP)	3.14 %	1.21 %	-0.797	0.38 %
 <i>Total Labor Force 1960-1988</i>				
France	0.85 %	2.57 %	0.771	3.01 %
Germany	0.41 %	1.79 %	0.843	4.39 %
Japan	1.07 %	3.43 %	0.762	3.19 %
United States	1.76 %	0.72 %	-0.692	0.41 %
U.S. (BLS TFP)	1.76 %	1.21 %	-0.010	0.68 %
Manufacturing TFP Growth				
<i># Scientists & Engineers in R&D, 1965-1987</i>				
France	3.62 %	1.76 %	-0.421	0.49 %
Germany	4.14 %	1.74 %	-0.643	0.42 %
Japan	5.77 %	5.24 %	0.163	0.91 %
U.S. (1960-87)	3.15 %	1.98 %	-0.096	0.63 %
U.S. (BLS TFP)	3.14 %	2.19 %	0.010	0.70 %
 <i>Total Labor Force 1960-1988</i>				
France	0.84 %	1.87 %	0.690	2.22 %
Germany	0.41 %	1.96 %	0.856	4.78 %
Japan	0.99 %	5.24 %	0.856	5.26 %
United States	1.80 %	1.98 %	0.375	1.10 %
U.S. (BLS TFP)	1.76 %	2.19 %	0.444	1.24 %

Notes: Calculations follow equation (11). The estimates for France and Japan, the countries with negative trends in TFP growth, will represent upper bounds on ϕ . For the U.S., TFP growth measures from the Bureau of Labor Statistics (BLS) are also used. The implied steady state growth rate is evaluated at $n=.01$, i.e. a population growth rate of 1 % per year for each country, to preserve comparability.

Table 2
Nonlinear Least Squares Estimation of ϕ
Results for the United States

	Private Business Sector TFP Growth (BLS)		Manufacturing TFP Growth (BLS)	
	Estimate	Standard Error	Estimate	Standard Error
<i># of Scientists & Engineers in R&D, 1950 - 1988</i>				
<i>1. Basic Specification</i>				
$\phi(\lambda=1.00)$	-1.282	(0.320)	-0.144	(0.328)
$\phi(\lambda=0.75)$	-0.712	(0.240)	0.142	(0.246)
$\phi(\lambda=0.50)$	-0.141	(0.160)	0.428	(0.164)
$\phi(\lambda=0.25)$	0.429	(0.080)	0.714	(0.082)
π	0.302	(0.042)	0.603	(0.173)
R^2	.241	...	.104	...
<i>2. Two-Year Lag $L_A/A^{1+\lambda}$</i>				
$\phi(\lambda=1.00)$	-1.120	(0.286)	-0.216	(0.298)
π	0.325	(0.044)	0.568	(0.139)
R^2	.241	...	.136	...
<i>3. Autoregressive Model</i>				
$\phi(\lambda=1.00)$	-1.209	(0.338)	-0.176	(0.292)
π	0.312	(0.048)	0.587	(0.146)
R^2	.254	...	.123	...
<i># of Scientists & Engineers in Manufacturing R&D, 1961 - 1988</i>				
<i>4. Basic Specification</i>				
$\phi(\lambda=1.00)$	...	...	0.004	(0.309)
π	...	...	0.693	(0.215)
R^2	...	...	.134	...
<i>Total Labor Force, 1950 - 1988</i>				
<i>5. Basic Specification</i>				
$\phi(\lambda=1.00)$	-1.947	(6.764)	0.427	(0.252)
$\phi(\lambda=0.25)$	0.263	(1.691)	0.856	(0.063)
π	0.234	(0.538)	1.201	(0.527)
R^2	.093	...	.042	...

Notes: This table reports the estimates of ϕ and π obtained using Nonlinear Least Squares to estimate the model in equation (13) for the United States. TFP growth measures are taken from the Bureau of Labor Statistics [1992] for the period 1950-1988. Standard errors are reported in parentheses.

Table 3
Nonlinear Least Squares Estimation of ϕ
Panel Results

Variable for L_A (Assumed Value of λ)	Aggregate TFP Growth		Manufacturing TFP Growth	
	Estimate	Standard Error	Estimate	Standard Error
<i># of Scientists & Engineers in R&D, 1965 - 1988</i>				
<i>1. Basic Specification</i>				
$\phi(\lambda=1.00)$	-1.366	(0.286)	-0.555	(0.181)
$\phi(\lambda=0.75)$	-0.774	(0.215)	-0.167	(0.136)
$\phi(\lambda=0.50)$	-0.183	(0.143)	0.222	(0.090)
$\phi(\lambda=0.25)$	0.409	(0.072)	0.611	(0.045)
π	0.292	(0.035)	0.444	(0.052)
<i>Total Labor Force, 1960 - 1988</i>				
<i>2. Basic Specification</i>				
$\lambda=1.00$				
ϕ F/G/J	0.668	(0.039)	0.575	(0.137)
ϕ U.S.	-4.763	(36.284)	0.426	(0.233)
π F/G/J	2.077	(0.246)	1.623	(0.523)
π U.S.	0.120	(0.754)	1.201	(0.487)

Notes: This table reports the estimates of ϕ and π obtained using Nonlinear Least Squares to estimate the model in equation (13) using the four country panel. With the exception of the Total Labor Force specifications, a Chow test cannot reject the null hypothesis that all four countries share the same coefficient for ϕ . For the Labor Force specifications, the data suggest a breakdown between the France/Germany/Japan group and the U.S., and the two corresponding sets of coefficients are reported. Country-specific constant terms and country-specific δ 's are estimated in addition to ϕ . Standard errors are reported in parentheses.

Table 4
Nonlinear Least Squares Estimation of ϕ in the U.S.
Extended Specifications

		Private Business Sector TFP Growth (BLS)	Manufacturing TFP Growth (BLS)
<i>Scientists & Engineers versus Labor Force: Cobb-Douglas Weights</i>			
$\lambda=1.00$	ϕ	-1.242	0.064
	π	0.308	0.737
	Exponent on L_1	1.000	0.544
	R^2	.242	.122
$\lambda=0.50$	ϕ	-0.131	0.542
	π	0.305	0.753
	Exponent on L_1	1.000	0.481
	R^2	.242	.120
<i>Scientists & Engineers versus L_A Share: Cobb-Douglas Weights</i>			
$\lambda=1.00$	ϕ	-0.959	-0.075
	π	0.352	0.642
	Exponent on L_1	0.707	1.000
	R^2	.246	.118
$\lambda=0.50$	ϕ	0.023	0.446
	π	0.353	0.623
	Exponent on L_1	0.681	1.000
	R^2	.246	.111

Notes: See notes to Table 2. The extended specification is

$$\frac{A}{A} = \alpha + \delta \frac{L^\lambda}{A^{1-\phi}} + \epsilon, \quad L = L_1^w L_2^{1-w} \quad w \in [0,1]$$

where L_1 denotes the number of scientists and engineers engaged in R&D and L_2 denotes the alternative measure. Standard errors are not reported because the parameter estimates are not asymptotically normal.

Table 5
Sensitivity Analysis: NLLS Estimates of ϕ with and without a Time Trend
Results for the United States

	Private Business Sector TFP Growth (BLS)		Manufacturing TFP Growth (BLS)	
	Estimates Without Trend	Estimates With Trend	Estimates Without Trend	Estimates With Trend
<i># of Scientists & Engineers in R&D, 1950 - 1988</i>				
<i>1. Basic Specification</i>				
$\phi(\lambda=1.00)$	-1.282	-1.018	-0.144	-2.595
$\phi(\lambda=0.75)$	-0.712	-0.513	0.142	-1.696
$\phi(\lambda=0.50)$	-0.141	-0.009	0.428	-0.798
$\phi(\lambda=0.25)$	0.429	0.496	0.714	0.101
π	0.302	0.342	0.603	0.192
<i>2. Two-Year Lag $L_A/A^{1-\phi}$</i>				
$\phi(\lambda=1.00)$	-1.120	-1.114	-0.216	-3.734
π	0.325	0.326	0.568	0.146
<i>3. Autoregressive Model</i>				
$\phi(\lambda=1.00)$	-1.209	-1.082	-0.176	-3.937
π	0.312	0.331	0.587	0.140

Notes: This table reports the estimates of ϕ and π from Table 2, as well as comparison estimates obtained when a linear time trend is included in the specification. See notes to Table 2.

Table 6
Interpreting Parameter Estimates for the Manufacturing Sector
The Degree of Overinvestment/Underinvestment in R&D

λ	ϕ	s^{DC}	s^{SP}	s^{DC}/s^{SP}
$\alpha = .67$				
1.00	-0.144	9.9%	24.0%	0.41
0.75	0.142	9.9%	20.7%	0.48
0.50	0.428	9.9%	16.2%	0.61
0.25	0.714	9.9%	9.8%	1.01
1.00	-0.144	9.9%	24.0%	0.41
1.00	0.142	11.6%	29.7%	0.39
1.00	0.428	14.1%	38.7%	0.36
1.00	0.714	18.0%	55.8%	0.32
$\alpha = .33$				
1.00	-0.144	18.2%	24.0%	0.76
0.75	0.142	18.2%	20.7%	0.88
0.50	0.428	18.2%	16.2%	1.12
0.25	0.714	18.2%	9.8%	1.85
1.00	-0.144	18.2%	24.0%	0.76
1.00	0.142	21.0%	29.7%	0.71
1.00	0.428	25.0%	38.7%	0.65
1.00	0.714	30.8%	55.8%	0.55

Notes: The estimates of ϕ are taken from the first panel of estimates for the U.S. in Table 2. The parameter α measures the elasticity of output with respect to labor input in the final goods sector.

Table 7
The TFP Growth Slowdown in the U.S.
1952 - 1988

Measure	Actual TFP Growth	Predicted TFP Growth	Predicted TFP Growth (Lag=2)
<i>Private Business Sector</i>			
1952 - 1959	1.78 %	1.91 %	...
1954 - 1959	1.55 %	...	1.43 %
1960 - 1969	1.96 %	1.87 %	2.15 %
1970 - 1979	0.70 %	0.23 %	0.35 %
1980 - 1988	0.88 %	1.40 %	1.13 %
<i>Manufacturing Sector</i>			
1952 - 1959	1.11 %	0.51 %	...
1954 - 1959	0.94 %	...	0.01 %
1960 - 1969	2.05 %	2.61 %	2.70 %
1970 - 1979	1.47 %	1.50 %	1.74 %
1980 - 1988	2.86 %	2.75 %	2.47 %

Notes: Data are taken from the Bureau of Labor Statistics [1991]. Fitted values are computed from the Nonlinear Least Squares estimation in Table 2 using scientists and engineers engaged in R&D and a value of $\lambda=1.00$. Fitted values are reported for the contemporaneous specification and for the specification based on a two-year lag. Average annual growth rates are reported.

Table 8
Duplicating the Regressions in the
Productivity Literature

	Without a Trend		With a Trend	
	Estimate	S.E.	Estimate	S.E.
Private Business Sector				
Depreciation $\delta = 0$				
θ	0.175	(0.027)	0.562	(0.111)
ϕ	-2.262	(0.614)	0.463	(0.242)
Depreciation $\delta = .10$				
θ	0.250	(0.024)	0.388	(0.068)
ϕ	-1.068	(0.267)	-0.090	(0.311)
Manufacturing Sector				
Depreciation $\delta = 0$				
θ	0.309	(0.037)	0.167	(0.254)
ϕ	-0.542	(0.269)	-2.443	(6.292)
Depreciation $\delta = .10$				
θ	0.431	(0.051)	0.208	(0.143)
ϕ	0.088	(0.190)	-1.622	(2.280)

Notes: These estimates are taken from the Griliches [1980]-like regression:

$$\ln A_t = \text{Const} + \theta N_t + \epsilon_t,$$

$$\text{where } N_t = \sum_{r=0}^t (1-\delta)^r R_r + N_0.$$

Then, ϕ is calculated according to the formula $\phi = 1 - \alpha(1-\theta)/\theta$ and standard errors are calculated using the delta method. Newey-West [1987] robust standard errors are reported in parentheses.

(Asymptotic normality applies in the regressions excluding a time trend because of the argument in West [1988], while the estimates including a time trend will have limiting normal distributions only if the R&D Stock variable is strictly exogenous).

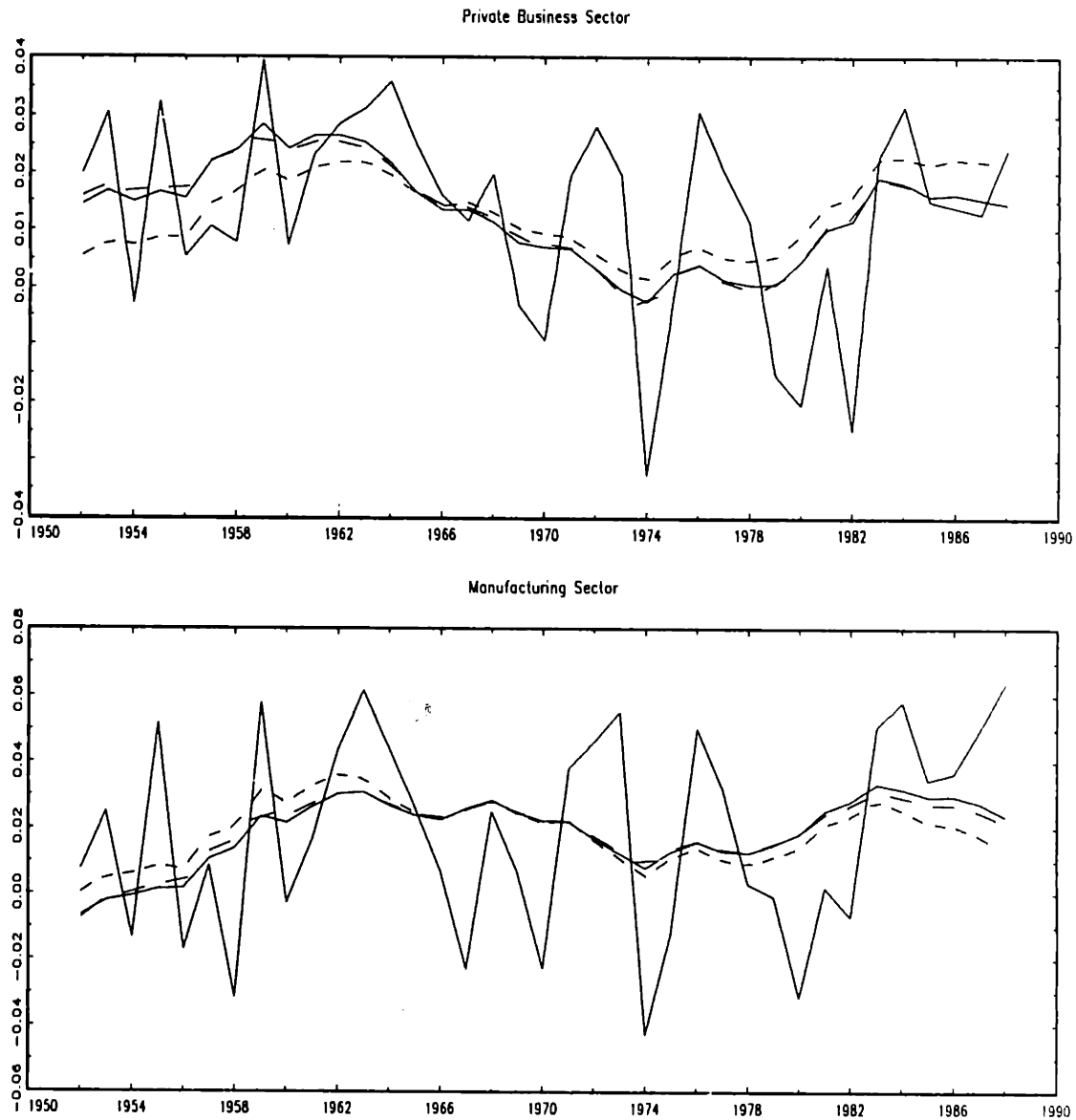
Figure 1

Actual and Predicted TFP Growth for the U.S.

Solid Line: NLLS in True Model

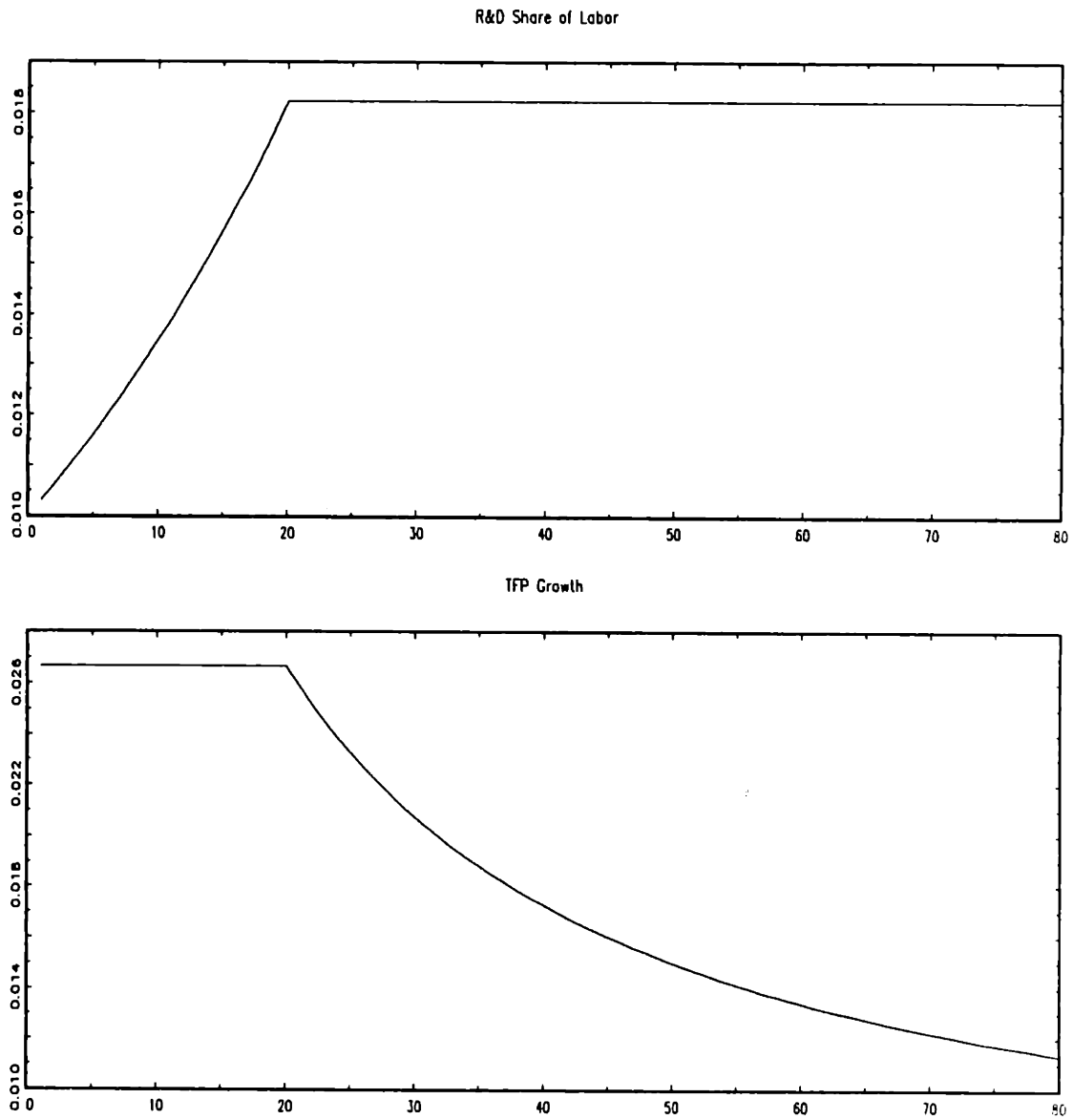
Long Dashes: NLLS in Approximated Model

Short Dashes: Two-Step Cointegration Method



Source: *Bureau of Labor Statistics* [1992] and author's calculations.

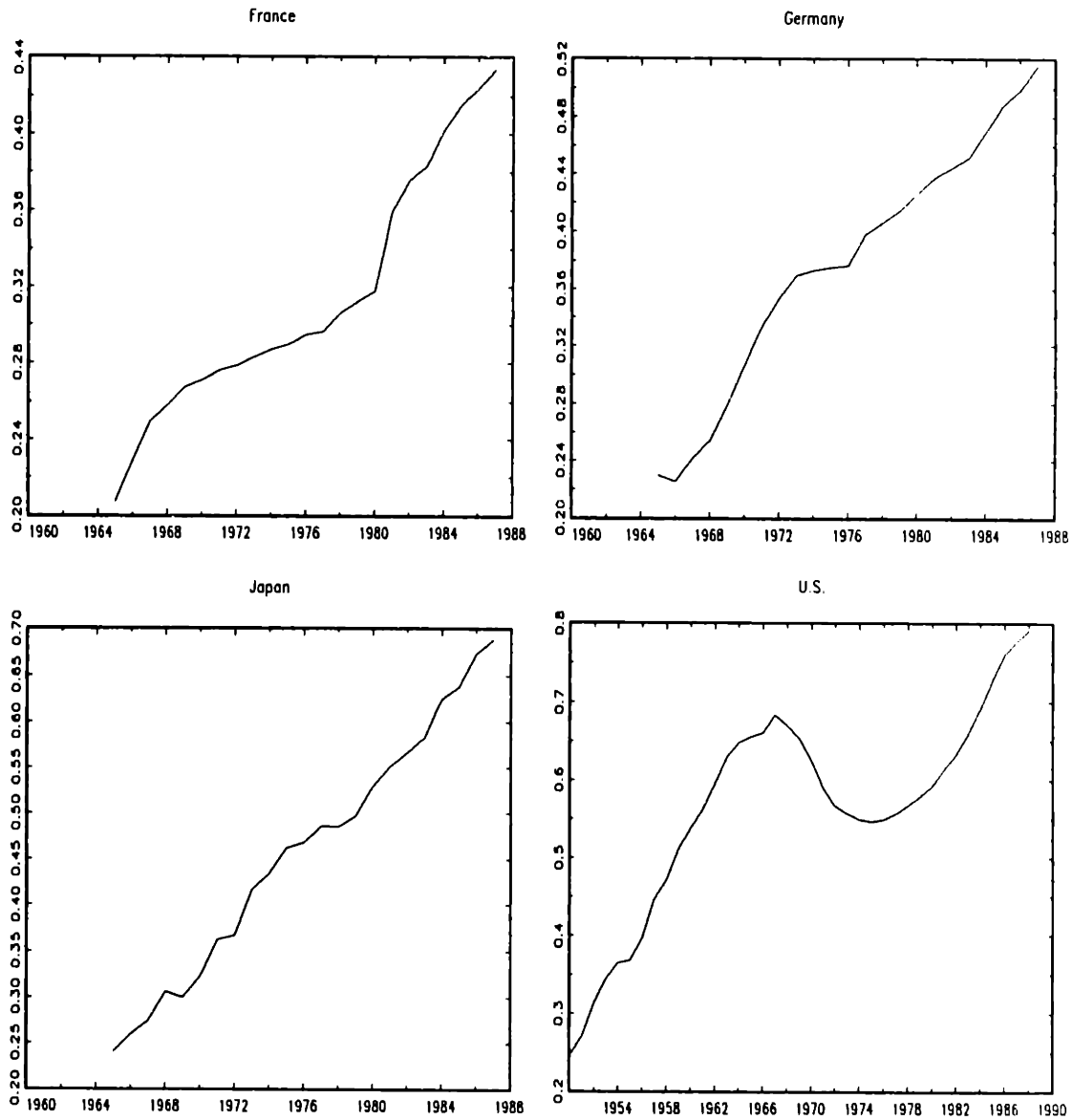
Figure 2
Transition Path Simulation



Source: Author's calculations.

Figure 3

**Scientists and Engineers Engaged in R&D
As a Share of the Labor Force
(Percent)**



Source: *NSF Science and Engineering Indicators 1989* and *Bureau of the Census* (various). Labor force data from Summers and Heston [1991].

Chapter 4

Economic Growth and the Relative Price of Capital

I. Introduction¹

The notion that a tax on capital will have a negative effect on the growth rate of a closed economy comes as no surprise to modern economists. Under plausible assumptions, such a tax raises the price of capital, resulting in a decline in new investment undertaken by firms. This decline in capital accumulation in turn reduces the growth rate of the economy in any standard growth framework.² When open economy models are considered, this line of reasoning extends naturally to tariffs on capital imports.³ Together, these arguments suggest that an important determinant of economic growth in both closed and open economy models is, *ceteris paribus*, the price of capital. Yet while the theoretical relationship between growth and the price of capital is fairly obvious, little empirical analysis has been conducted to estimate the magnitude of this effect. In the public finance literature, much has been written concerning investment tax credits and their effect on capital accumulation [e.g. Summers (1981)], but the linkage to growth has not been estimated since only a single country is usually considered. Also, a long tradition of work in development has focused on trade, tariffs, and growth; Edwards (1989) provides an excellent review of this literature, but concludes appropriately that no good measures of price distortions have been found and that the issues are far from settled.

¹After the first version of this paper was completed, I discovered that De Long and Summers (1991) were conducting parallel research. Their work focuses primarily on the relationship between growth and the quantity of investment whereas this paper emphasizes the effect of distortions in the relative price of investment on economic growth. The important differences between our two papers are discussed in a later section.

²Some exceptions are notable, though not surprising. For instance, in models without endogenous growth such as the Solow model, it is clear that only the level of output and not its growth rate will be affected in the long run. The crucial distinction between effects on level and effects on rate of change was highlighted by Lucas (1988).

³Again, certain exceptions are possible. For example, in models by Krugman (1987) tariffs can be "optimal," at least in the space of second-best solutions. Consider the case of an infant industry in a developing country that exhibits increasing returns to scale over some range but cannot enter a market because of initially high average costs. Protection of such an industry in the short run could allow it to achieve the scale necessary to compete in the international market.

This paper takes advantage of the disaggregated benchmark data used to construct the Summers and Heston (1988) Penn World Tables in order to analyze the effect of the price structure of capital on economic growth. Because of the nature of the data, it is more appropriate to speak of "price structure" than to speak directly about taxes; however, the empirical results apply immediately to issues of government-imposed price distortions such as tariffs and taxes. Using the disaggregated data, I find that a decrease in the tax applied to capital (or an increase in subsidy) can have a substantial positive effect on the growth rate of output. Furthermore, the component of capital that appears most crucial for economic growth is machinery, a subaggregate that includes capital ranging from tractors to computers.

II. Theory

As mentioned in the introduction, numerous models yield the implication that a tax on investment will reduce the rate of capital accumulation and therefore reduce the growth rate. What has not been made clear in these models, however, is the role of prices. Since the empirical work in the sections which follow will be based on prices instead of tax rates, it is worth considering briefly the manner in which the price of the capital input and the price of output affect the growth rate.

To introduce prices, consider a simple model in which there are two goods: an output/consumption good and a capital input good. If the output/consumption good has price P_Y and the capital good has price P_K , then the budget constraint for a representative firm/household can be written as

$$P_Y Y_t = P_Y C_t + P_K I_t \quad (1)$$

where Y_t represents output, C_t is consumption, and I_t is investment. Relative prices are determined in this model in the following way. We make the convenient assumption here that

the output/consumption good can be transformed into the capital good using a linear technology and that this linear rate, say $1/\phi$, is invariant over the relevant time frame. Clearly this assumption could be relaxed. Since the marginal rate of transformation must equal the relative price under competition, the relative price of capital to output in this economy will simply be ϕ .

Now consider a standard Ramsey growth model in which the population is normalized to unity.⁴ The representative household/firm maximizes the present discounted value of utility subject to the budget constraint in equation (1). Assuming that $Y_t = f(K_t)$, that capital K_t depreciates at rate δ , and that utility is CRRA with an intertemporal elasticity of substitution equal to σ , it is trivial to show that the growth rate of this economy, γ_t , is given by

$$\gamma_t = \frac{\sigma}{\phi} [f'(K_t) - \phi(\rho + \delta)] \quad (2)$$

where ρ is the discount rate. According to this result, the growth rate of the economy is proportional to the difference between the marginal product of capital, $f'(K_t)$, and the user cost of capital, $\phi(\rho + \delta)$. Anything that bounds this difference away from zero will result in a model of endogenous growth, as was pointed out by Jones and Manuelli (1989). For simplicity, we follow Barro and Sala-i-Martin (1990), among others, and assume that the marginal product of capital is constant and greater than the user cost. The relative price of capital to output (or, more simply, the relative price of capital) affects the growth rate of this economy in two fundamental ways. First, a higher relative price of capital raises the user cost of capital which reduces investment and growth. Second, a higher relative price reduces the factor of proportionality in equation (2). For a given marginal product and a given user cost, a higher relative price of capital will still reduce the growth rate.

As this model illustrates, the relative price of the capital input to output is an important

⁴See Blanchard and Fischer (1989), Chapter 2, for example.

determinant of growth.⁵ To the extent that different countries have different input-output price ratios, we should find a corresponding variation in growth rates in a cross section of countries. Before turning to the empirical work, however, it is important to consider what drives the variation in the relative price of capital across countries. In the model, the relative price will vary across countries as a result of differences in the marginal rate of transformation between the consumption good and the capital input. This is a technological difference. However, differential taxation will also cause the relative price to vary. Tariffs on capital imports and taxes on domestic capital, for instance, will raise the relative price of capital and reduce growth, through both the user cost effect and through the multiplier effect. The remainder of this paper exploits the relatively large cross sectional variation in the relative price of capital in order to estimate the effect of changes in capital taxation on growth.

III. Data Issues

Measuring the Relative Price of Capital

The benchmark surveys from which the Summers and Heston (1988) Penn World Tables are derived provide an excellent opportunity for comparing relative prices because they incorporate differences in purchasing power parity across countries.⁶ Although benchmark data is available for only a restricted sample of sixty-five countries, data quality is generally much higher for countries which participated in a benchmark survey. Thus, data from developing as

⁵In more complicated models such as Rebelo (1991), one must be careful about exactly which relative price matters. For instance, if the Y_1 good is actually an intermediate good so that Y_1 can be used to produce consumption or to produce more capital, the rate at which Y_1 is transformed into the consumption good will not affect the growth rate. The growth rate will depend only on the rate at which Y_1 is transformed into the investment good, i.e. on the relative price of K_1 and Y_1 .

⁶See Summers and Hestons (1988) for a discussion of their methods and the advantages and disadvantages of their data.

well as developed countries can be used in the estimation with less concern for standard issues of measurement error. The reader is referred to Kravis, Heston, and Summers (1978, 1982) for a more detailed discussion concerning the benchmark data.

The theoretical model outlined in Section II has the clear prediction that the ratio of the capital input price to the output price should be negatively correlated with growth. As a measure of this price ratio, I use the Summers and Heston benchmark estimates of the price of investment goods divided by the price of consumption goods.⁷ There are several problems with this measure. The most obvious problem is that countries produce multiple goods using other goods as inputs -- the output for one firm is often the input for another. Ideally, we would like to obtain an index of the relative price of capital input to output for each firm or industry and then aggregate these measures in some way. In practice, this is unrealistic. The merit of the Summers and Heston benchmark data is that it reports the price of a single basket of investment goods and a single basket of consumption goods for many different countries so that these prices are comparable. As a coarse approximation, the price of the consumption basket should correspond to a measure of the output price faced by firms while the price of the investment basket should correspond to a general input price.

Another problem with this measure is that the consumption price index represents the price faced by consumers, not the price received by producers.⁸ An output tax will generally raise the consumer price and reduce the producer price. The true measure of the relative price of capital should rise in this situation, but our observed measure will in fact fall. In practice, I suspect that this is only a minor problem for the following reason. General sales tax revenue as

⁷Consumption is used as a measure of the output good instead of GDP because the GDP price index includes investment prices. A switch to GDP has little effect on the results, however.

⁸Note that for the investment price it is the "consumer" price which is in fact relevant, so this problem does not apply.

a proportion of GNP or consumption is actually fairly small (usually less than 10% for consumption), as is evident from simple calculations using the IMF's *Government Finance Statistics*.⁹ However, these criticisms of the measure of the relative price of capital serve to indicate that measurement error may be a problem. This is dealt with specifically near the end of the paper when instrumental variables estimation is employed.

With these problems recognized, the benchmark data offer a final important advantage. Benchmark estimates are available at a more disaggregated level than is the Summers and Heston Penn World Tables data set, and I use this disaggregated data to construct measures of the relative price of capital and several of its components. Domestic capital formation (or total investment) is made up of two categories: construction and producer durables. From the construction category, I use the nonresidential subaggregate. From the producer durables category, I construct relative price levels for all three major subaggregates: transportation equipment, electrical machinery, and nonelectrical machinery. Relative price levels are constructed by dividing the prices of these variables by the price of consumption.

From the disaggregated benchmark data for 1980, I obtained relative prices for 56 countries. Then, using preliminary benchmark data from 1985 and the benchmark data from 1975 I was able to add another nine countries to the sample. The technique of Seemingly Unrelated Regression (SUR) was used to construct 1980 fitted values from either a 1975 or a 1985 benchmark. SUR makes use of the fact that the residuals of a regression of the 1980 price of durables on the 1975 price of durables will be correlated with the residuals of a regression of

⁹I obtained data for sixty-two of the sixty-five countries in my sample for 1985 on General Sales and VAT Revenue. Dividing by total consumption for 1985 produces a rough estimate of the average sales tax rate. This normalization is likely to overstate the true average tax rate since investment goods and some government goods are purchased and subject to these taxes. Nevertheless, the mean for this sample was only 6.2% with a standard deviation of 5.2%. Seventy-five percent of the countries had an estimate less than 10% and ninety-five percent of the countries had estimates below 15%.

the 1980 price of construction on its 1975 value, etc. The 1980 fitted values for the nine additional countries were joined with the original 1980 data for the 56 countries to produce the sixty-five country sample.¹⁰

Growth Rates, Initial GDP, and the Relative Price of Machinery

The empirical results presented below indicate that the components of investment that are most highly correlated with growth, at least insofar as relative prices are concerned, are the electric and nonelectric machinery categories. In other words, nonresidential and residential construction seem to be much less important for growth than the other primary component of investment, producer durables. And within producer durables, the two machinery components are distinctly correlated with growth in contrast to the transportation equipment category. Statistical evidence for these findings will be presented later, although we can note now that this confirms with price data the finding of De Long and Summers (1991) for quantities. For the moment, we turn to a more careful examination of the relative price of the machinery component and its effect on growth.

Figure 1 presents a simple scatterplot of the growth rate from 1960-1985 and the relative price of machinery for the sixty-five country sample using the standard World Bank country codes as plot symbols. The growth rate and the relative price of machinery appear to be negatively related, and indeed, the simple correlation coefficient for these two variables is -0.31 (s.e. is 0.12). Countries with higher relative prices of machinery in 1980 tend to have slower growth rates over the period. Apart from problems with using only a simple correlation (these problems will be dealt with in the regression analysis below), an obvious question about this result involves causality: does the correlation arise because a high relative price causes slower

¹⁰The basic results are not sensitive to the exclusion of the nine additional countries.

growth, or does slower growth result in a high relative price by 1980? This is a question which I will postpone until after the empirical results are presented, but in the end it cannot be resolved completely.

Figure 2 shows the relative price of machinery plotted against the initial level of GDP per capita, that is in 1960, in thousands of 1980 U.S. dollars. A strong negative relationship is readily apparent in this graph:¹¹ 1960 GDP and the relative price of machinery have a simple correlation of -0.58 (s.e. is 0.10). Thus, it is crucial to include 1960 GDP in any growth regression; otherwise the relative price of machinery could simply be capturing differences in the initial stage of development.

IV. Results

In order to analyze economic growth, I follow closely the methodology employed by Barro (1991). The growth rate from 1960 to 1985 for a cross section of countries in the Summers and Heston data set is regressed on several variables that are, or at least are close to being, exogenous. Thus, variables such as the investment share or population growth are excluded from the regression, as these variables are endogenous in many growth models. The Barro (1991) specification includes the starting level of GDP, two proxies for human capital, a government consumption variable, and several variables used to capture basic country characteristics that may plausibly have an effect on growth. Table 1 lists all variables used in this paper together with summary statistics.

The first line of results in Table 2 corresponds to the Barro regression for our sixty-five country sample using data from the Barro-Wolf data set discussed in Barro (1991). The results found by Barro are broadly confirmed. Namely, holding proxies for human capital constant, the

¹¹Interestingly, this relationship is one of the predictions of some endogenous growth models with fixed factors, e.g. in Rebelo (1991).

initial level of GDP has a significant negative coefficient, suggesting the qualified convergence result observed in previous studies. The enrollment ratios for secondary and primary schools that proxy for human capital have positive coefficients, although their standard errors are generally larger than those found by Barro. The ratio of government consumption (i.e. non-defense and non-education spending) to GDP enters negatively and very significantly, and Barro argued that this results from the distorting effects of government taxation and government expenditure programs. Several country characteristic variables (see Table 1) were also included in the regression, but their coefficients are omitted from the table. The signs and significance levels for these variables are consistent with the findings of Barro.

In the remainder of this paper, I will focus primarily on specifications in which the relative price variables are added to the regression. Barro (1991) provides a detailed analysis of the results from the more basic specification.

Growth and the Relative Price of Machinery

When the relative price of machinery is included in the basic Barro specification, it enters negatively and significantly, as shown in the second regression of Table 2.¹² According to the cross sectional evidence of this regression, a unit increase in the relative price of machinery is associated with a reduction in the annual growth rate of a country of three-quarters of a percentage point. Figure 3 illustrates this graphically. The figure plots the relative price of machinery against the portion of growth that is unexplained when all variables except the relative price of machinery are taken into account. Thus, a simple regression line when plotted in Figure 3 would have the slope of $-.0076$. The graph also shows that even though Peru is an outlier, the

¹²This equation represents the basic specification used throughout this paper. However, some equations are estimated without including the country characteristic variables because of collinearity. See the table notes for exact information.

negative relationship between growth and the relative price of machinery is clear even when this country is omitted.

An important issue in using the Summers and Heston data is that of measurement error. Data quality varies across countries, and not surprisingly, this variation is related to a country's level of GDP [see Summers and Heston (1988)]. One suspects that such data problems could mask the relationship between growth and relative price, but in the regression above, a significant negative relationship is still evident. Nevertheless, Table 2 also reports results for various subsamples: those with an initial level of GDP greater than 10% and 20% of that in the United States. The basic result that the relative price of machinery is negatively related to growth is magnified when the country subset is further restricted. Indeed, for the 20% subset the coefficient on the relative price of machinery is $-.0195$ with a standard error of $.0048$. One caveat for interpreting this result is relevant, however: because of collinearity resulting from the smaller sample size, the country characteristics variables are not included in the subset regressions. In particular, the Africa and Latin America indicator variables are omitted. Thus, to some extent the machinery price may be capturing unobserved region effects as well, or at least the data is unable to separate the two effects.

An additional explanation is plausible. That is, the split to countries with "high" GDP suggests a split between more developed and less developed countries. And as was shown in Figure 2, the more developed countries tend to have on average lower values for the relative price of machinery. Thus, the regressions could be suggesting that changes in the relative price that would be "small" for the less developed countries still have a significant impact on growth when the changes occur in more developed countries. However, this hypothesis is rejected by a simple Chow test: when an interaction term between the price of machinery and an indicator variable for developed countries (those with GDP greater than 20% of U.S. GDP in 1960) is included, it enters with a small and insignificant coefficient. This makes the former explanation

seem more likely.

In addition to considering various subsamples of countries, I also examined the growth regressions using different time periods. The middle panel of Table 2 presents the regression results when the growth rate from 1960 to 1975 is used, and the final panel reports similar regressions when the 1970 to 1985 period is considered. This sensitivity analysis provides some evidence that using the relative price data from 1980 is not the crucial factor driving the results. The results for the relative price variable are strong in all subsamples when the 1960 to 1975 period is considered. For the 1970 to 1985 period, though, the relative price enters significantly only when the 20% subsample is used. Possibly, this reflects some of the measurement error problems. Another explanation also seems relevant. This latest period was marred by two oil shocks and ends with a recession year for many countries; consequently, many countries had average annual growth rates that were actually negative. This, together with the fact that 1970-85 is a relatively short period, could account partially for the less robust results.

Growth and Other Relative Price Variables

Table 3 presents the regression results when the other relative price variables are included in the basic specification. The main result of this table is summarized nicely in the first row, where non-machinery investment denotes all investment other than the machinery component. When the relative price of machinery and the relative price of non-machinery are included together, the coefficient on the non-machinery price is only 0.0001 with a standard error of 0.0026. In stark contrast, the coefficient on the machinery price is unchanged from Table 2 and highly significant. In terms of the relative price of capital, then, the machinery component is clearly the driving force behind growth.

The remainder of Table 3 illustrates the robustness of this result by including a single relative price measure for various subaggregates of investment. When relative prices for either

total investment or non-machinery investment are included individually, the coefficients are negative but insignificant. Total investment can be split into construction and producer durables. The construction relative price (only nonresidential is reported but the results are the same for residential and for total construction) has a negative coefficient, but its standard error is larger in magnitude. In contrast, the producer durables relative price enters negatively and significantly. The producer durables component consists of transportation equipment, electric machinery, and nonelectric machinery, and the final rows of Table 3 report the regression results when the relative price for each of these variables is included separately. The two machinery relative prices enter negatively, while the transportation equipment variable enters insignificantly. Once again, the results highlight the importance of the machinery component of investment.

Investment and the Relative Price of Machinery

Thus far, the channel through which the relative price of machinery affects growth has been assumed but not discussed. Presumably, an increase in the relative price of machinery reduces capital accumulation and therefore reduces the growth rate of the economy. Table 4 explicitly examines the relationship between the relative price of machinery and investment. If one assumes an open economy model in which the supply of capital to small countries is perfectly elastic, then a regression of investment on the relative price of machinery will trace out a demand schedule. In Table 4, the relative price of machinery enters negatively with a very small standard error. This is true whether the left-hand side variable is the average total investment share in GDP for 1960-85, average total investment for 1970-85, or the machinery investment share for 1980.

While the result for the machinery investment share needs no explanation, it is slightly puzzling, perhaps, that the results for total investment are so strong. Several explanations are possible, but according to other regression results that are not reported, one seems likely. In

other regressions with the total investment share on the left-hand side, I included the machinery share of investment and the relative price of total investment, both individually and together. Both of these variables were always significant and had the expected sign. When the relative price of machinery was included with either of these other variables, they still retained their significance. However, the relative price of machinery also entered significantly. This suggests that much of investment may in fact be driven by machinery investment. Holding fixed the relative price of total investment or the share of machinery investment, a higher relative price of machinery investment reduces the total investment share. The relative price of machinery is crucial for determining not only the share of investment devoted to machinery, but also for determining the total share of investment within an economy.

Empirical Results using Other Price Distortion Measures

Because of the potential problems with using the relative price variables that were mentioned earlier, I have constructed several other "price distortion" measures in an attempt to confirm the results obtained with the relative price data. The first of these price distortion variables is the average share of revenue generated by tariffs in central government revenue for 1976-1978, the earliest period for which data on a large number of countries could be obtained. The data for this variable is taken from the IMF's *Government Finance Statistics*.

The second distortion variable I use is the effective rate of protection in the manufacturing sector (ERP). Two steps were used to obtain an estimate of the effective rate of protection in each country. First, a wide variety of sources were consulted, yielding estimates of the effective rate of protection for various years during the 1960-1985 period.¹³ Unfortunately, these data were generally only available for a single year for any given country. The few cases in which

¹³A complete bibliography of these sources is available from the author upon request.

estimates were available from different studies for the same country highlight the problems with this data. For example, Yeats (1976) reported a high and a low estimate for the effective rate of protection in Iran during the period 1963-1968 of 153 and 53 respectively. Similarly, two different studies reported values of 61 and 20 for the effective rate of protection in Mexico in 1960. Despite these problems, the first step in constructing the ERP variable was to obtain a straight arithmetic average of the estimates found in the literature.

In the second step, I exploited the high correlation between the effective rate of protection and the nominal rate of protection that has been noted by several authors, e.g. Baldwin (1988).¹⁴ Using average tariff rates (mostly for manufactured and related products) acquired during the search for effective rates of protection, I extend the sample for which ERP is available. I found average tariff rates for 34 countries, 11 of which did not also have an associated ERP number. Because these two variables are highly correlated (the sample correlation I found was .93), I regressed the preliminary effective protection rate series on a constant and the average tariff rates, and then used the resulting equation to "fit" values of ERP for the 11 additional countries. This method produces the final version of the effective rate of protection series, which covers 51 countries in this sample.

Finally, Agarwala (1983) used a similar method to consider the effect of price distortions on economic growth. Noting the general problems with using the effective rate of protection data which I mentioned above, however, he reduced his series of effective rates of protection to a qualitative indicator variable. This variable took the value of "high" if the effective rate of protection in a country was greater than .80, "medium" if it was between .40 and .80, and "low" if it was less than .40. Following Agarwala, I constructed an indicator variable taking values of

¹⁴The nominal rate of protection ignores the effect of a staggered tariff structure which alters the price of inputs as well as the price of the final good. Thus, it is simply equal to the ad valorem tariff rate.

0, 1, and 2 to represent low, medium, and high effective rates of protection.

Needless to say, each of these variables is extremely problematic as a measure of price distortion. Indeed, this is one of the basic reasons why the relative price variables from the Summers and Heston data set are so appealing. However, these additional measures permit independent confirmation of the basic hypothesis of this paper. The results of including these variables in the growth regression are presented in Table 5, and a tentative confirmation is indeed obtained as these variables enter negatively with varying degrees of (in)significance.

Measurement Error, Endogeneity, and Instrumental Variables Correction

Several aspects of the empirical model estimated above suggest that measurement error may be a problem, particularly for the relative price variables. First, the basic quality of the data is questionable, especially for the low-income countries included in the sample, although this is likely to be less important since only countries participating in benchmark surveys are included. In addition, the theoretical analysis in Section II indicated that the input-output price ratio was a critical determinant of growth. The relative price of capital is most certainly only a proxy for this price ratio and will therefore induce measurement error. Finally, because the relative price of machinery is taken from data at the end of the sample period instead at the beginning, there exists a basic question about endogeneity and causality.

In an attempt to address these issues, I use as instruments the alternative price distortion measures discussed above. These instruments are correlated with the relative price variables but are likely to be uncorrelated with the error in measurement. Because the variables are constructed using data from throughout the period, they are also less likely to be endogenous. Clearly, these instruments are themselves measured with error. However, as long as the error in measurement for the instruments is asymptotically orthogonal to the error in measurement for the relative price of machinery, consistent estimates will be obtained.

The results of IV estimation treating the relative price of machinery as endogenous are presented in Table 5. Similar estimation is also undertaken using the ERP indicator variable instead of the relative price of machinery (clearly, the ERP indicator variable is measured with error). In all of the IV regressions, the price variable has the appropriate negative sign. However, the standard errors are generally large, particularly for the relative price of machinery. Hausman (1978) specification tests were conducted, but because of the large standard errors, the null hypothesis of no measurement error could never be rejected. In the end, nothing in the IV regressions is particularly surprising, but no strong results are obtained.

Endogeneity and a Comparison to the De Long and Summers (1991) Results

The basic finding of De Long and Summers (1991) is that the share of machinery investment (which they call "equipment investment") in GDP is a crucial determinant of economic growth. The results discussed above are consistent with those obtained by De Long and Summers but extend and clarify their analysis in several important ways. The primary difference is, of course, that this paper focuses on the estimation of the relative price effect on growth while De Long and Summers focus on the quantity effect. Estimation of the relative price effect is likely to be more useful for two key reasons. First, it is more immune to endogeneity arguments than is the estimation of the quantity effect. And second, because policy instruments work through prices to affect the quantity of investment and the rate of growth, estimating the link between prices and growth is more useful from a policy standpoint. Each of these issues is discussed further below.

De Long and Summers focus primarily on the relationship between economic growth and

the share of machinery investment in a sample of 25 "high productivity" countries.¹⁵ While this relationship is of interest, issues of endogeneity make it a problematic relationship to analyze. The converse of their conclusion may well apply: economic growth could result in a higher share of machinery investment in total output rather than vice versa. This endogeneity could lead De Long and Summers to overstate the effect of machinery investment on growth.¹⁶

In an open economy model, this "reverse causality" argument will not affect my analysis. Because of the open economy assumption, economic growth will increase the machinery investment share only through the demand side. These demand side effects will leave unchanged the price of machinery, which is exogenously given by the world price plus any price distortions. However, changes in the price of machinery (e.g. due to a change in government policy) will still affect machinery investment and hence the rate of economic growth. Thus, focusing on the price instead of the quantity successfully addresses these endogeneity issues in an open economy framework.

In a closed economy model, the "reverse causality" argument can be understood in terms of two nonexclusive effects: economic growth increases the share of investment in output by raising either the demand for investment or the supply of investment. If economic growth increases investment demand, one would expect to find a positive relationship not only between

¹⁵When De Long and Summers do examine the effect of the relative price of machinery on growth, their results are unclear. The only significant and negative coefficients arise when the restricted "high productivity" sample is considered. However, they only estimate the price effect when a variable measuring the share of investment in GDP is included in the regression. Since I have argued above that it is exactly through this channel that the relative price of machinery influences the growth rate of the economy, their results are not surprising. My analysis reveals that when this investment variable is removed from the specification, a strong negative relationship between the price of machinery and economic growth emerges, not only for a small sample of "high productivity" countries, but also for the broadest sample available using the Summers and Heston benchmark data.

¹⁶De Long and Summers make several arguments that endogeneity is not driving their results, including the use of the relative price as an instrument.

growth and the quantity of investment, but also between growth and the price of investment, *ceteris paribus*. To the extent that this type of endogeneity is a problem, my results will be biased in a positive direction--i.e. they understate the true impact of relative price movements on growth. However, if economic growth increases the supply of investment goods, the quantity of investment will rise and the price will fall, suggesting that my results for the price of investment are negatively biased and overstate the true impact of capital taxation on growth.

The net of these two effects in a closed economy model is that reverse causality will produce an unambiguous positive correlation between growth and the quantity of investment. This makes the identification of the impact of machinery investment on economic growth which De Long and Summers attempt to estimate extremely difficult. However, these two effects bias the estimated partial correlation between growth and the price of investment in opposite directions, so the net bias will be ambiguous. Furthermore, to the extent that an open economy model applies, the magnitude of this ambiguous bias will be reduced, while the positive bias in the growth-investment relationship will continue to persist. In this context, it is clear that focusing on the price of investment rather than the quantity is preferable.

Estimation of the price effect instead of the quantity effect is important in its own right for another reason. From a policy standpoint, the magnitude of the price effect is arguably more useful than the magnitude of the quantity effect. Policy instruments such as tax rates and investment tax credits have a direct interpretable effect on the relative price of capital.¹⁷ However, the effect on quantity variables is indirect and more difficult to estimate, so that understanding the relationship between growth and the relative price of capital provides the crucial link between policy and growth. This advantage is exploited in the next section.

¹⁷The only potential problem with interpretation here is in knowing how much of the tax or subsidy is borne by the producer and how much is borne by the consumer. We abstract from this important issue here.

V. The Dynamic Effect of Changes in the Tax Treatment of Machinery

The estimates computed above provide a direct measure of the effect of a change in the relative price of machinery on the growth rate. Coefficients range from a low of about $-.0075$ to a high of about $-.0150$ or even $-.0200$. Taking $-.01$ as an approximate value does not seem implausible, and this implies that a unit increase in the relative price of machinery will reduce the average annual growth rate of the economy by a full percentage point. Recall from Table 2 that this value may slightly overestimate the effect for the less-developed India and slightly underestimate the effect for more developed countries such as the United States. Nevertheless, it serves as a useful benchmark for the comparison of different policies.

While knowledge of these coefficients is very helpful, a crucial piece of information that is absent from this analysis is the current tax treatment of machinery. One would like to know how changing the tax rate (or subsidy rate) on machinery will affect the growth of the economy, and for this we need specific information about the tax rates in a given country.

Ahmad and Stern (1987) present a very detailed view of the tax system in India for 1979-80, including a table of effective tax rates for specific categories in the national accounts. The effective tax rate takes into account both indirect and direct taxes, which Ahmad and Stern argue is crucial to an understanding of the tax system in most developing countries. Using their data it is straightforward to construct an effective tax rate for machinery for the 1979-80 period, and my calculations yield an effective tax rate of 0.218 .¹⁸ Simple manipulation reveals that absent these taxes the relative price of machinery would have been lower by 0.5 .¹⁹ Given a

¹⁸The effective tax rate, as defined by Ahmad and Stern, includes main central government taxes, excise taxes, import duties, and state level taxes. It excludes taxes on capital inputs to production, which will cause the effective tax to understate the true effective tax.

¹⁹According to the benchmark data, the relative price of machinery in 1980 was 2.76 . Using the fact that the absolute price of consumption was 0.428 , it is easy to show that absent the taxes the relative price of machinery would have been 2.27 .

coefficient of $-.01$ on the relative price variable in the growth regression, this suggests that the tax on machinery was responsible for reducing growth in India by approximately one-half of a percentage point. Since the average annual growth rate for 1960-1985 was only 1.4%, the effective tax on machinery had a substantial effect on growth.

Countries such as India with a high relative price of machinery have the most to gain from a reduction in proportional capital taxation, as the following example illustrates. Consider an investment tax credit in the United States, which had a per capita GDP of \$12,532 in 1985. Growing at its 1960-85 average annual growth rate of 2.1%, per capita GDP will reach \$21,185 by the year 2010. Now suppose an investment tax credit of ten percent were introduced. Using the rather pessimistic coefficient of $-.01$ for the effect of the relative price of machinery on growth, U.S. GDP would grow at 2.2% each year to a level of \$21,721 in twenty-five years. With a more optimistic coefficient of $-.02$, the growth rate of output would be raised to 2.3%, and U.S. per capita GDP would reach \$22,271 by 2010--more than one thousand dollars more per person.²⁰ This change is not as dramatic as that for India or other high price countries, but it is by no means negligible.

VI. Conclusions

The effect of capital taxation on the growth rate of the economy will most certainly depend on the context in which the distortions are imposed. However, the analysis I have presented provides a basic framework in which to analyze this effect. Theoretically, it is clear that policies that increase the relative price of capital goods above a competitive level will reduce the growth rate of the economy except in very special circumstances. Conversely, policies that

²⁰Ideally, one would like to consider revenue neutral changes in the tax code. Implicitly, I am assuming that the revenue lost from an investment tax credit or from reducing the tax on machinery would come from a source that would not affect the growth rate substantially.

reduce the relative price of capital such as the reduction of a capital tax or the addition of an investment tax credit will enhance economic growth. Empirically, I find strong support for this hypothesis in a cross section of countries.

Within investment, it appears that the machinery component is particularly important for economic growth. Policies that decrease the relative price of machinery increase the share of investment in gross domestic product, not only by raising machinery's share in output, but also by increasing other components of investment. This increase in investment promotes economic growth, which can have large effects on the level of output over a relatively short span of time. The direct implication of this result is that tax policy designed to stimulate economic growth should focus not only on investment, but more specifically on the components of investment in the machinery category.

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TABLE 1
Variable Statistics

Variable (N=65 unless noted)	Mean	S.D.	Minimum	Maximum
Basic Barro (1991) Variables				
Growth Rate, 1960-85	0.024	0.016	-0.016	0.066
Growth Rate, 1960-75	0.031	0.017	-0.007	0.071
Growth Rate, 1970-85	0.018	0.020	-0.041	0.063
GDP in 1960	2.228	1.895	0.208	7.380
GDP in 1970	3.152	2.627	0.283	9.459
Sec. School E.R., 1960	0.265	0.230	0.010	0.860
Sec. School E.R., 1970	0.396	0.274	0.020	1.000
Prim. School E.R., 1960	0.844	0.292	0.050	1.440
Prim. School E.R., 1970	0.920	0.245	0.170	1.290
Govt. Cons. Share, 1970-85	0.101	0.051	0.014	0.240
Country Characteristic Variables				
War Indicator Variable	0.385	0.490	0.000	1.000
Number of Revolutions	0.138	0.189	0.000	0.850
Socialist Govt. Indicator	0.062	0.242	0.000	1.000
Latin America Indicator	0.277	0.451	0.000	1.000
Sub-Saharan Africa Ind.	0.200	0.403	0.000	1.000
Relative Price Variables				
Total Investment	1.423	0.526	0.518	2.745
Nonres. Construction (N=60)	1.540	1.036	0.557	5.535
Producer Durables	1.768	0.738	0.814	3.639
Transport Equipment	1.863	1.078	0.668	6.245
Machinery	1.787	0.713	0.787	3.438
Electrical Machinery	1.973	0.962	0.612	4.798
Nonelectrical Machinery	1.760	0.689	0.754	3.440
Non-machinery Investment	1.349	0.564	0.428	3.147
Investment Share in GDP Variables				
Investment Rate, 1960-85 Avg.	0.199	0.073	0.055	0.369
Investment Rate, 1970-85 Avg.	0.204	0.072	0.052	0.383
Machinery Inv. Share, 1980	0.054	0.027	0.015	0.145
Other Price Distortion Variables (N=51)				
Tariff Revenue Share	0.152	0.140	0.001	0.480
Effective Rate of Protection	0.595	0.608	0.020	2.650
E.R.P. Indicator (0,1,2)	0.745	0.821	0.000	2.000

TABLE 2

Growth and the Relative Price of Machinery
Dependent Variable: Annual Growth Rate of GDP per capita

Sample	Initial GDP per capita	Initial Secondary School E.R.	Initial Primary School E.R.	Average Govt Consumption/ GDP	Relative Price of Machinery	S.E.E.	R ²
1960-1985							
Total* (N=65)	-.0068 (.0011)	.0191 (.0073)	.0052 (.0050)	-.0952 (.0347)	...	.0106	.64
Total* (N=65)	-.0075 (.0010)	.0088 (.0096)	.0023 (.0045)	-.0864 (.0307)	-.0076 (.0036)	.0100	.68
GDP > 10% of U.S. (N=50)	-.0071 (.0015)	.0308 (.0120)	.0197 (.0071)	-.1322 (.0424)	-.0072 (.0035)	.0112	.53
GDP > 20% of U.S. (N=29)	-.0072 (.0018)	.0123 (.0115)	-.0034 (.0068)	-.0725 (.0435)	-.0195 (.0048)	.0107	.62
1960-1975							
Total* (N=65)	-.0084 (.0011)	.0094 (.0103)	-.0010 (.0077)	-.0973 (.0318)	-.0148 (.0037)	.0111	.64
GDP > 10% of U.S. (N=50)	-.0084 (.0013)	.0264 (.0108)	.0083 (.0108)	-.1557 (.0410)	-.0118 (.0038)	.0116	.56
GDP > 20% of U.S. (N=29)	-.0082 (.0015)	.0092 (.0127)	-.0217 (.0131)	-.1086 (.0344)	-.0203 (.0061)	.0099	.72
1970-1985							
Total* (N=65)	-.0058 (.0016)	-.0016 (.0158)	.0063 (.0082)	-.1037 (.0399)	-.0049 (.0045)	.0142	.58
GDP > 10% of U.S. (N=50)	-.0049 (.0023)	.0392 (.0170)	.0295 (.0136)	-.1474 (.0501)	-.0034 (.0051)	.0166	.34
GDP > 20% of U.S. (N=29)	-.0059 (.0026)	.0338 (.0199)	.0184 (.0245)	-.0826 (.0600)	-.0188 (.0051)	.0146	.46

NOTES: A constant term is suppressed in the results. Regressions labelled with an asterisk (*) have the following country characteristics variables taken from Barro (1991) suppressed as well: War indicator variable, Number of revolutions during 1960-1985, Socialist government indicator, and indicator variables for the Latin American and Sub-Saharan Africa regions. These variables are omitted from the other specifications. White heteroskedasticity-robust standard errors are reported in parentheses.

TABLE 3
Growth and the Sub-aggregates of Capital Formation
Dependent Variable: Annual Growth Rate of GDP per capita, 1960-1985

Relative Price Variable	Relative Price Variable (See First Column)	Relative Price of Machinery	S.E.E.	R ²
Non-Machinery Investment	.0001 (.0026)	-.0076 (.0034)	.0101	.68
Nonres. Construction (N=60)	.0008 (.0016)	-.0086 (.0039)	.0105	.68
Transport Equipment	.0018 (.0011)	-.0095 (.0041)	.0100	.69
Total Investment	-.0056 (.0039)	...	.0104	.66
Non-Machinery Investment	-.0027 (.0034)	...	.0106	.64
Nonres. Construction (N=60)	-.0012 (.0022)	...	.0111	.63
Producer Durables	-.0058 (.0032)	...	.0103	.66
Transport Equipment	-.0013 (.0012)	...	.0106	.61
Electric Machinery	-.0040 (.0023)	...	.0103	.67
Nonelectric Machinery	-.0076 (.0035)	...	.0101	.68

NOTES: The sample size is sixty-five countries unless noted. The "Relative Price Variable" in the second column differs in each regression and is given by the first column. A constant term, the country characteristics variables, and the Barro (1991) variables included in Table 2 were included in each specification. White heteroskedasticity-robust standard errors are reported in parentheses.

TABLE 4

Investment Rates and the Relative Price of Machinery

Dependent Variable	Initial GDP per capita	Initial Secondary School E.R.	Initial Primary School E.R.	Average Govt Consumption/ GDP	Relative Price of Machinery	S.E.E.	R ²
Total Investment Share of GDP, 1960-85 Avg.	-.0132 (.0054)	.0849 (.0559)	.0727 (.0298)	-.0655 (.1041)	-.0581 (.0114)	.0499	.61
Total Investment Share of GDP, 1970-85 Avg.	-.0172 (.0051)	.0629 (.0589)	.0619 (.0302)	-.0678 (.1133)	-.0666 (.0133)	.0498	.59
Machinery Investment Share of GDP, 1980	-.0033 (.0021)	.0053 (.0210)	-.0108 (.0107)	-.0229 (.0427)	-.0293 (.0063)	.0180	.63

NOTES: A constant term and the following country characteristics variables taken from Barro (1991) are suppressed in the results: War indicator variable, Number of revolutions during 1960-1985, Socialist government indicator, and indicator variables for the Latin American and Sub-saharan Africa regions. These variables are omitted from the other specifications. White heteroskedasticity-robust standard errors are reported in parentheses.

TABLE 5

IV Estimation and Other Price Distortion Measures
Dependent Variable: Annual Growth Rate of GDP per capita

Price Distortion Variable	Initial GDP per capita	Initial Secondary School E.R.	Initial Primary School E.R.	Average Govt Consumption/GDP	Price Distortion Variable	S.E.E.	R ²
<i>OLS Estimation</i>							
Tariff Revenue Share (N=51)	-.0070 (.0013)	.0106 (.0082)	.0127 (.0069)	-.1174 (.0318)	-.0167 (.0115)	.0096	.69
Effective Rate of Protection (N=51)	-.0069 (.0013)	.0129 (.0089)	.0108 (.0074)	-.1251 (.0318)	-.0042 (.0033)	.0095	.70
E.R.P. Indicator (N=51)	-.0070 (.0013)	.0102 (.0083)	.0088 (.0074)	-.1214 (.0300)	-.0062 (.0026)	.0090	.73
<i>Instrumental Variables Estimation</i>							
Relative Price of Machinery ^{b,c} (N=46)	-.0055 (.0013)	-.0052 (.0110)	.0072 (.0056)	-.0980 (.0296)	-.0066 (.0046)	.0085	...
Relative Price of Machinery ^{a,c} (N=46)	-.0054 (.0013)	-.0033 (.0115)	.0078 (.0059)	-.1020 (.0308)	-.0052 (.0049)	.0082	...
E.R.P. Indicator ^a (N=51)	-.0069 (.0013)	.0110 (.0087)	.0096 (.0074)	-.1227 (.0305)	-.0048 (.0034)	.0090	...
E.R.P. Indicator ^{a,c} (N=51)	-.0069 (.0013)	.0112 (.0087)	.0097 (.0074)	-.1229 (.0305)	-.0045 (.0034)	.0089	...
E.R.P. Indicator ^{a,d} (N=51)	-.0052 (.0013)	.0025 (.0088)	.0088 (.0062)	-.1138 (.0279)	-.0025 (.0032)	.0077	...

NOTES: A constant term and the country characteristic variables listed in Table 2 are suppressed in the results. White heteroskedasticity-robust standard errors are reported in parentheses. In the IV estimation regressions, only the price distortion measure is assumed to be endogenous. The instruments used in each regression are listed as superscripts with the following meanings:

- (a) Effective Rate of Protection (E.R.P.)
- (b) E.R.P. Indicator Variable
- (c) Tariff Revenue Share in Total Revenue
- (d) Relative Price of Machinery

The construction of these instruments is discussed more fully in the text.

Figure 1

Annual GDP Growth vs. Machinery Price (N=65)

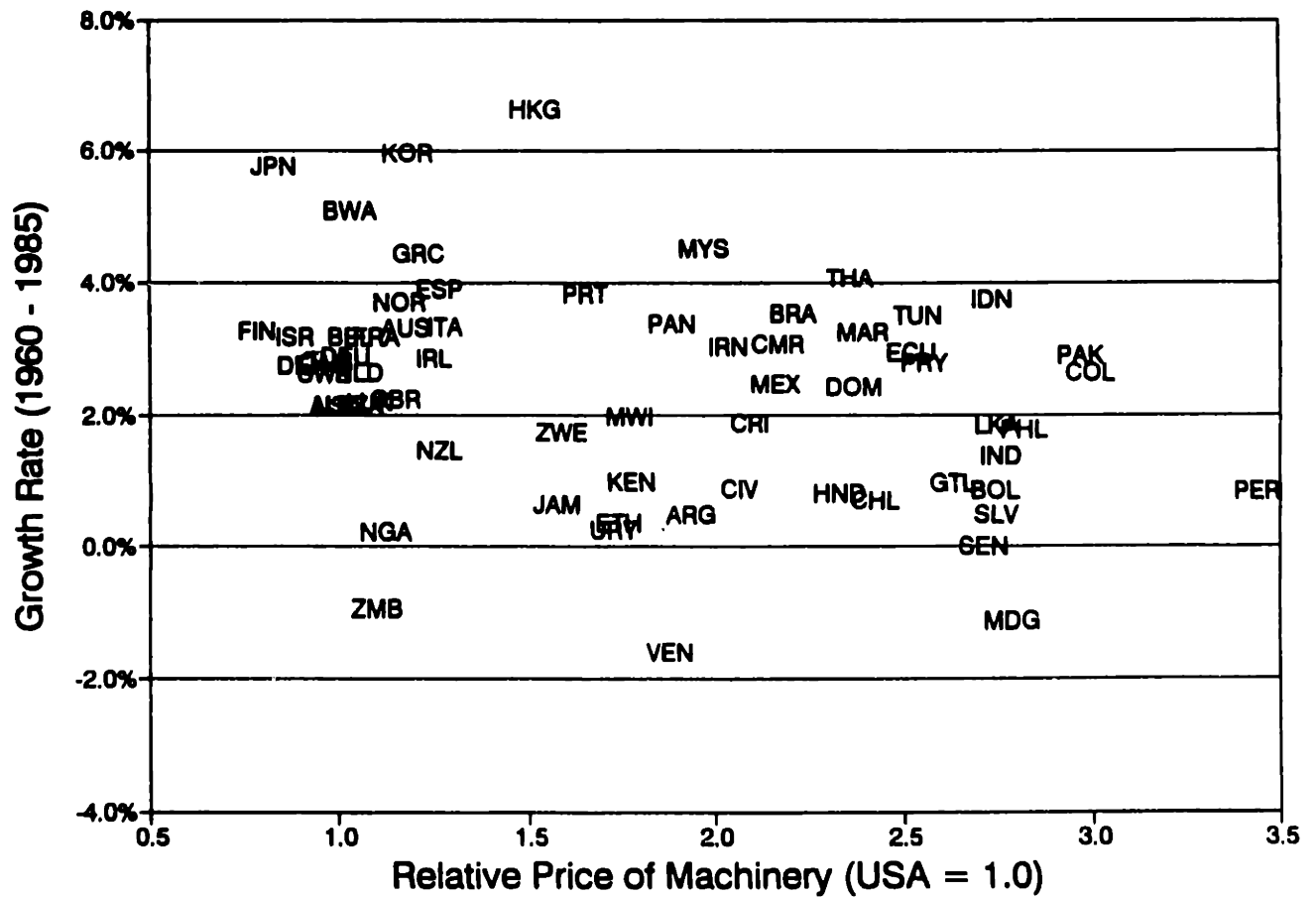


Figure 2

Initial GDP p.c. vs. Machinery Price
(N=65)

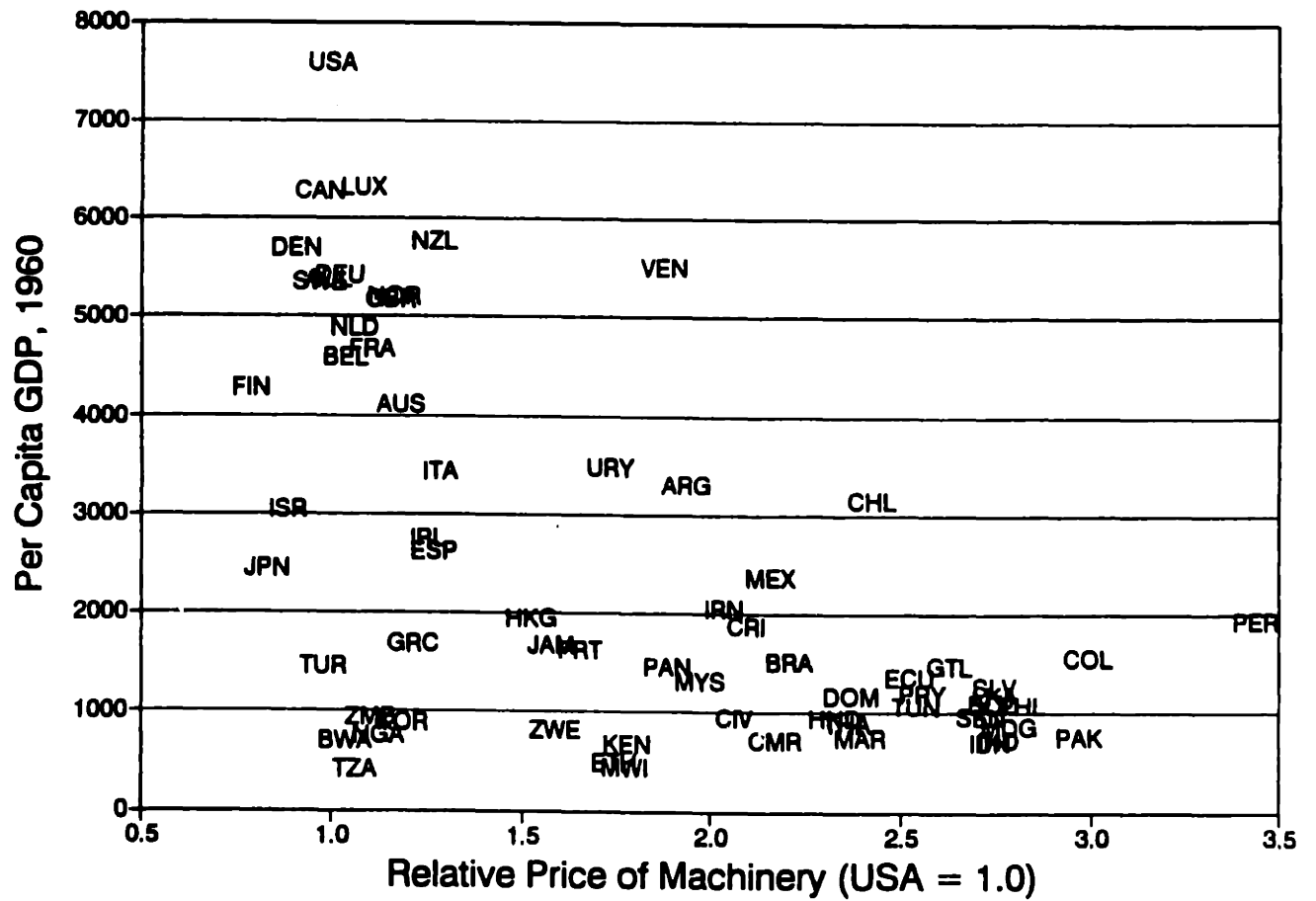


Figure 3
Annual GDP Growth vs. Machinery Price
Partial Correlation (N=65)

